Evaluation of Wave-Adaptive Modular Vessel Suspension Systems for Improved Dynamics

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Abstract

A study is conducted to test the dynamics of the 33ft Wave-Adaptive Modular Vessel (WAM-V) when outfitted with different suspension systems. Instrumented with an array of sensors, the vessel is tested with two different suspension arrangements to characterize how they affect WAM-V dynamics, and to ultimately select a suspension that is most suitable for the 33ft WAM-V and other vessels that are planned for the future.

Optimizing the suspension can reduce the magnitude of accelerations at the payload tray, benefiting both the operator and the payload. Reduced accelerations can significantly improve comfort and risk of injury to the operator, while also lessening the likelihood of any damage to any sensitive cargo onboard. The stock suspension components are characterized through in-house tests conducted at the Center for Vehicle Systems and Safety (CVeSS) at Virginia Tech (VT). Based on the stock characterizations, new suspension components are chosen to better fit the needs of the 33ft WAM-V.

Sea trials are conducted with both suspension systems at the Combatant Craft Division (CCD), a division of the Naval Surface Warfare Center, Carderock Division (NSWCCD), in Norfolk, VA to quantitatively and qualitatively determine the differences between the two suspensions. The 33ft WAM-V is instrumented with a series of accelerometers and potentiometers for measuring accelerations and displacements. The data is analyzed for the sea trials conducted at CCD and the results of the analysis indicate that the suspension selection can significantly affect the transmission of shock and vibrations from the pontoons to the operator or payload tray. Both suspensions are able to mitigate a significant amount of the shocks seen at the pontoons, however, the results do not definitively show which suspension is the better of the two. This is due to the fact that each suspension is not subjected to the exact same wave conditions, and

therefore the resulting suspension dynamics vary. For instance, during a 2-foot wave event, the new suspension attenuates more shock than the stock suspension, 76% versus 71%. However, during a 4-foot wave event, the stock suspension attenuates more shock than the new suspension, 66% versus 60%.

Additionally, the suspension selection can significantly influence the ride height. The stock suspension provides a 70/30 ratio between extension and compression stroke, while the new suspension provides a 50/50 ratio. The more balanced split between the extension and compression strokes allow for better utilizing the total available stroke for the suspension in both directions. This significantly reduces the resulting high-g impacts since the suspension does not frequently bottom out when the vessel is subjected to a large wave.

It is recommended that the results of this study be extended through laboratory dynamic testing that allows for more repeatable dynamic events than sea trials in order to better establish the influence of each suspension parameter on the vessel dynamics. Such tests will also allow for a better understanding of the dynamics of the vessel in response to various inputs at the pontoons, both subjectively (visually) and objectively (through measurements).

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Chapter 1 Introduction

Wave-Adaptive Modular Vessel (WAM-V) technology was developed by Marine Advanced Research, Inc. (M.A.R.) to use the advantages of catamarans in conjunction with suspension systems typically found on road vehicles to increase stability of the vessel and reduce the magnitude of the accelerations at the payload tray. The WAM-V concept uses a suspension with ball joints located between the payload tray and front arch to mitigate the motions of the pontoons, letting the front arch move independently from the payload tray. The suspension systems also move independently of each other, letting one pontoon move without influence from the other. The Center for Vehicle Systems and Safety (CVeSS) at Virginia Tech (VT) and the Combatant Craft Division (CCD) of the Naval Surface Warfare Center, Carderock Division (NSWCCD) are working together in testing efforts to capture the dynamics of the 33ft WAM-V. Figure 1-1 shows the 33ft WAM-V, the third generation WAM-V design.

Figure 1-1: 33ft WAM-V

The United States Navy has a need for versatile vessels that can perform many different kinds of mission objectives. With a relatively large payload tray given the size of the vessel, the WAM-V is capable of transporting a number of items at one time. One such mission for the WAM-V is to transport unmanned vehicles closer to their destination before the vehicles take off using their own fuel supply, thus lengthening the mission time of the individual vehicles. In order to ensure that the unmanned vehicles arrive at the destination in a condition to function properly, the

WAM-V needs to be capable of mitigating the shocks from the ocean to the payload tray. Large accelerations can easily be transmitted to the payload tray with an inadequate suspension system, potentially damaging the unmanned vehicles onboard. The WAM-V is also capable of retrieving such vehicles upon mission completion.

With a low draft and jet propulsion system, the later generations of WAM-V can act as a landing craft. Landing crafts are used to transport personnel and supplies to areas where a larger ship cannot dock [15]. Typically, they are crafts that are able to pull up to the land, then reverse and return to open waters without getting stuck. WAM-Vs outfitted with jet propulsion systems will be able to carry out landing craft missions, delivering supplies or unmanned ground vehicles to the shore.

The WAM-V platform also has the capability of loitering for a prolonged period of time for surveillance or data-collecting purposes. The WAM-V can be outfitted with a data acquisition system to survey an area before personnel are deployed, or to simply collect wave data. These data acquisition systems can be powered by a generator located on the payload tray or by using energy harvesting technologies. Energy harvesting technologies are being developed at CVeSS to utilize the movement seen in suspension systems to generate energy [9]. The movement of the WAM-V suspension, even when standing still, can be used to generate the power to run auxiliary systems.

1.1 Motivation

The motivation for this research is to optimize the suspension in order to reduce the shocks and accelerations experienced at the payload tray and thereby improve payload and operator comfort.

With the possible objective of delivering unmanned vessels to their mission area, the WAM-V must be capable of reaching the mission area with the vessels ready for deployment. Shock-mitigating seats are used onboard high speed crafts to reduce the shocks to the personnel (soldiers, Marines, etc.) during transport [8]. Just as the shock-mitigating seat reduces the amount of shock to the personnel, the suspended payload tray reduces the shock transmission to the payload.

Regulations state that all prototype vessels that are undergoing testing, even those meant to be unmanned, must have at least one personnel onboard the vessel. The suspension needs to be optimized to provide the most attenuation between the pontoons and where the operator is situated, the payload tray. The remote controls used to pilot the WAM-V require two hands, such that the operator has to remove his hands from the remote controls to brace against impact. The role of the suspension is to mitigate enough of the shock seen at the waves so the operator has a relatively smooth ride while operating the WAM-V.

1.2 Objectives

The objectives of this project are to:

1) characterize the 33ft WAM-V stock suspension,
2) suggest and implement new suspension components based on characterization of the stock suspension,
3) characterize the new suspension components,
4) conduct sea trials with both suspensions and compare the results, and
5) provide recommendations for future testing of the 33ft WAM-V.

1.3 Approach

In-house testing of the stock suspension system is conducted to characterize the stock suspension of the 33ft WAM-V. Based on the characterization of the stock suspension, new suspension components are selected to better fit the needs of the 33ft WAM-V. Testing of the WAM-V with the stock suspension is conducted at sea, followed by testing of the new suspension. The tests include running the WAM-V in Sea State 1 (SS1) and Sea State 2 (SS2) conditions. The data is analyzed to compare the performance of the WAM-V with the two different suspensions. Based on the analysis, recommendations are made for further studies of the 33ft WAM-V suspension.

1.4 Contribution

This study has contributed to the validation of a multi-body dynamics model of WAM-V technology under development at CVeSS [1, 2, 12]. This model, which is not within the scope of this thesis, is being designed to be scalable for various sizes of WAM-Vs. For example, with differing pontoon diameters, vessel length and beam, and suspension characteristics, the multi-body dynamics model will be able to simulate the response of the WAM-V without having to build and test an actual WAM-V with those characteristics.

By choosing suspension components that are better suited for the 33ft WAM-V, the performance of the vessel can be greatly improved. Choosing suspension components that can be easily changed and adjusted provides a large range of suspension characteristics that can contribute to fully validating the WAM-V model.

1.5 Thesis Organization

This document includes six chapters. Chapter 2 discusses the background of the WAM-V concept, as well as what is typically found in a conventional road vehicle suspension system. Chapter 3 details the tests that were conducted to characterize the stock suspension and how the new suspension components are chosen from the results of those tests. Chapter 4 describes the test setup of the 33ft WAM-V, including details of the instrumentation, test patterns conducted, and sea trial setup. Chapter 5 discusses the analysis of the data collected during testing, and Chapter 6 summarizes the findings of the research and ends with recommendations for future work towards improving future WAM-V designs.

Chapter 2 Background Information

The purpose of this chapter is to provide background information on the three generations of the WAM-V and on conventional suspension systems used in road vehicles.

2.1 Wave-Adaptive Modular Vessels

A WAM-V is a catamaran vessel outfitted with ball joints and suspension systems to mitigate the shocks and accelerations experienced at the pontoons from being transmitted to the operator. The suspension systems, like those typically found in road vehicles, absorb and dissipate the shocks experienced due to sea conditions, thereby reducing the amount of shock and accelerations experienced by the operator of the vessel. The third generation WAM-V design, the 33ft WAM-V, is developed based on the analysis conducted from testing the first two WAM-V generations, the 100ft Proteus and the 12ft unmanned surface vessel (USV).

2.1.1 First Generation: 100ft Proteus

The first generation WAM-V, shown in Figure 2-1, is the 100ft Proteus. Proteus is equipped with two suspension points connecting each pontoon to two arches for a total of four suspension points. Two arches, one in the front and one in the rear, connect the suspension points to the payload tray and cabin. The main ball joint is situated between the front arch and the payload tray and cabin.

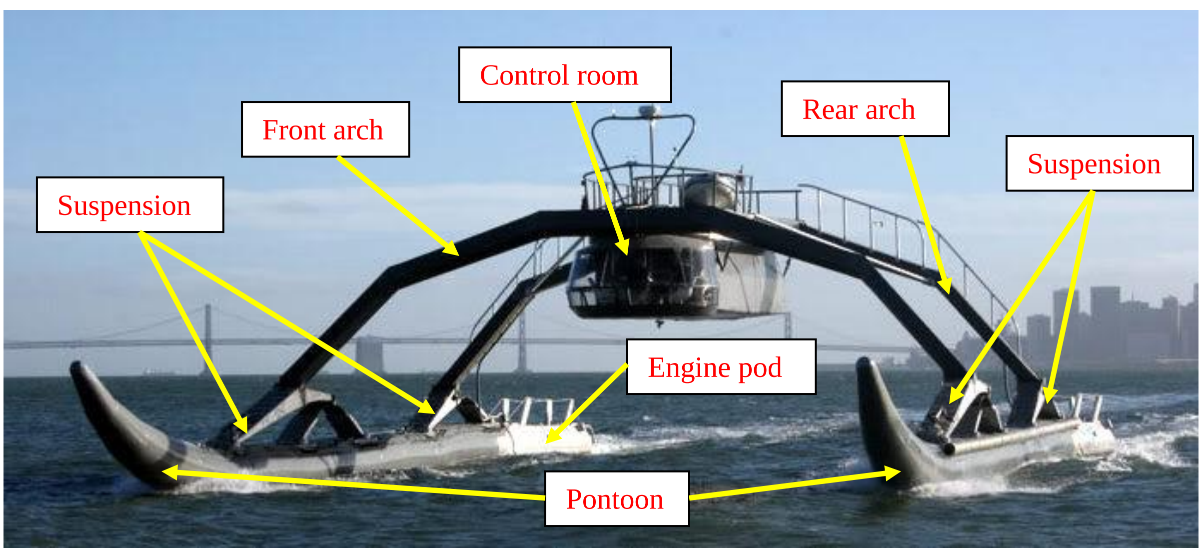

Figure 2-1: First generation WAM-V, 100ft Proteus

By having the front arch connected to the payload tray and cabin with a ball joint, the two structures can move independently from each other, thus limiting the roll seen in the payload tray and cabin. The engine pods at the rear of both pontoons are not rigidly connected to the pontoons, but are hinged so that they can move independently from the pontoons. By having the hinged connection, the engine pods can stay in contact with the water as Proteus travels through the waves.

Each suspension point of Proteus consists of leaf springs to mitigate the shocks from the pontoons to the payload tray and cabin. The suspension does not include a damper, as shown in Figure 2-2.

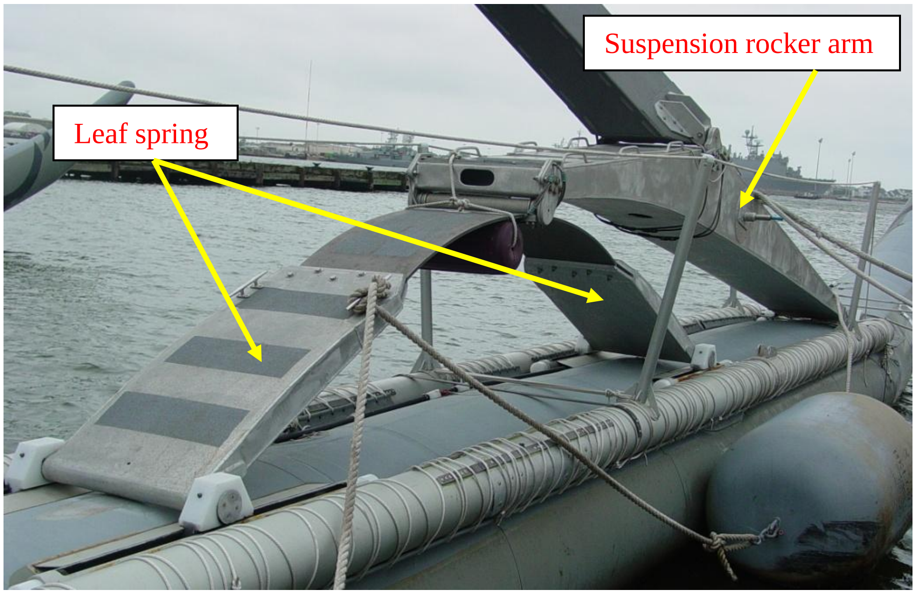

Figure 2-2: 100ft Proteus suspension

Due to the softening of the suspension, the Proteus suspension is prone to bottoming out in compression, causing large impact loads at the crew compartment [6]. Proteus has been scrapped after serving its useful life.

2.1.2 Second Generation: 12ft USV

The second generation of the WAM-V concept is the 12ft USV, shown in Figure 2-3. This vessel is significantly smaller than the first generation Proteus and is controlled via remote control with the possibility of autonomous operation. The 12ft USV has almost the same components as Proteus but with some changes based on what was learned from testing Proteus.

One thing determined from Proteus testing is that the two connection points at the rear should not be suspended for better roll stability. Instead of having four suspension points, the 12ft USV only has two suspension points at the front, and joints at the two rear points allowing rotation about the transverse and vertical directions. The payload tray is still connected to the front arch through a ball joint and rigidly connected to the rear arch.

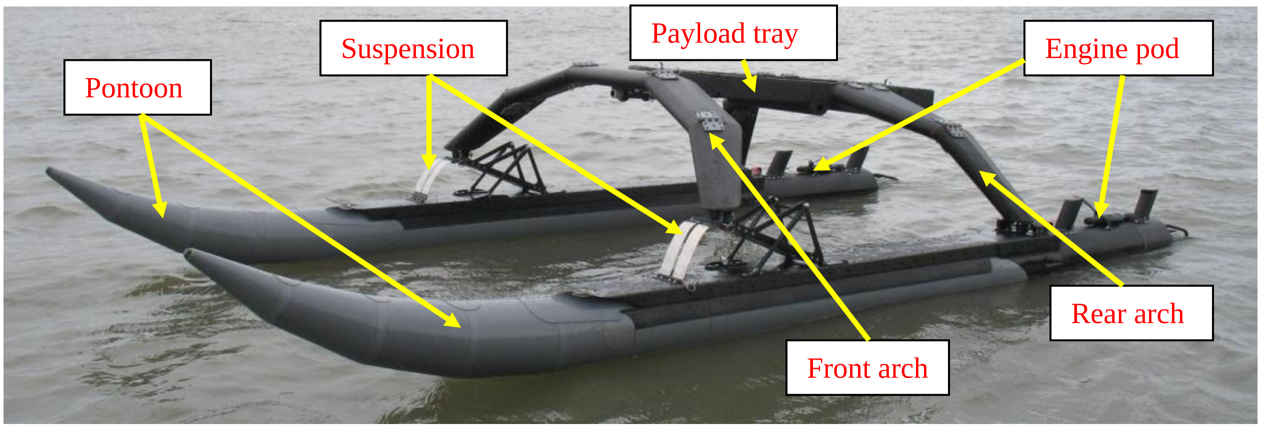

Figure 2-3: Second generation WAM-V, 12ft USV

The suspension is also slightly altered from Proteus by adding an airspring, to increase the amount of restoring force, in addition to a leaf spring. However, no damper is incorporated into the 12ft USV suspension design. Another change to the USV suspension is the addition of a ball joint between the front arch and suspension, allowing independent movement between the two components [6]. Figure 2-4 shows the 12ft USV suspension system.

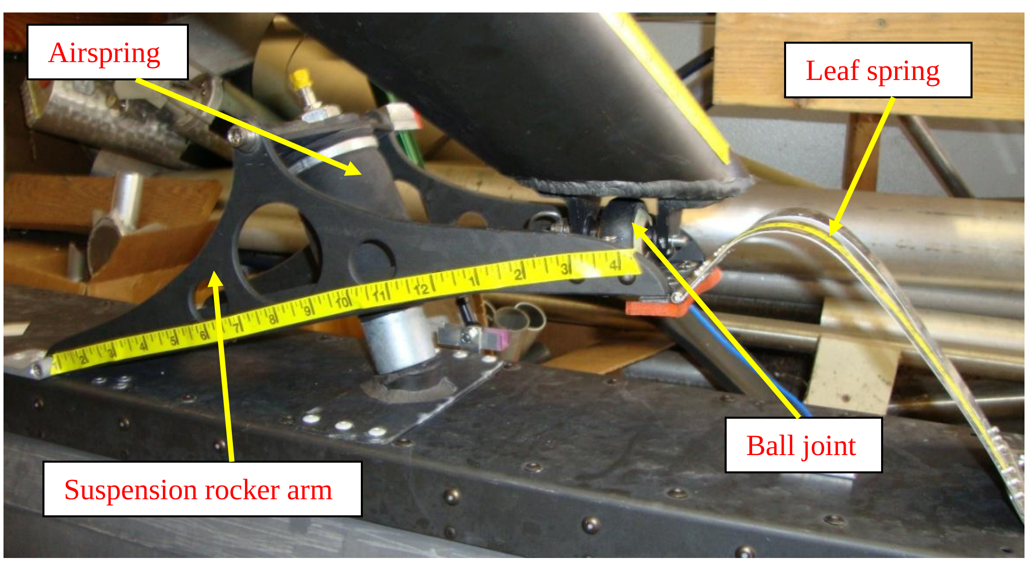

Figure 2-4: 12ft USV suspension

Since no damper is incorporated in the 12ft USV as well, analysis is done to approximate the amount of damping seen that is generated by non-linear friction damping of the leaf spring and airspring present. A linear rate of 30N-s/m is chosen as the baseline damping rate for the 12ft USV, even though the damping present is non-linear [6]. The third generation WAM-V suspension is modified to have one airspring and two dampers.

2.2 Third Generation: 33ft WAM-V

The third generation WAM-V is the 33ft WAM-V, and is the subject of this research. The 33ft WAM-V has two suspension systems at the front, a main ball joint connecting the front arch to the payload tray, a rigid connection between the payload tray and rear arch, and connections between the rear arch and pontoons that only allow rotation about the transverse and vertical directions. Figure 2-5 shows the 33ft WAM-V.

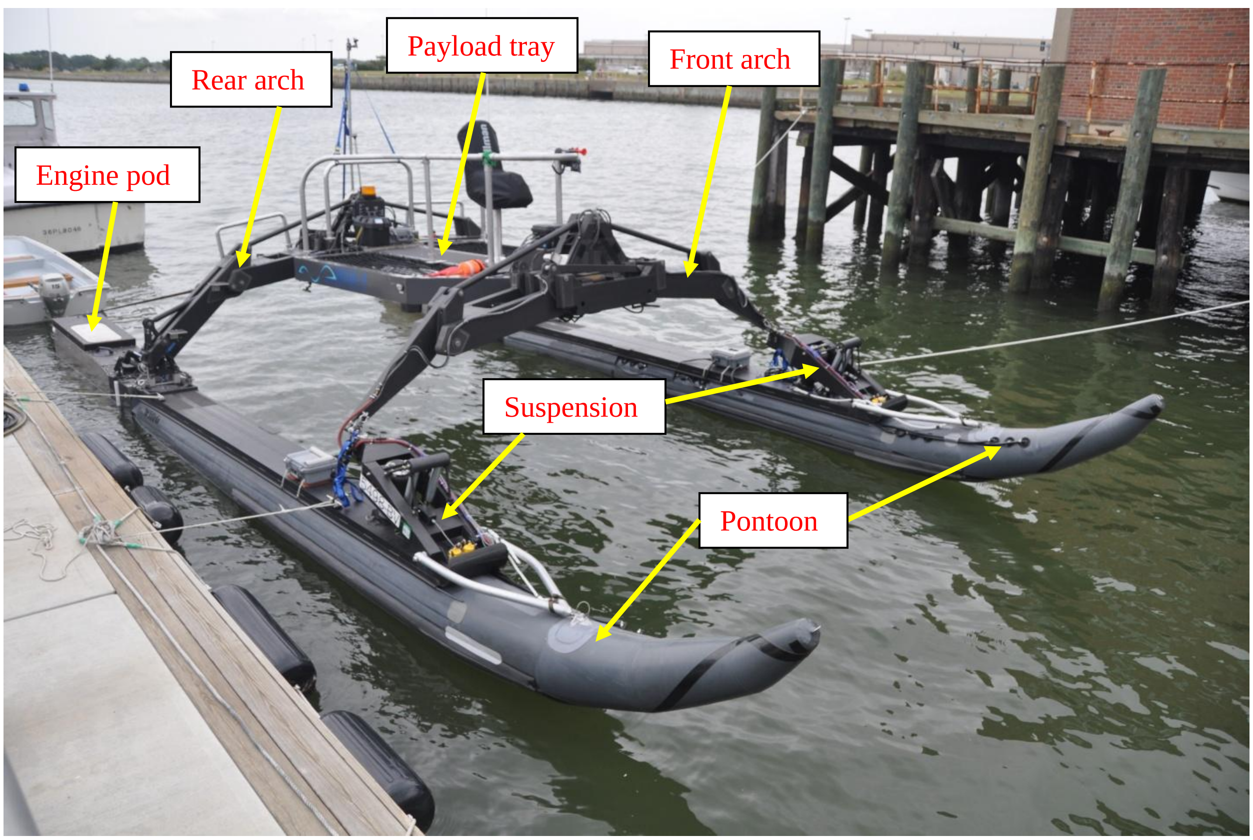

Figure 2-5: Third generation WAM-V, 33ft WAM-V

A big change made to the third generation design is that it can hydraulically fold and unfold. At the request of the Office of Naval Research (ONR), the 33ft WAM-V is capable of fitting inside an 8 foot x 20 foot x 8 foot shipping container. With arches that can fold and unfold hydraulically, the width of the 33ft WAM-V can be reduced from 16 feet to 8 feet. By deflating the pontoon bows and rotating the engine pods underneath the payload tray, the length of the 33ft WAM-V can be reduced from 33 feet to 19 feet. Figure 2-5 showed the WAM-V fully unfolded, while Figure 2-6 shows the WAM-V on its trailer in the folded configuration; however, the pontoon bows have not been deflated and folded back, so the WAM-V remains a little longer than 19 feet.

Figure 2-6: 33ft WAM-V folded up on its trailer

Another big change made to the 33ft WAM-V is the suspension system. Instead of having leaf springs and airsprings like the 12ft USV, the 33ft WAM-V uses one airspring and two dampers for each suspension. Figure 2-7 shows the 33ft WAM-V suspension.

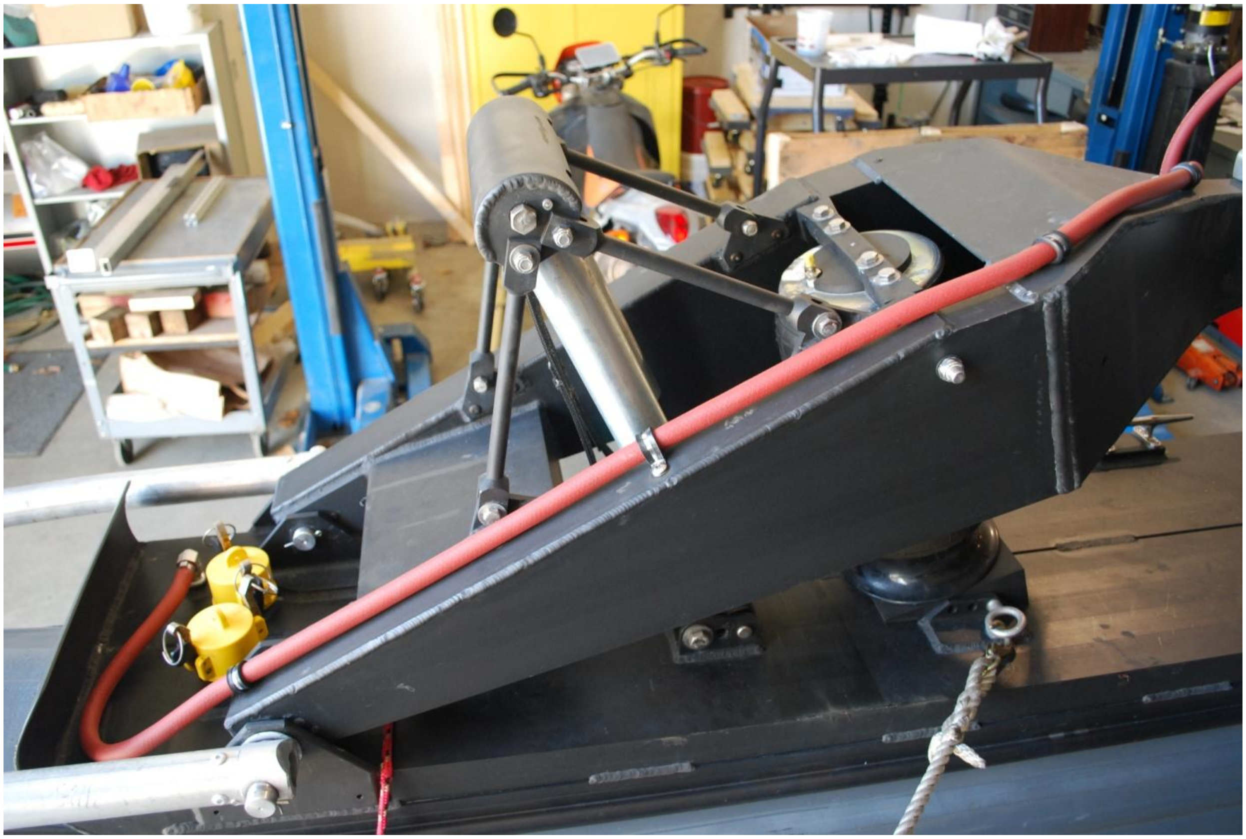

Figure 2-7: 33ft WAM-V suspension

The remainder of this thesis is concentrated on the characterization and improvement of the 33ft WAM-V suspension system.

2.3 Conventional Road Vehicle Suspensions

While conventional boats do not have suspension systems, the WAM-V concept attempts to use them to their advantage. Since the suspension is quite similar to road vehicles, a similar approach is taken to characterize the WAM-V suspension.

A conventional vehicle suspension is comprised of a spring and damper attached between the sprung and unsprung weight of the vehicle. The sprung weight is usually comprised of all the components above the suspension, while the unsprung weight is comprised of everything below the suspension [7]. Figure 2-8 shows a schematic of a suspension system, which is represented by a quarter car model.

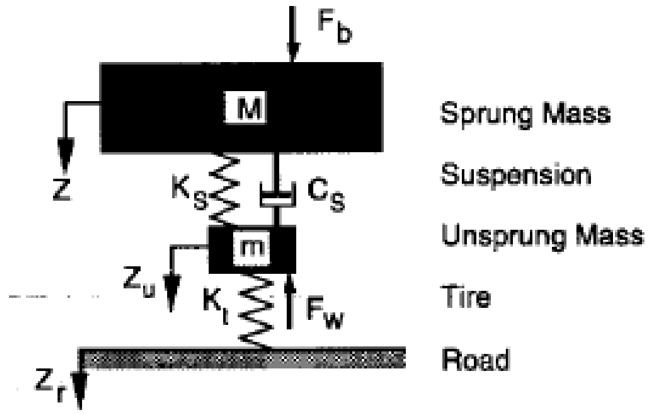

Figure 2-8: Quarter car model representing conventional vehicle suspension system [7]

In conventional road vehicle suspension systems, the spring and damper characteristics determine the effectiveness of the suspension. Based on the amount of weight the suspension must support at the suspension corner, a spring of the correct size can be chosen. The spring rate is determined by the suspended weight and by how much travel is available [13]. Equation (2-1) shows that the minimum spring rate is determined by those two factors:

$$k_{\min} = \frac{\Delta M_{\max} g}{\Delta u_{\max}} \tag{2-1}$$

where $k_{\min}$ is the minimum allowable spring rate in lb/ft, $\Delta M_{\max}$ is the maximum load on that suspension corner in slugs, g is the acceleration due to gravity in ft/s^2, and $\Delta u_{\max}$ is half the maximum amount of travel allowed in feet. $\Delta u_{\max}$ is constrained this way to ensure that the spring does not deflect more than half of the maximum value from the load alone [13].

A conventional road vehicle suspension typically has a higher damping value in extension than in compression. A common compression/extension damping ratio is 30/70 for passenger cars, but can also vary from 20/80 to 50/50. With motorcycles, the ratios are even more skewed towards the extension side, with ratios of 20/80 to 5/95 [4].

Since there are typically two different values of damping with a conventional road vehicle suspension, the average of the total damping is taken to determine the total damping of the system. A typical passenger vehicle will have an average total damping ratio, ζ, of 0.2 to 0.4, while competition cars will have higher values of 0.4 to 1.0 [4]. Damping ratio is determined by Equation (2-2):

$$\zeta = \frac{c}{2\sqrt{km}} \tag{2-2}$$

where ζ is the damping ratio, c is the damping rate in lb-s/in, k is the spring rate in lb/in, and m is the mass in slugs.

Figure 2-9 shows the effect of different damping ratios over time.

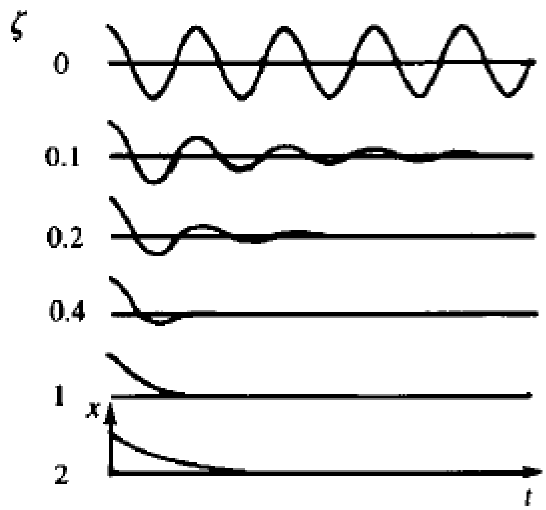

Figure 2-9: Various damping ratios over time [3]

Under-damped damping values, $0 \le \zeta < 1$, will cause the system to oscillate repeatedly before finally settling down, with values close to zero oscillating more than values approaching 1. A critically damped ratio, $\zeta = 1$, returns the system back to its original position in the shortest amount of time without any oscillation or overshoot. A damping ratio of $\zeta = 2$ is over-damped and will return to the original position without overshoot; however, it will take a longer time to do so than the critically damped case [3].

More damping in extension is usually desired due to the fact that during compression, energy is stored in the spring of the suspension system. The damping value in extension is there to dissipate the energy that has been stored in the spring. Too little damping in compression leads to more suspension movement than necessary to travel over a bump, possibly leading to the wheel losing contact with the road, as nothing stops the wheel from traveling upwards. Too much compression damping leads to a very harsh ride where the entire sprung mass is also moved upwards and the wheel also potentially loses contact with the road. With too little damping in extension, the sprung mass of the vehicle can oscillate uncontrollably, and the movement of the chassis can lead to the wheels losing contact with the road. Too much damping in extension and the wheel is not able to follow the profile of the bump after compression, leading to a very slow extension of the damper and once again, the possibility of the wheel losing contact with the road [14].

With a spring and damper that are correctly sized for the application, a vehicle suspension is able to reduce the amount of accelerations transmitted from the wheels to the driver and passengers.

Chapter 3 Suspension Characteristics

This chapter covers the characterization of the 33ft WAM-V suspension. The stock suspension components are characterized, followed by describing in-house tests that were conducted to help choose new suspension components better suited for the 33ft WAM-V. The chapter ends with choosing and characterizing the new suspension components.

3.1 Stock Suspension Description

The 33ft WAM-V arrived at CVeSS with a suspension comprised of three components within a suspension rocker arm: one airspring and two monotube dampers. The stock airspring is manufactured by Firestone, and the stock dampers by Fox Racing Shox. In addition to the suspension components, two limit straps are positioned in front of the dampers in order to keep the suspension from extending too far upwards, which could potentially damage the suspension components. The stock suspension setup is shown in Figure 3-1 with all its components. The individual components, dampers and airspring, are shown in Figures 3-2 and 3-3, respectively.

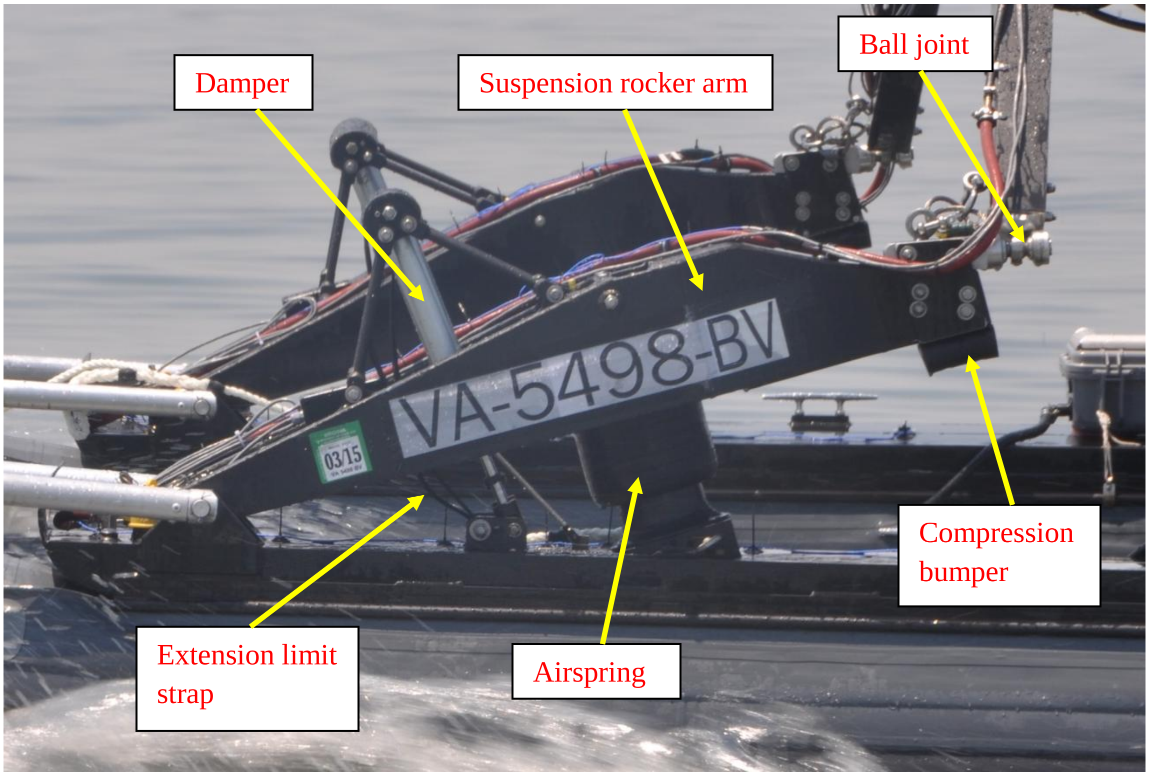

Figure 3-1: 33ft WAM-V stock suspension

Figure 3-2: 33ft WAM-V stock dampers

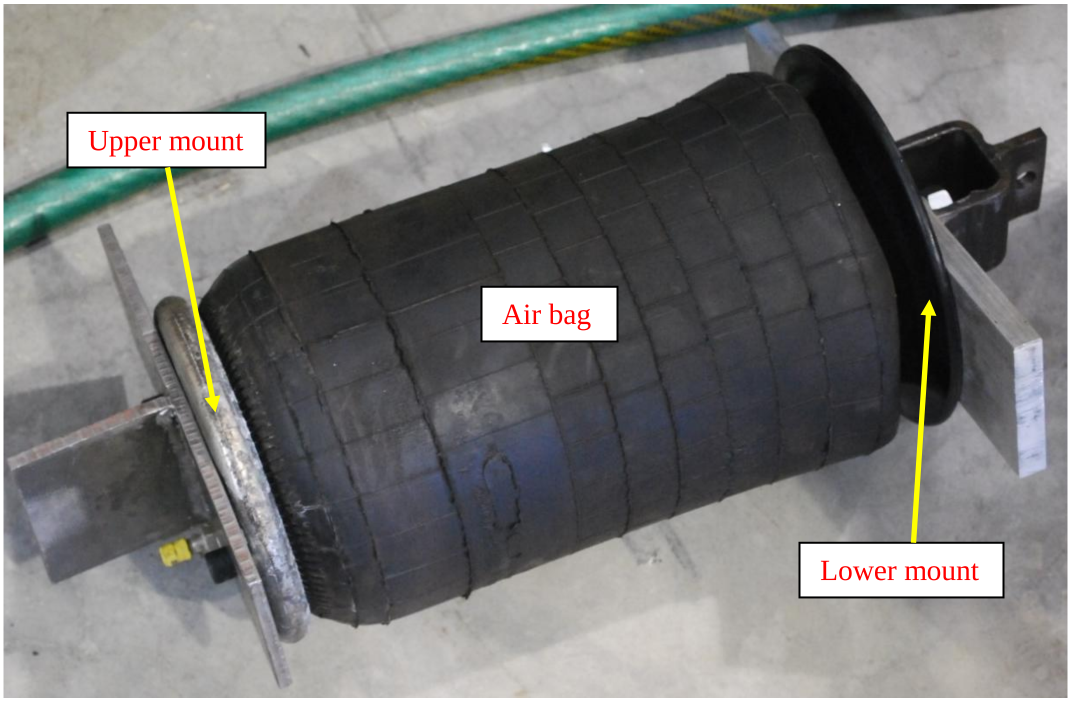

Figure 3-3: 33ft WAM-V stock airspring

The motion ratios between the suspension ball joint, airspring position, and stock damper position are found by measuring the heights of each suspension component. Figure 3-4 shows a drawing of the suspension. The ball joint height, B, is measured from the top of the ski to the middle of the suspension ball joint. The airspring height, A, is measured from the base of the airspring, an angled platform, to the top of the airspring. The damper height, D, is determined by measuring the distance from the lower bump stop of the damper to the bottom of the damper body.

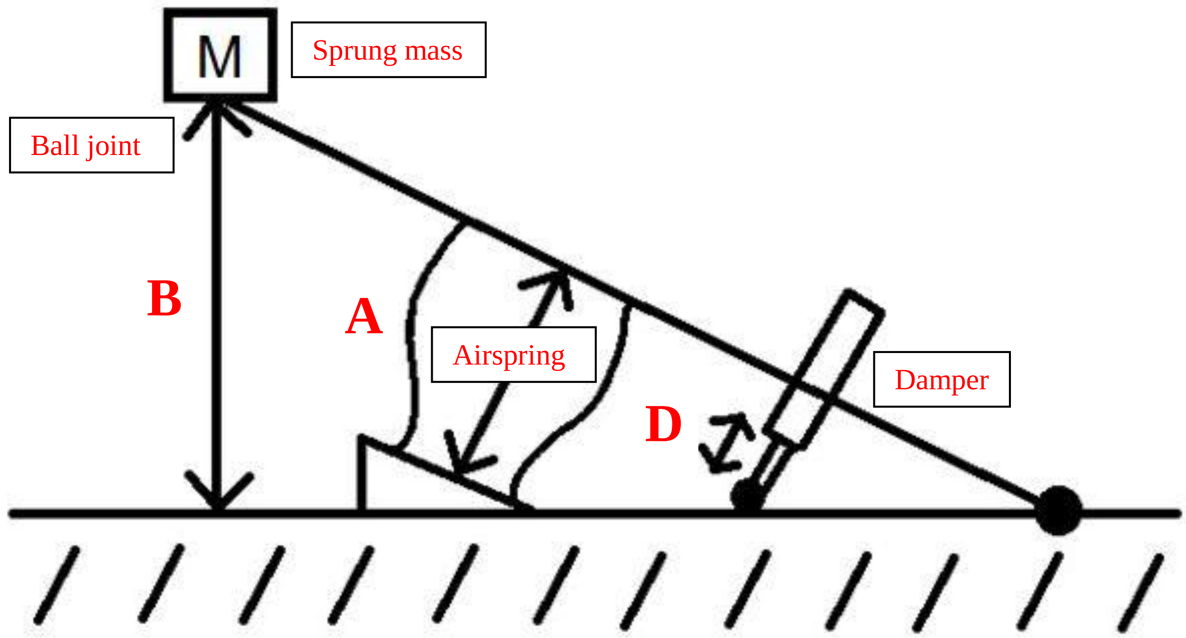

Figure 3-4: Drawing of the measurements taken to determine motion ratios

The motion ratio between ball joint and airspring position is 0.515, which means that for every inch the ball joint moves, the component at the airspring position moves 0.515 inches. The motion ratio between ball joint and stock damper position is 0.359. Knowing these motion ratios helped calculate the equivalent spring and damping rates at the ball joint, seen in the later sections of this chapter.

Figures 3-5 and 3-6 show the linear relationships between ball joint height and airspring and damper heights for the stock suspension, respectively. The equations shown on the figures are used to calculate the equivalent spring rates and damping values at the suspension ball joint. The suspension contacts the compression bumper at a ball joint height of 6 inches.

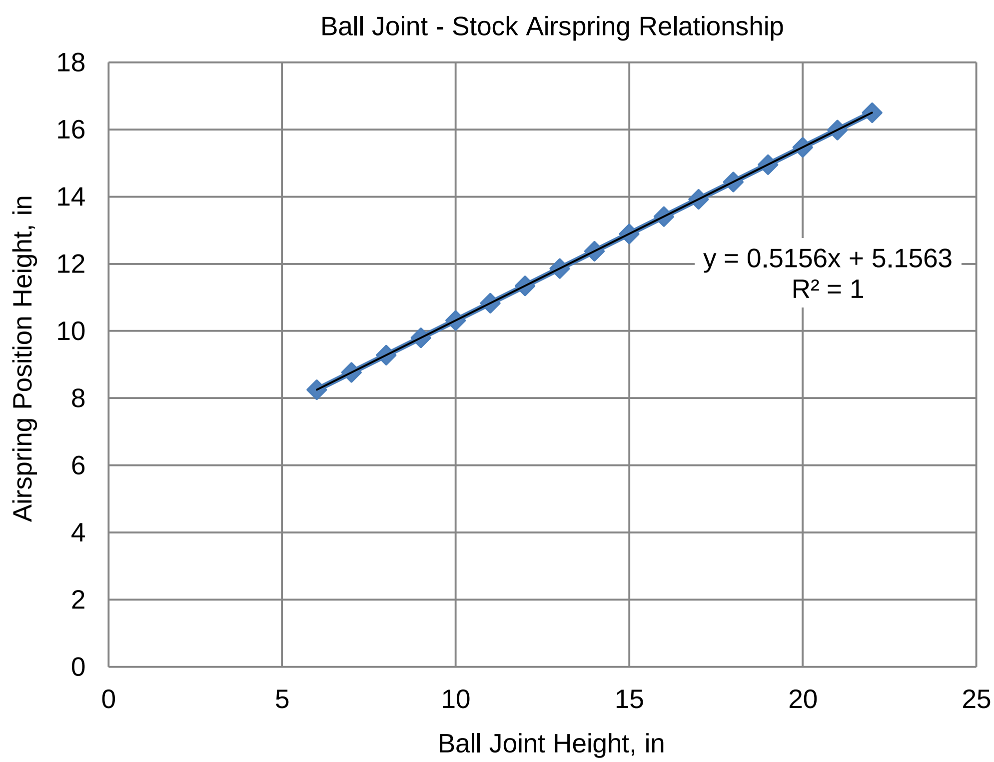

Figure 3-5: Relationship between ball joint and stock airspring height

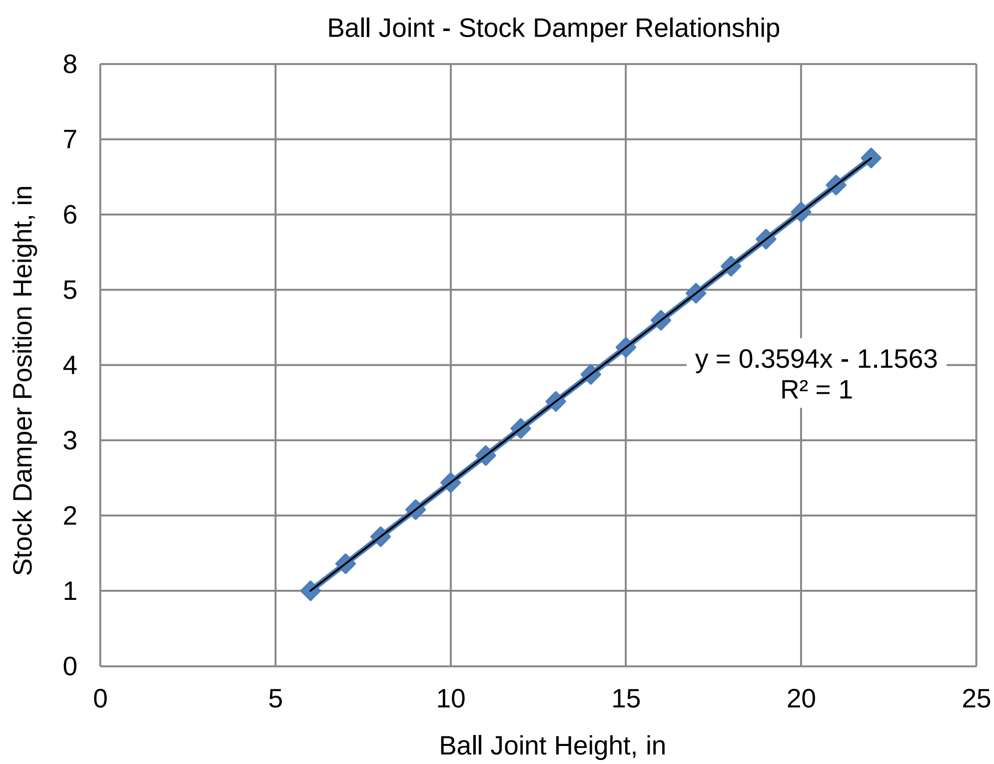

Figure 3-6: Relationship between ball joint and stock damper height

3.2 Stock Damper Characteristics

The stock dampers were not supplied with a data sheet detailing the damping curves. With no way of identifying the stock dampers and their corresponding damping characteristics, the two dampers on the starboard suspension were removed and tested in a Roehrig dynamometer located at CVeSS. Figure 3-7 shows the Roehrig dynamometer.

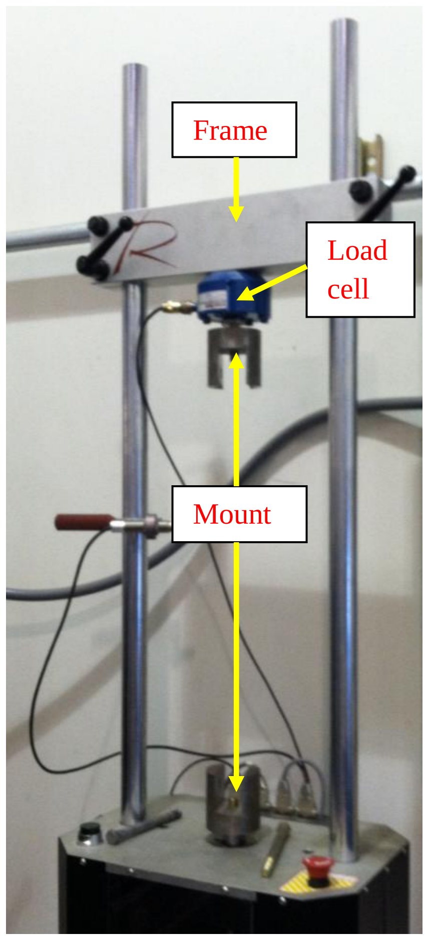

Figure 3-7: Roehrig dynamometer test rig

The two dampers were tested independently of each other; one was marked with a “1” and the other with a “2” to keep the test data organized. The spherical bearings at each end of the damper were bolted to removable mounts, also shown in Figure 3-7, and mounted to the Roehrig. Once the damper was set up, two tests were run to characterize each damper.

For the first test, the damper was set up near full compression. The Roehrig was programmed to run a test that oscillated the damper through a total stroke of 1 inch. These runs were named

“Stbd1 – Comp” and “Stbd2 – Comp,” with respect to the specific damper, signifying that the damper was set up near full compression. The second test was the same as the first except that the damper was set up near full extension. These tests were named “Stbd1 – Ext” and “Stbd2 – Ext,” signifying near full extension. Running tests with the damper both compressed and extended can determine whether the damping characteristics are consistent through the entire stroke of the damper, with the total stroke of the stock dampers being 8 inches.

Figure 3-8 is a plot of all four tests. Within the figure, the solid line is the first damper being tested near full compression; the dashed line is the first damper near full extension; the dash-dotted line is the second damper tested near full compression; and the dotted line is the second damper near full extension. The values in Quadrant I of the graph are the damping forces during compression, and the values in Quadrant III are the damping forces during extension.

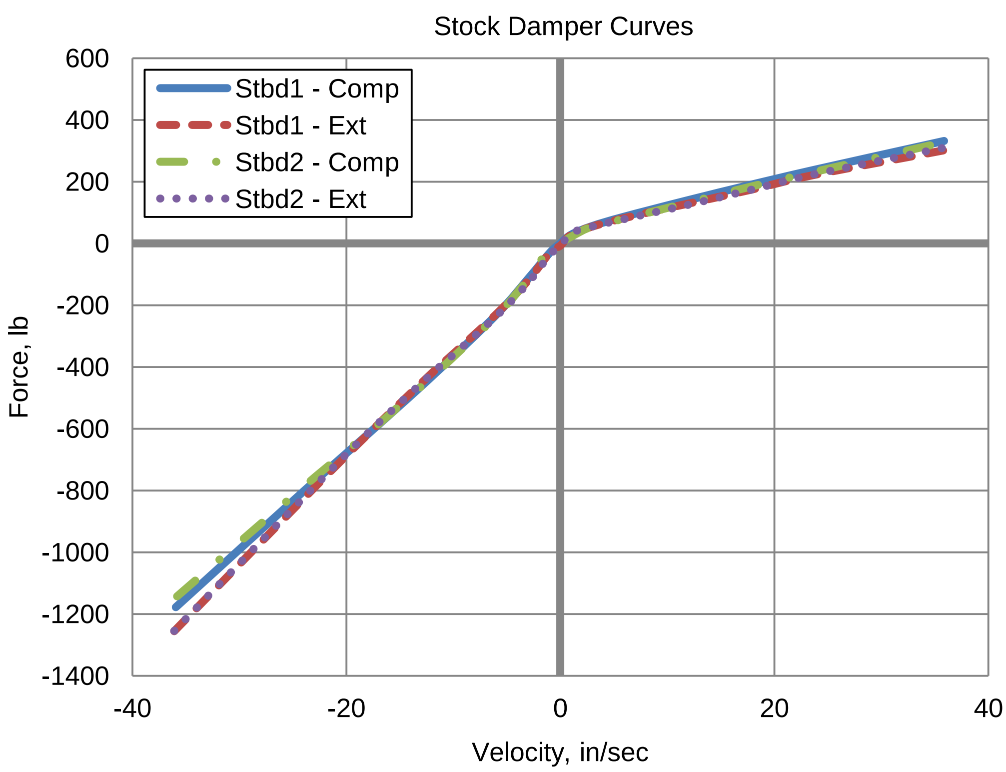

Figure 3-8: Stock damper curves

From this plot, the damping curves of both dampers at both extended and compressed setups are very close to each other, confirming that 1) both dampers have consistent damping through their entire stroke, and 2) the dampers are similar to one another.

By taking one damping curve and manipulating the values into Quadrant I of the graph, the ratio between damping forces seen during extension and compression was easily determined. Figure 3-9 shows the modified damping curve plot. The solid line is the forces seen during extension, and the dashed line is the forces seen during compression.

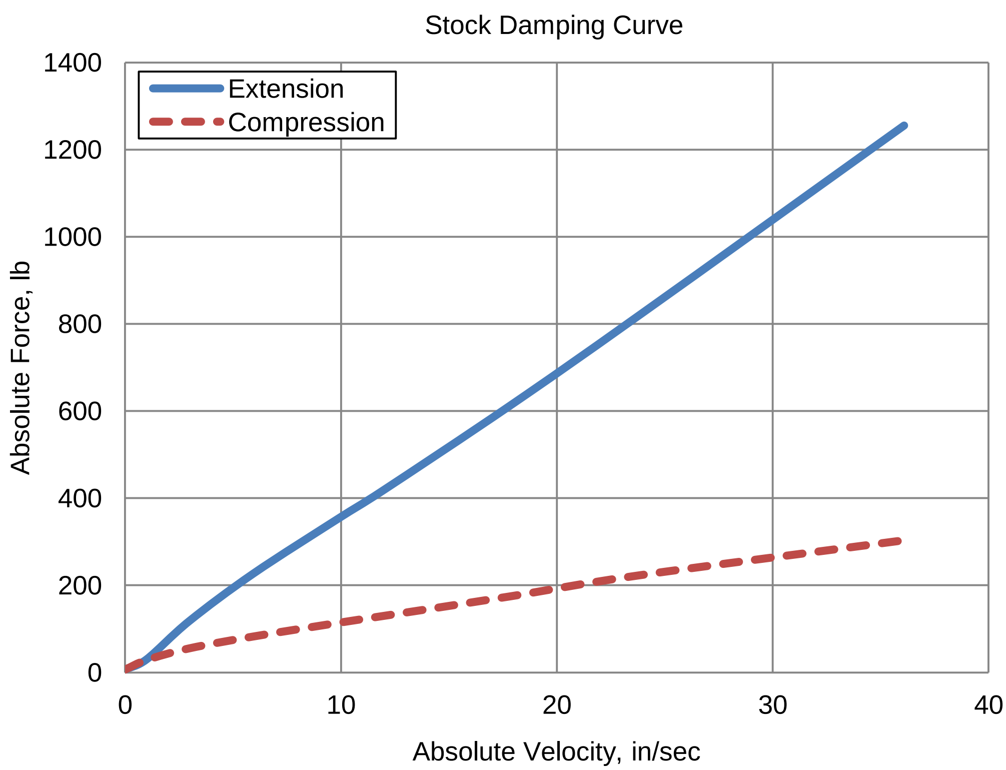

Figure 3-9: Plot of one damping curve from the Roehrig tests

The damping curve shows that the forces during extension are greater than the values during compression at a ratio of approximately 4:1.

3.3 Stock Airspring Characterization

The stock airspring is a Firestone 1T14C-3. The 1T14C-3 is both an Airstroke™ actuator and an Airmount™ isolator, and can be used as an actuator or an industrial isolator, respectively [5]. The data sheet for the stock airspring is found in Firestone's 2007 *Engineering Manual & Design Guide* [5], shown in Figure 3-10.

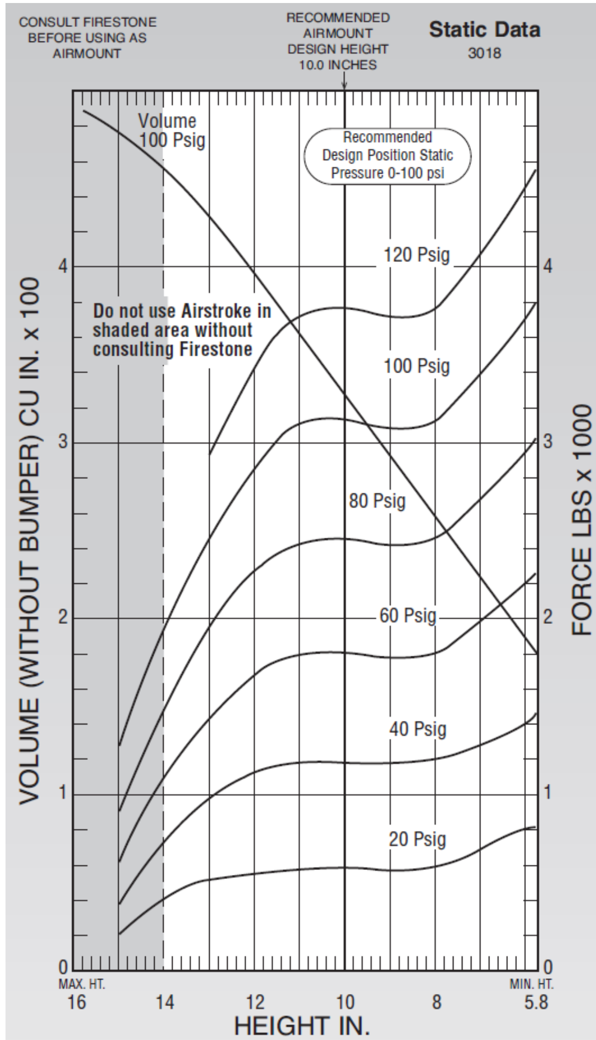

Figure 3-10: Data sheet for 33ft WAM-V stock airspring, Firestone 1T14C-3 [5]

The 1T14C-3 is a nonlinear airspring, shown by the flat section of the curves in the data sheet. The flat sections indicate that there is no change in restoring force in response to the suspension height. This can present itself as a hysteresis-like characteristic.

The manufacturer's data sheet for the 1T14C-3 assumes that the airspring is kept at a constant pressure, most likely by using an external reservoir. In-house tests were performed at CVeSS to generate a dynamic curve that takes into account pressure changes that occur as the airspring extends and compresses during WAM-V operation.

The tests to characterize the stock airspring were conducted on an MTS load frame at CVeSS. Since the maximum stroke of the load frame is 6 inches, two tests were conducted to capture the full characteristics of the 1T14C-3, which has a total stroke of 10 inches. The test setup is shown in Figure 3-11 with the airspring already mounted.

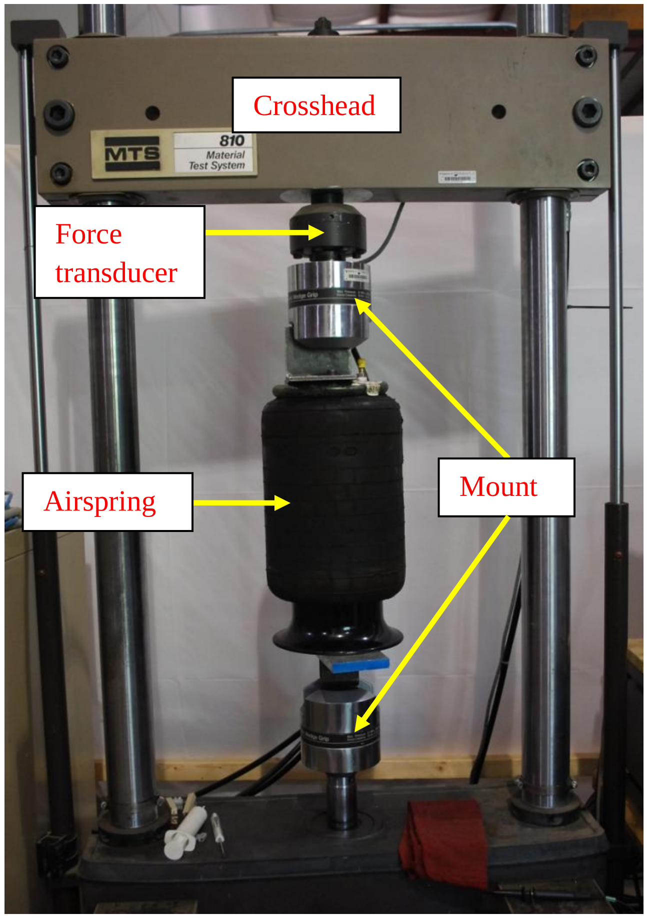

Figure 3-11: 1T14C-3 airspring mounted in the MTS

The first test conducted ran the airspring from a height of 10 inches to 16 inches. At a height of 15 inches, the pressure of the airspring was set to 25psi, which is the same ride height and pressure used during sea trials. The test started at 14 inches, extended to 16 inches, compressed to 10 inches, extended again to 16 inches, and returned to the starting height. Figure 3-12 shows the force versus airspring height graph generated by this first test.

In the second test, the airspring deflected from 6 inches to 12 inches. The test started at a height of 10 inches, extended to 12 inches, compressed to 6 inches, extended again to 12 inches, and returned to the start height of 10 inches. Figure 3-13 shows the force versus airspring height graph generated by the second test.

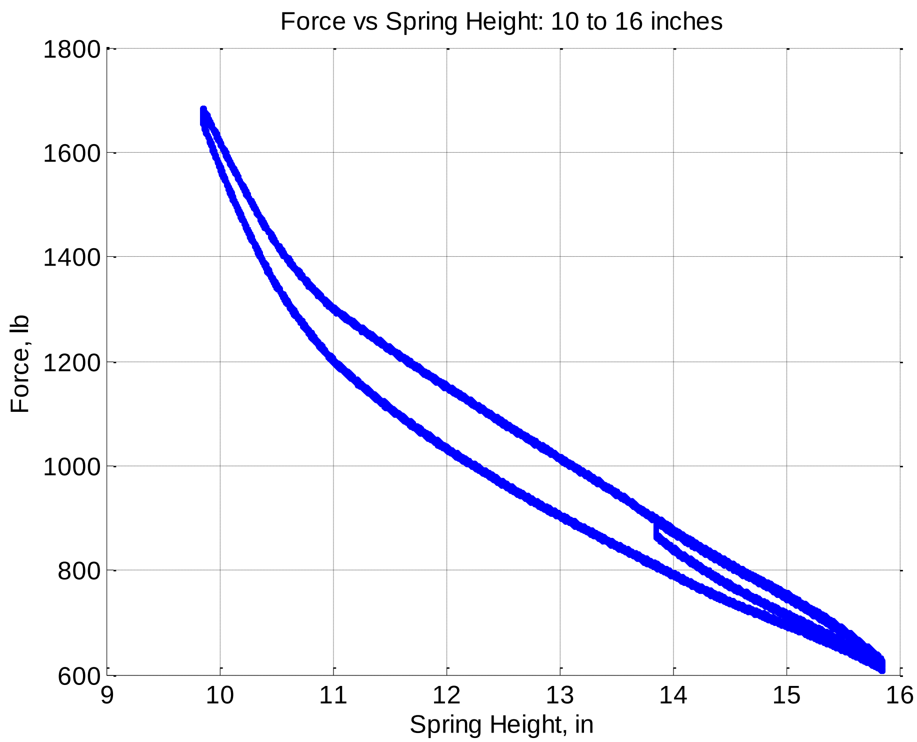

Figure 3-12: Force versus airspring height of first test from 10 to 16 inches

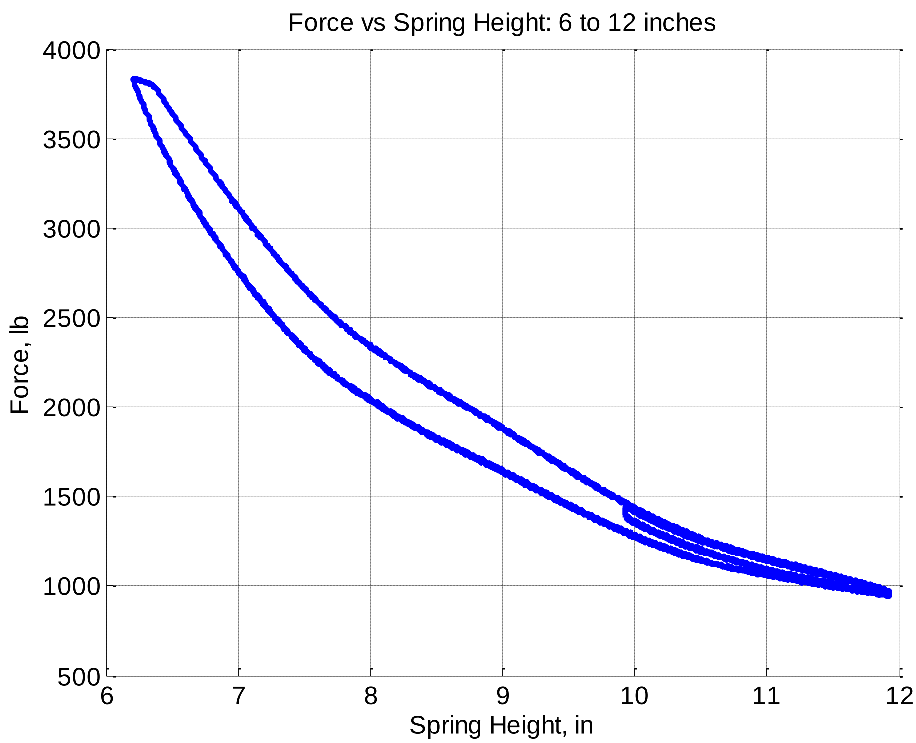

Figure 3-13: Force versus airspring height of second test from 6 to 12 inches

The difference in force readings at specific airspring heights is the hysteresis-like behavior previously mentioned: at a given height, the airspring can generate a range of forces, however, at a given force value, the airspring can also be within a range of heights. Due to this behavior, determining the ride height and restoring force was often inconsistent and difficult during testing.

In the transition between the first and second test, the pressure within the airspring was recorded in 1-inch increments from 16 inches to 10 inches. The corresponding force values were also recorded. No pressure readings were taken below 10 inches due to the high pressures and for safety reasons. Table 3-1 shows the pressure and force readings from the airspring tests. The change in pressure was significant as the spring was extended and compressed, proving that the two tests were needed to correctly characterize the dynamic airspring behavior.

Table 3-1: Pressure and Force Readings between Airspring Tests

Spring Height inches	**Pressure** psi	**Force** lb
10	40	1436
11	36	1167
12	31	1020
13	29	902
14	26	786
15	23.5	700
16	21.5	600

To determine the relationship between force and airspring height, the data generated from the two tests are used to determine Equation (3-1). The curves are plotted and shown in Figure 3-14. The curve in the 10- to 16-inch range represents the first test, and the curve in the 6- to 12-inch range represents the second test. A cubic trend of Equation (3-1), the dashed line, was fitted to both curves to characterize the nonlinear behavior of the airspring.

$$y = -7.02x^3 + 277x^2 - 3730x + 18000 \qquad (3\text{-}1)$$

where y is the force in pounds and x is the airspring height in inches.

The cubic trend found from Figure 3-14 was used to find the spring rate of the airspring. The spring forces and rates are plotted in Figure 3-15. The spring rate is represented by the solid line, the corresponding y-axis on the left, and the spring force by the dashed line, the corresponding y-axis on the right.

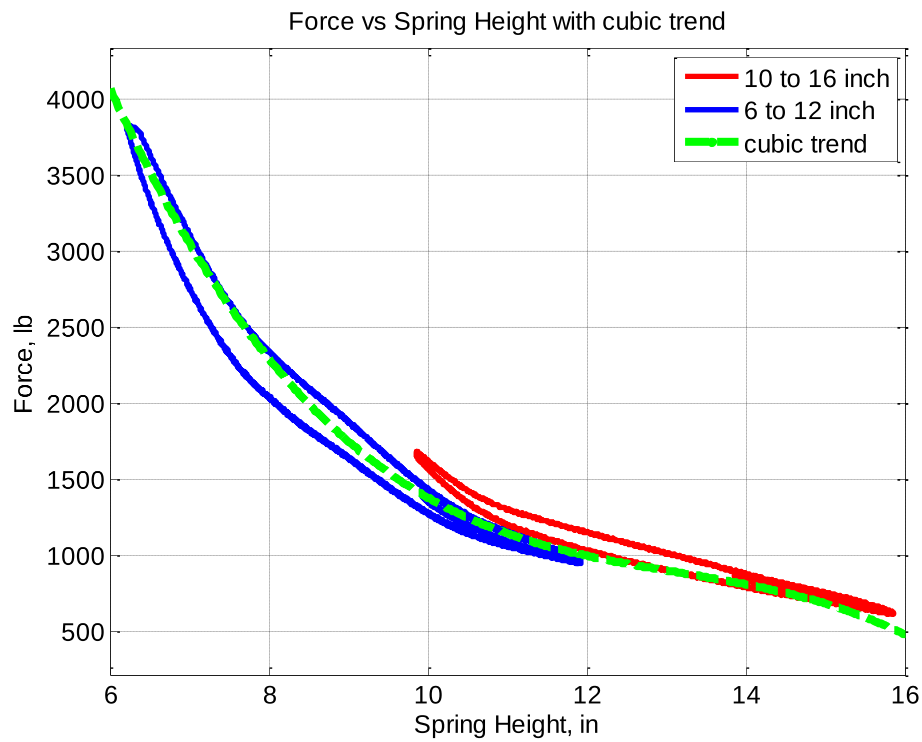

Figure 3-14: Force versus spring height of both airspring tests with cubic trend

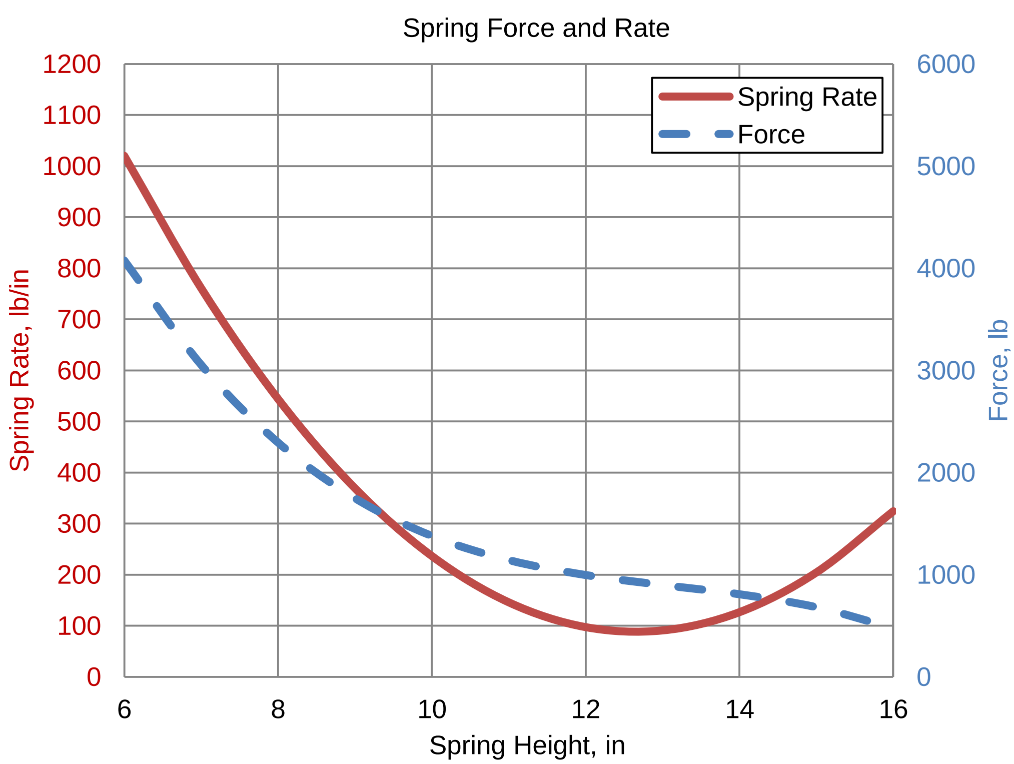

Figure 3-15: Spring force and rate of stock airspring

The spring rate is very high when compressed, but softens as the suspension extends. At the WAM-V ride height of 15 inches at the airspring, the airspring provides a spring rate of about 200lb/in. It should be noted that the airspring height of 15 inches falls within the "do not operate zone" of the manufacturer's data sheet.

3.4 33ft WAM-V Weight Calculations

Before selecting new suspension components, tests were conducted to find the weight of the 33ft WAM-V. The weight of the vessel helped determine the correct sizes for the spring and damper for the new suspension.

3.4.1 Sprung-Unsprung Mass (Weight) Ratio

When dealing with road vehicles, the sprung weight includes everything that is above the suspension, while the unsprung weight is everything below. The same can be said when applied to the 33ft WAM-V. The sprung weight of the 33ft WAM-V is everything above the suspension, such as the front and rear arches and payload tray, and the unsprung weight is everything below, such as the skis and pontoons. Figure 3-16 illustrates the sprung and unsprung portions of the 33ft WAM-V.

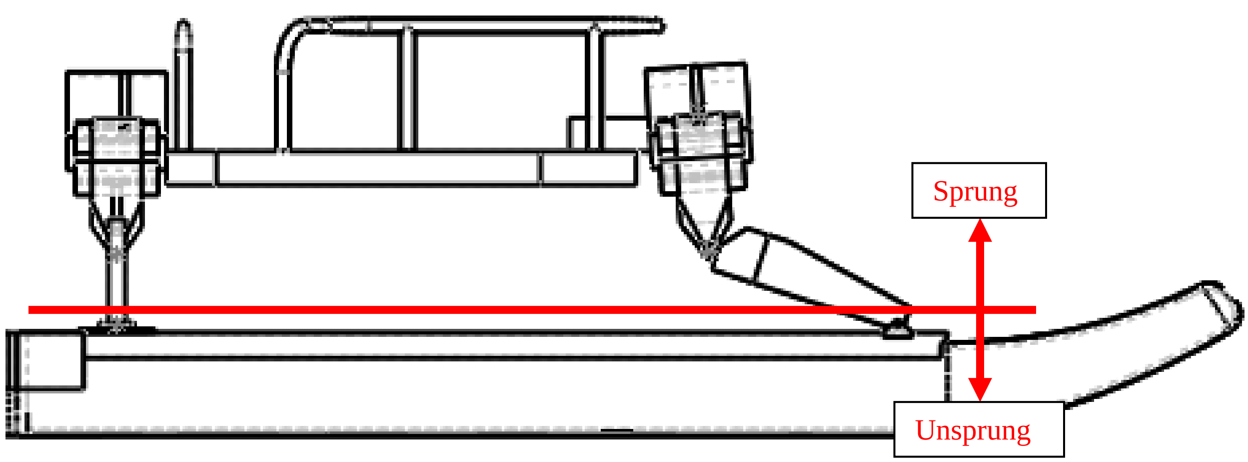

Figure 3-16: Profile view showing sprung and unsprung portions of 33ft WAM-V

The 33ft WAM-V was lifted and scales that are used to weigh automobiles were placed under the pontoons, two at the front and two at the rear, to find its total weight. The engine pods were disconnected for this test. Figure 3-17 shows the 33ft WAM-V lifted onto the scales.

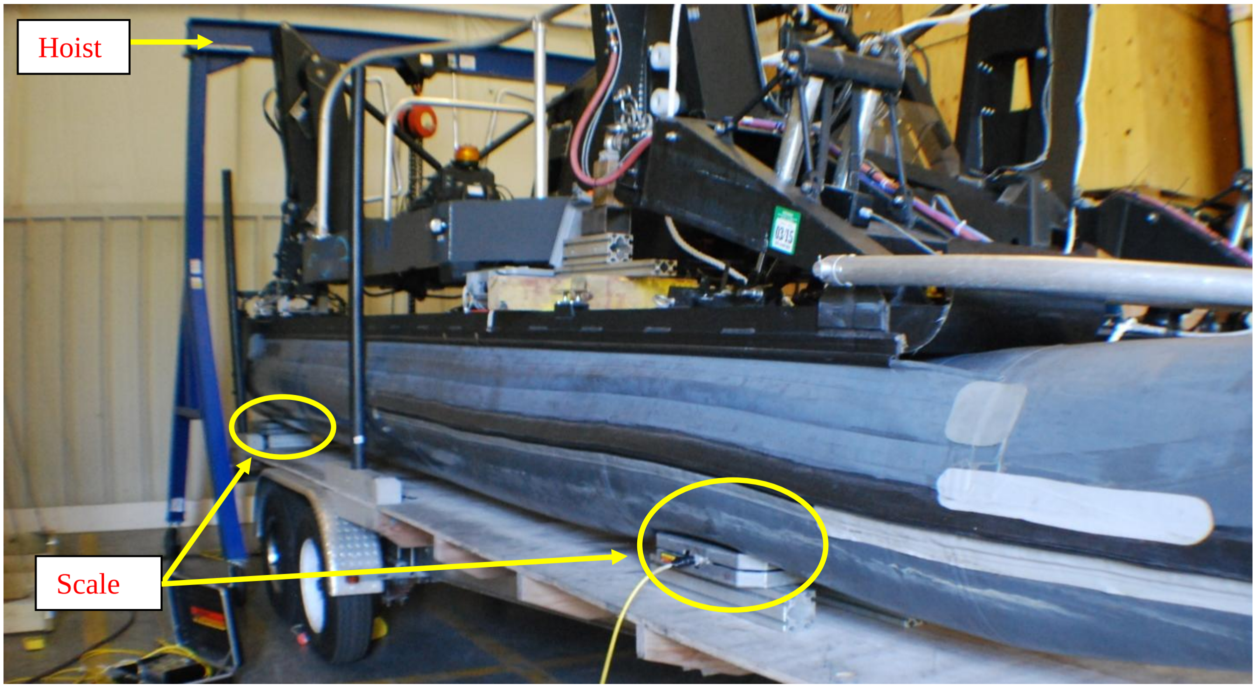

Figure 3-17: 33ft WAM-V lifted onto scales

The entire boat, minus the engine pods which were unpinned, was weighed using a hoist to lift the WAM-V onto four scales. Each pontoon had two scales under it: one up front near the suspension, and one in the rear near the engine pod pivot, also called the can. Figure 3-18 shows the scale under the front and rear of the pontoon, respectively. The scales were placed on blocks to lift the WAM-V completely off the trailer.

Figure 3-18: Pontoon front (left) and rear (right) lifted onto scales

Out of the four scales available, only three were operational. To compensate for this, the WAM-V was weighed three times, with the broken scale first under the rear of the starboard pontoon, and then under the rear of the port pontoon. Table 3-2 shows the locations of the scales for each test and the corresponding weights in pounds. The "X" in the table shows the location of the broken scale. The locations of the scales are shown in Figure 3-19.

Table 3-2: Corner Weights of Entire 33ft WAM-V in Pounds

Scale Location	Test 1	Test 2	Test 3
LF	591.5	618.5	624.5
RF	628.5	640.5	635.5
LR	610.5	X	X
RR	X	667.4	657.5

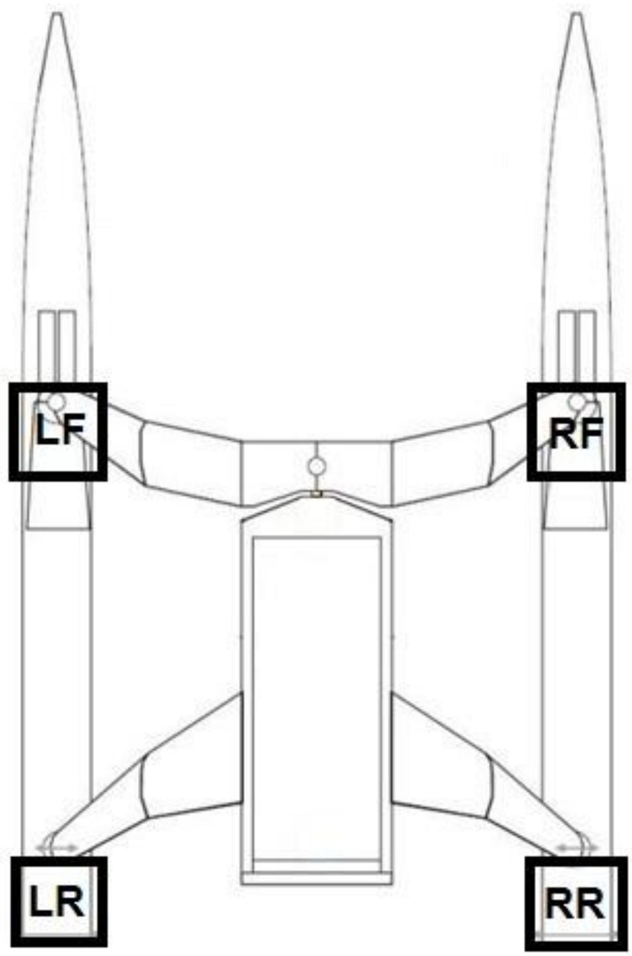

Figure 3-19: Location of scales

The weights were averaged, and corner weights for the front and rear of the 33ft WAM-V were determined. Each front corner weighs approximately 620lb, and each rear corner weighs approximately 660lb, making the total weight of the boat, without engine pods and operator, about 2600lb.

The engine pods, with a full day tank of fuel, were weighed separately. This was conveniently done due to the fact that the starboard engine pod was already unpinned and entirely off the trailer for maintenance. Figure 3-20 shows the engine pod on two scales. Each engine pod weighs 740lb with full fuel tanks.

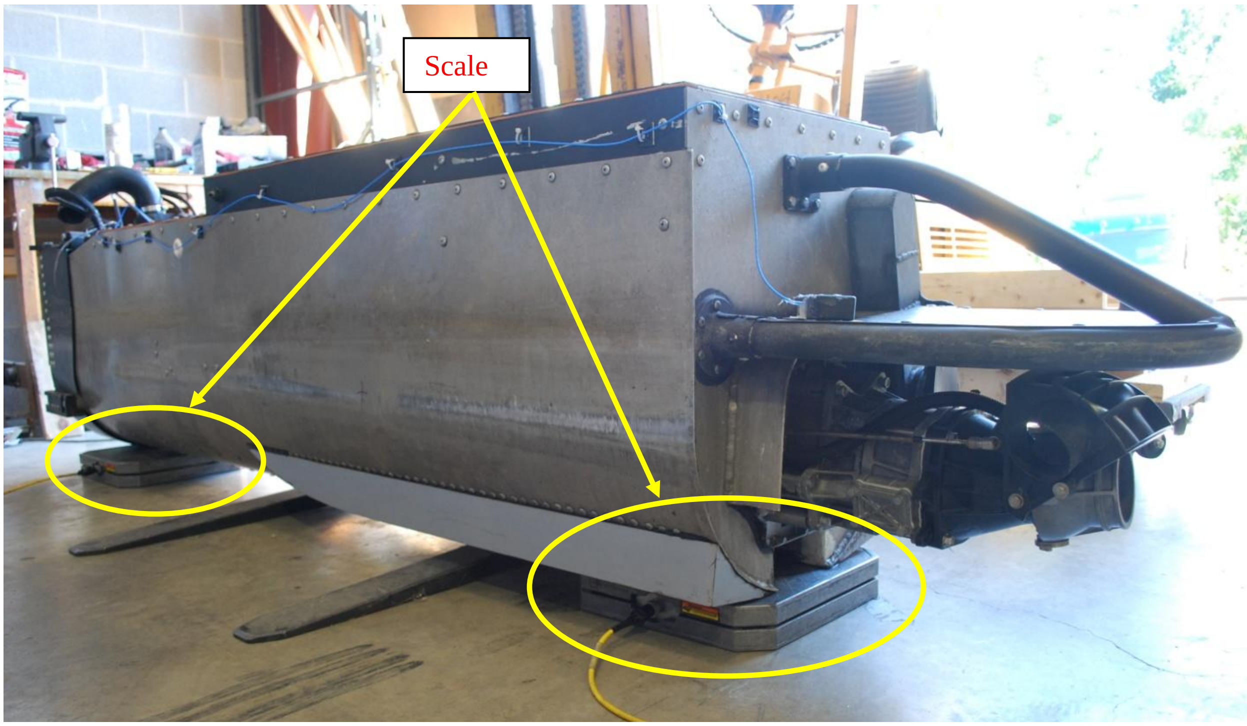

Figure 3-20: Engine pod lifted onto scales

The total weight of the 33ft WAM-V, including two engine pods with full day tanks of fuel and a 200lb operator, is approximately 4300lb.

Table 3-3 lists different components of the 33ft WAM-V and their corresponding weights. The individual component weights were initially determined by a combination of actually weighing them, determining their weights from a CAD model of the 33ft WAM-V generated by both VT and M.A.R., and by making an educated guess for the components that could not be easily weighed. Using the total weight of the 33ft WAM-V, additional weight was added to the components that may have been underestimated in their initial values.

Table 3-3: Weight Breakdown of 33ft WAM-V by Component

Item	Initial Weight, lb	Quantity	Additional Weight (each), lb	Total Weight, lb
Pod Components				
engine pods	640	2	0	1280
16 gallons of fuel	96	2	4	200
Platform Components				
platform	266	1	159	425
battery	30	1	10	40
rails	50	1	10	60
Ski Components				
skis	194	2	36	460
hull connector	30	2	10	80
pumps	10	2	0	20
pontoons	100	2	0	200
actuator assembly	15	2	0	30
Operator				
seat	35	1	20	55
operator	200	1	0	200
radio	10	1	0	10
Front Arch Assembly				
front arch	346	1	104	450
Rear Arch Assembly				
rear arch	475	1	75	550
Suspension Assembly				
airsprings	7.5	2	0	15
dampers	7.5	4	0	30
rockers	30	2	10	80
Data Acquisition Assembly				
camera box + cameras	25	1	5	30
data acquisition box + sensors	40	1	10	50
			TOTAL WEIGHT, lb:	**4265**

Knowing that the unsprung weight is comprised primarily of the “Ski Components” section in Table 3-3, the unsprung weight comes to about 800lb. With a total weight of 2600lb, without engine pods and operator, the sprung-unsprung ratio is approximately 2:1.

3.4.2 Suspension Sprung Mass (Weight)

After weighing the entire 33ft WAM-V, the value of the front corner sprung mass, which is the portion that the suspension has to support, was determined. One scale was placed under the ball joint of the front suspension, and was propped up by a number of blocks to reach the desired ball joint height of 18 inches. The ball joint was raised to this height to correspond to a level payload tray and vertical front arch. Figure 3-21 shows the setup to weigh the front corner sprung mass of the 33ft WAM-V.

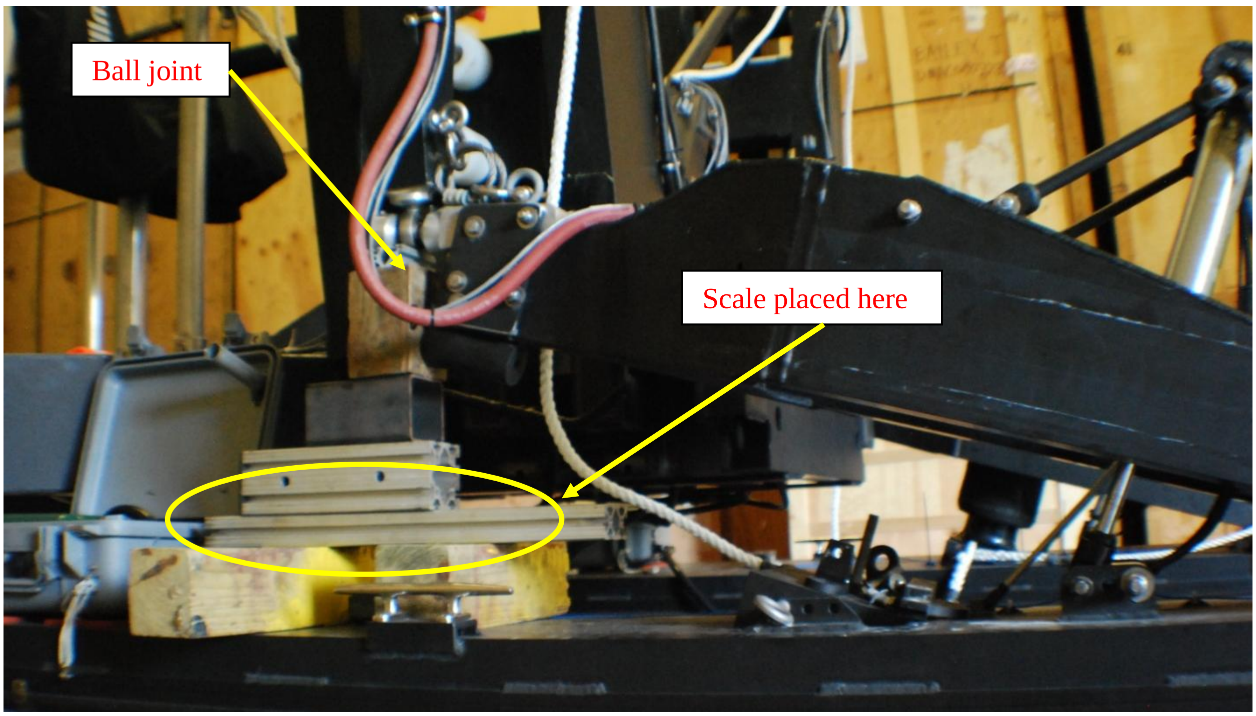

Figure 3-21: Suspension sprung mass measured by placing scale under ball joint

Three tests were conducted to determine the front corner sprung weight. All three tests were set up with a ball joint height of 18 inches. Test 1 values were recorded after putting the scale under the ball joint. Test 2 values were taken after shaking the payload tray to make sure no joints were in a bind, which would have kept certain components from being considered on the scales. For Test 3, a 50lb weight was placed on the operator seat to simulate an operator on board. From Test 3, it was determined that about 60% of the operator's weight acts on the front suspension. The results from the three tests conducted can be seen in Table 3-4. The locations of the scales are the same as before.

Table 3-4: Suspension Sprung Weight in Pounds

Scale Location	Test 1	Test 2	Test 3
LF	419.5	420.5	435.5
RF	422.5	428.5	443.4

Taking an average of Tests 1 and 2, the front suspension sprung weight on one corner is approximately 525lb with a 200lb operator on board.

3.5 New Suspension Selection and Characterization

By determining the amount of weight supported by the suspension and the sprung-unsprung weight ratio of the WAM-V, the sizing of the spring and dampers could be more finely tuned to the specific application of being on the 33ft WAM-V. Also, keeping in mind the geometry of the current suspension system, components were chosen so major changes were not needed to install a new suspension.

An Öhlins coil-over-spring suspension system was chosen as the new suspension for modularity in the sizing of the components and ease of implementation. A coil-over-spring suspension is comprised of one damper and a spring that wraps around the damper, shown in Figure 3-22. The Öhlins coil-over-spring suspension has two adjustment knobs to adjust the damping values of the damper. The fine adjustment knob is located on the external reservoir, and the main adjustment knob is located at the bottom of the damper. The Öhlins damper has a total stroke of 9 inches.

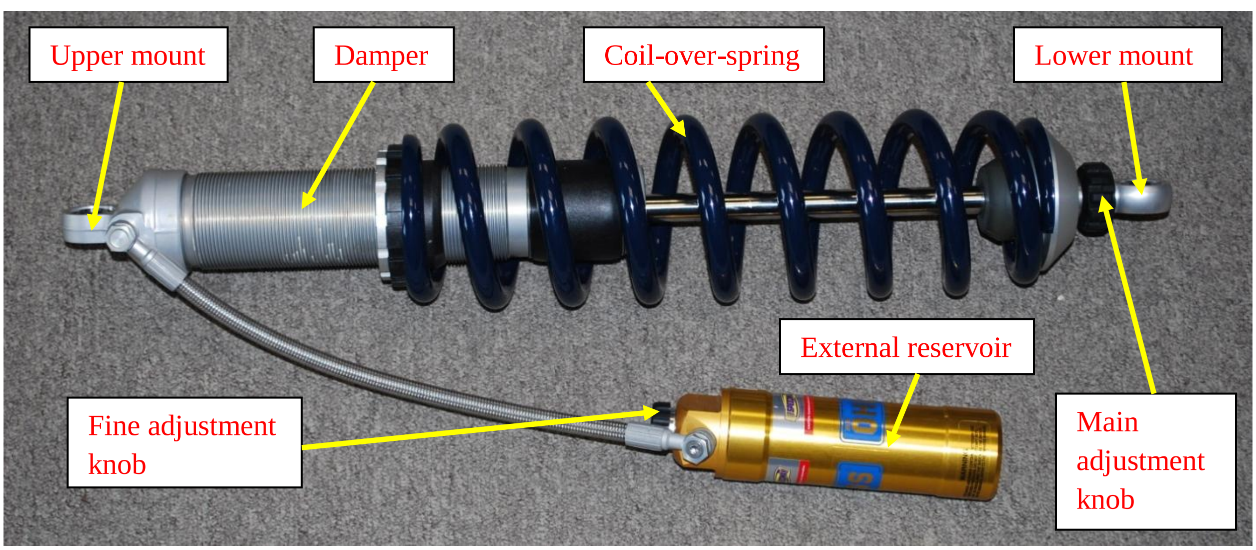

Figure 3-22: Öhlins coil-over-spring suspension

Öhlins provides a large range of linear spring rates. Two springs, rated at 400lb/in and 500lb/in, were chosen to be the possible replacements to accommodate the 525lb load on each suspended corner.

Assuming the new coil-over-spring suspension would be placed at the stock damper position to allow for more travel, Figure 3-23 shows the amount of travel that the ball joint of the suspension would have with the stock airspring and each linear spring. The triangles indicate the ball joint height from hitting the compression bumper with no load on the spring in place, with the proper motion ratios applied. The squares indicate the ball joint height from hitting the compression bumper with a 525lb load on the spring, with the proper motion ratios applied.

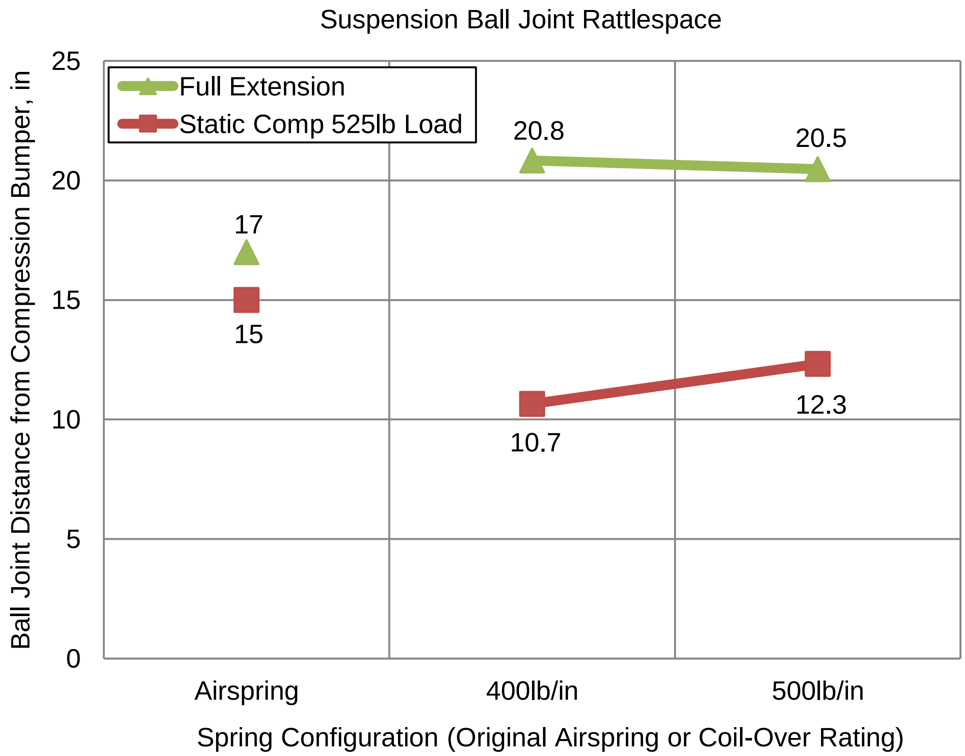

Figure 3-23: Ball joint travel with stock airspring and linear springs

Figure 3-23 showed that the stock airspring sits extremely close to full extension with a 525lb load. With the replacement linear springs, the height of the spring is near mid-stroke with a 525lb load. Figure 3-24 shows the percentage of compression travel available with the stock airspring and each linear spring, with 0% compression being contact with the compression bumper.

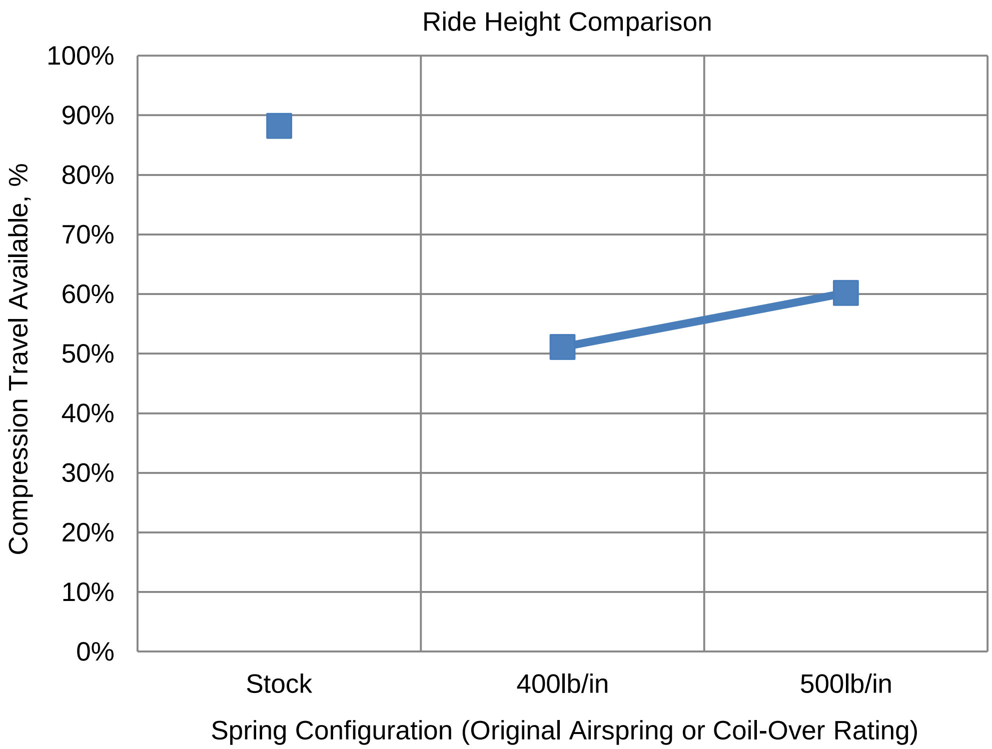

Figure 3-24: Compression travel available with stock and new suspensions

The stock suspension has an 88/12 compression-to-extension stroke ratio. With a 400lb/in and 500lb/in linear spring instead, the ratios are more equal with 50/50 and 60/40, respectively.

Equations (3-2) through (3-4) are used to calculate the values plotted in Figure 3-23:

$$full\ extension = (rated\ spring\ travel - preload) * mr \tag{3-2}$$

where $full\ extension$ is the maximum height of the suspension in inches, $rated\ spring\ travel$ is the amount the spring can travel in inches, $preload$ is the amount of preload on the spring in inches, and mr is the motion ratio between the ball joint and the location of the spring in question. In all three cases, the preload is zero. The motion ratio is 0.515 with the stock airspring, and 0.359 with the linear springs.

$$static\ \ compression = \frac{\left(load - mr * k_{\text{balljoint}} * preload\right)}{k_{\text{balljoint}}} \tag{3-3}$$

where $static\ \ compression$ is the amount of compression in inches, $load$ is the amount of loading each suspension has to support in pounds (in this case, 525lb), and $k_{\text{balljoint}}$ is the equivalent spring stiffness at the ball joint in lb/in.

$$k_{\text{balljoint}} = \frac{k}{mr^2} \tag{3-4}$$

where $k_{\text{balljoint}}$ is the equivalent spring stiffness at the ball joint in lb/in, and k is the spring stiffness of the air or linear spring in lb/in.

Figure 3-25 shows the equivalent spring rates at the ball joint. The first three values indicate the equivalent spring rate at the ball joint with the stock suspension at three different heights: ride height, 50% compressed height, and 75% compressed height. This shows that as the airspring is compressed, the spring becomes stiffer. With the Öhlins linear springs, the spring rate remains a constant value throughout the entire stroke.

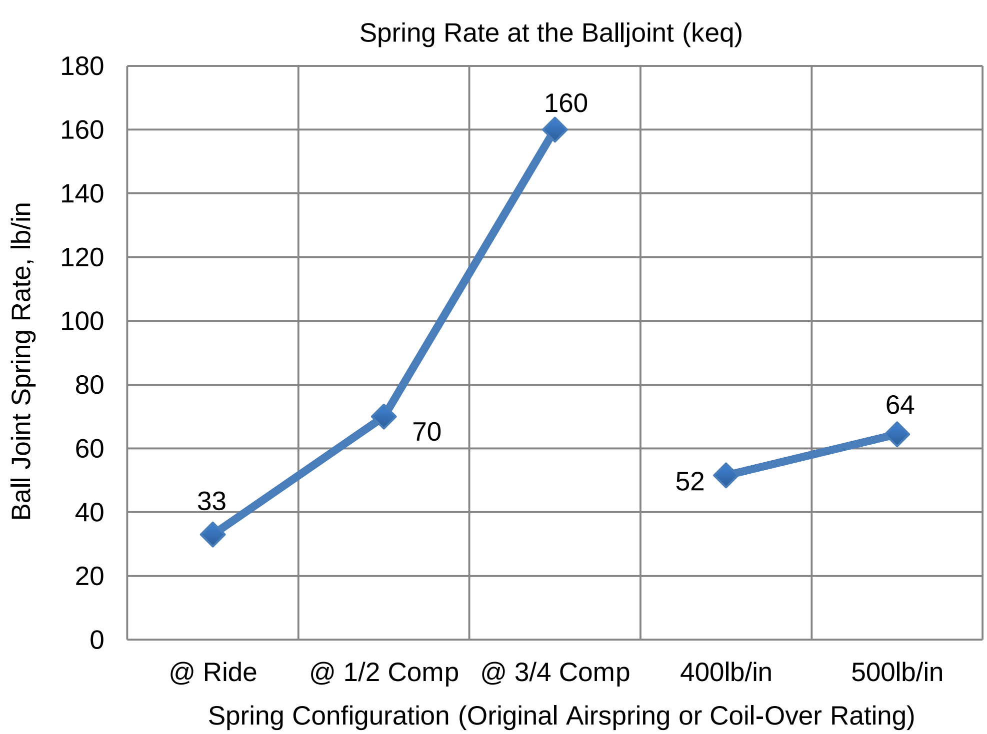

Figure 3-25: Equivalent spring rate at ball joint with stock and new suspensions

The damping ratio of the suspension is important in determining whether there will be sufficient damping present to reduce the oscillations of the vehicle or vessel. Figure 3-26 shows the damping ratios of the stock suspension along with the damping ratios of the 400lb/in and 500lb/in linear springs. A damping ratio of 1 is critical damping.

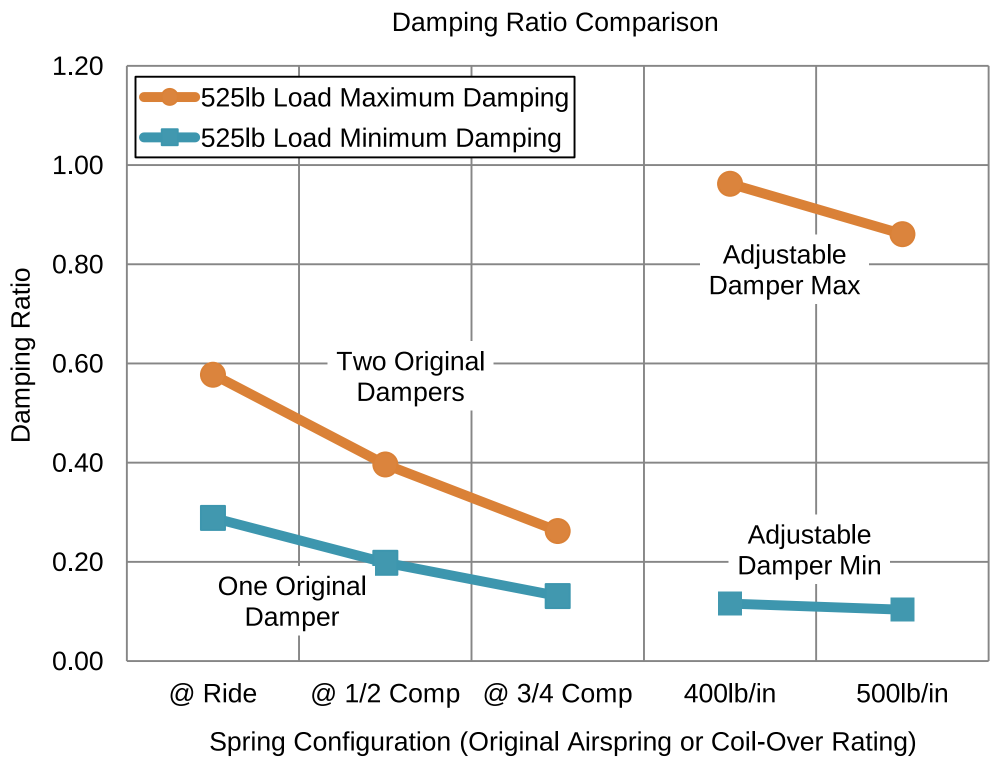

Figure 3-26: Damping ratios of stock and new suspensions

Table 3-5 shows the damping values of the stock and new suspension. The "minimum damping" values of the stock suspension are when only one stock damper is installed with the stock airspring instead of the usual two stock dampers.

Table 3-5: Minimum and Maximum Damping Ratios with a 525lb Load

	Minimum Damping	**Maximum Damping**
Stock @ Ride	0.28	0.57
Stock @ 1/2 Comp	0.19	0.39
Stock @ 3/4 Comp	0.13	0.26
400 lb/in	0.11	0.96
500 lb/in	0.10	0.86

The stock suspension does not provide enough damping as the suspension is compressed, supplying only 0.13 with each suspension at a 75% compressed height. Due to the adjustability of the new suspension, a wide range of damping values is available that encompass the damping values provided by the stock dampers.

Figure 3-27 shows a plot of the damper characteristics of the Öhlins damper. The solid and dashed lines with circle markers indicate the stock damper extension and compression values, respectively. The solid and dashed lines with square markers indicate the maximum extension and compression values of the new damper, respectively. The solid and dashed lines with triangle markers indicate the minimum extension and compression values of the new damper, respectively.

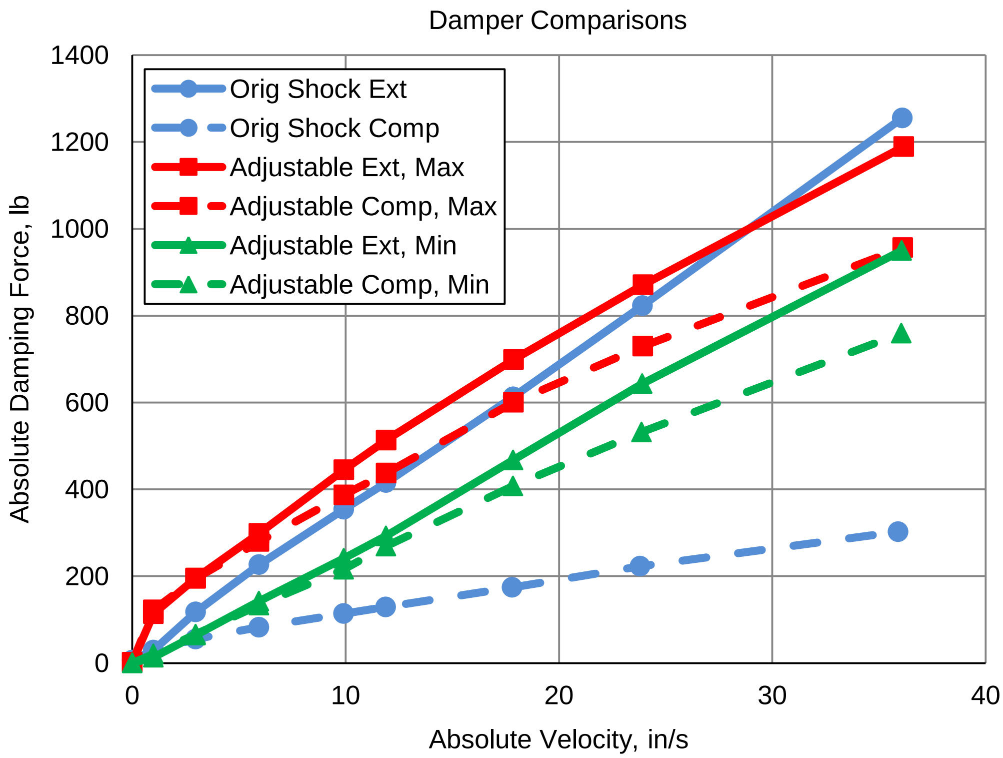

Figure 3-27: Damping characteristics of stock and new dampers

The damping values during compression and extension of a damper is important in how the suspension acts when encountering a bump in the road or, in the case of the 33ft WAM-V, a wave. Since the stock dampers were made to be used in road vehicles, their extension-compression damping ratio of 4:1 would typically be found in a road vehicle, where the sprung weight is significantly heavier than the unsprung weight. The sprung-unsprung weight ratio of the 33ft WAM-V, however, is closer at 2:1. With such similar values of sprung and unsprung weight, the extension damping values do not need to be greater than the compression values. The damping ratio of about 1:1 extension-compression provided by the Öhlins damper should be sufficient for the 33ft WAM-V.

Since the new coil-over suspension is placed at the stock damper position, the motion ratio between that position and the ball joint remains the same, 0.359. However, because the new suspension has different geometry than the stock damper, the relationship between the ball joint and new suspension height is slightly altered, shown in Figure 3-28.

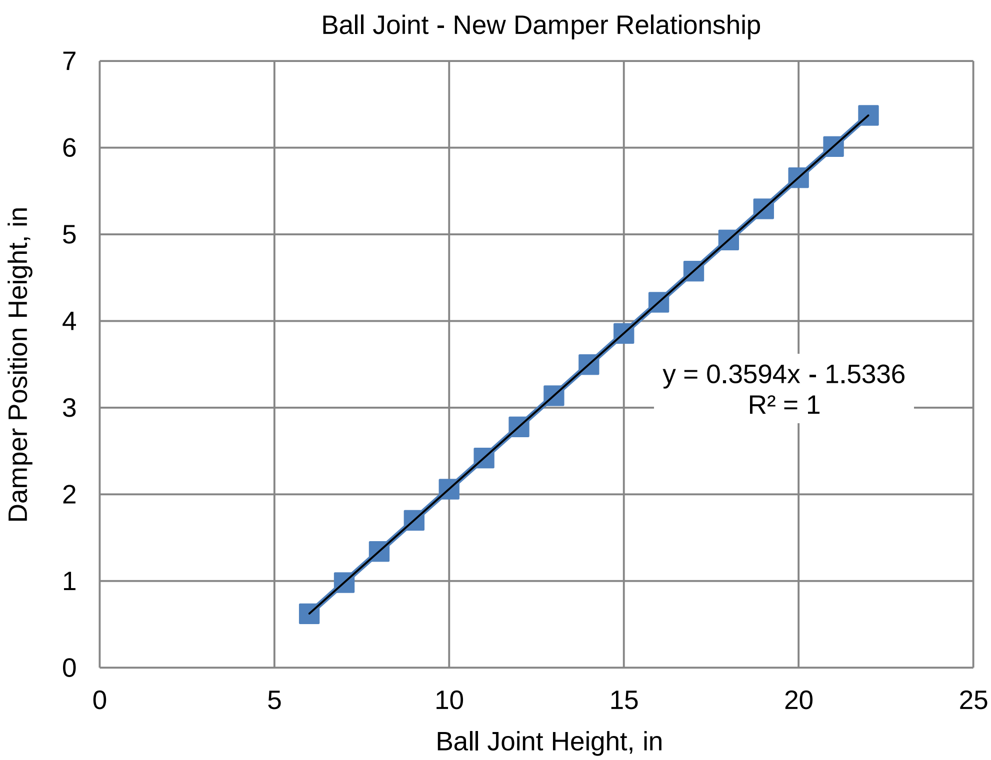

Figure 3-28: Relationship between ball joint and new damper height

The coil-over setup provides both a wide range of damping values and spring rates, making it easier to tune the suspension to the most optimal settings through testing. In addition, not only does the coil-over fit into the existing structure, but it is also easily implemented. Figure 3-29 shows the new coil-over suspension system installed on the 33ft WAM-V. The original limit straps are also replaced and repositioned to beside the coil-over setup, instead of in front, to make room for the spring component of the coil-over. The new suspension only has one extension limit strap, whereas the stock suspension has two. Details of the how each suspension is installed are covered in Chapter 4.

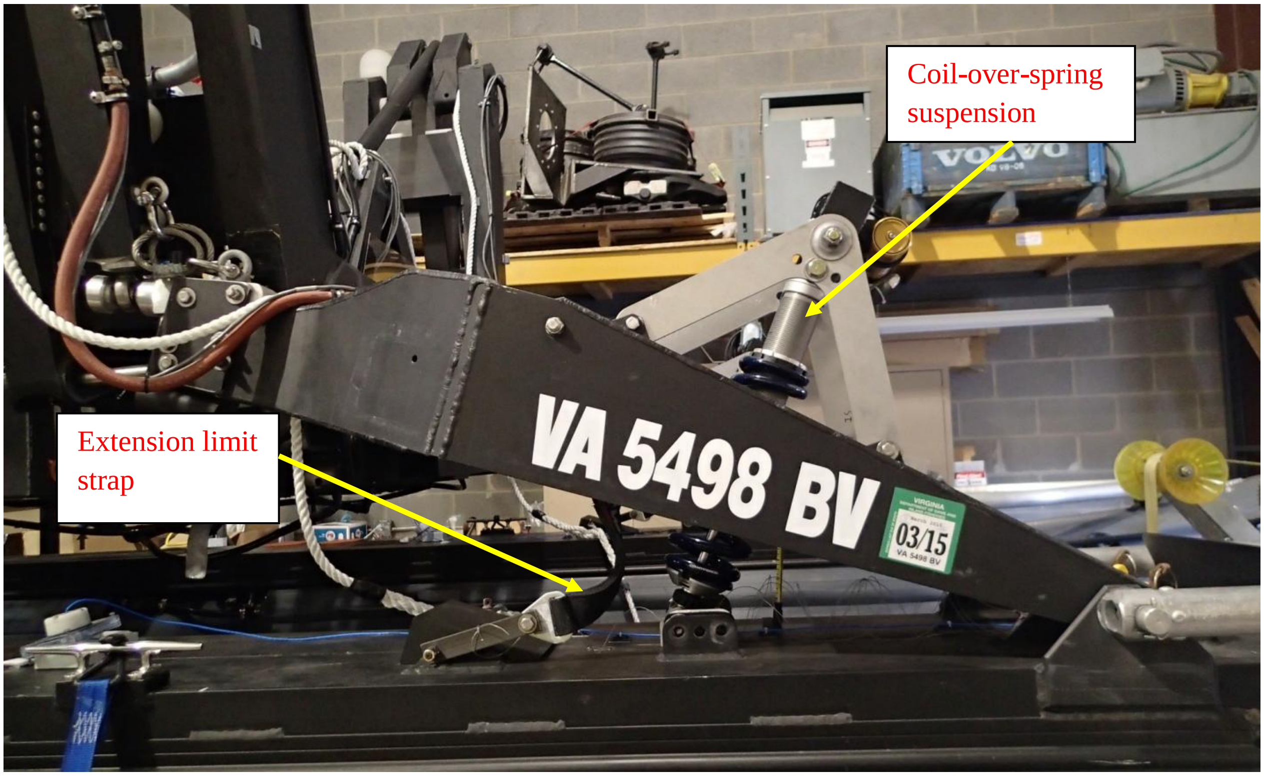

Figure 3-29: Coil-over suspension implemented into existing WAM-V structure

Chapter 4 33ft WAM-V Testing Setup and Procedure

This chapter discusses the sea trial setup and procedures followed for testing the 33ft WAM-V. The chapter starts with an explanation on how the two suspension systems are installed and changed during testing, followed by the instrumentation of the 33ft WAM-V in detail. The chapter ends by describing the patterns conducted and procedures followed during sea trials.

4.1 Suspension Installation

Making changes to the suspension during sea trials was a necessity in order to test each suspension in the same day in the hopes of collecting data for both suspensions operating in the same sea state.

In order to change between the two suspension systems in a safe and timely manner during sea trials, the new suspension system was designed to be installed easily without having to modify the structure being used by the stock suspension system. The installation procedure of the new suspension system was also designed to make changing between the new and stock suspension components as simple as possible.

4.1.1 Stock Suspension

The stock suspension system was designed by M.A.R. to have an airspring and two dampers sitting within a suspension rocker arm. The top of the airspring is mounted to the suspension rocker arm by bolting it to a bar spanning the width of the opening in the suspension arm, shown in Figure 4-1.

The bottom of the airspring is mounted on an angled platform to constrain the movement of the airspring to the vertical direction, shown in Figure 4-2. Figure 4-2 also shows the lower mounts for the stock dampers. Each damper uses two flanges mounted perpendicular from the pontoon ski to secure the damper lower mount spherical bearing. Cylindrical spacers are used to fill the space between the flanges and the bearing of the damper. The extension limit straps also use the flanges as their lower mounting point.

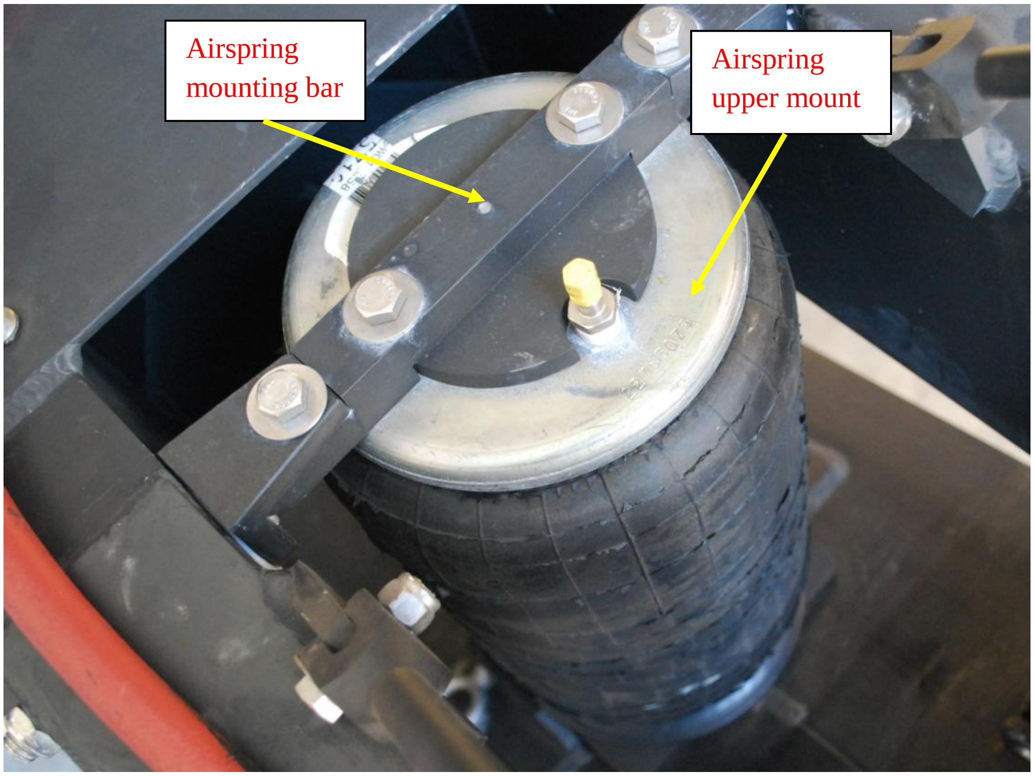

Figure 4-1: Upper mounting bar of stock airspring

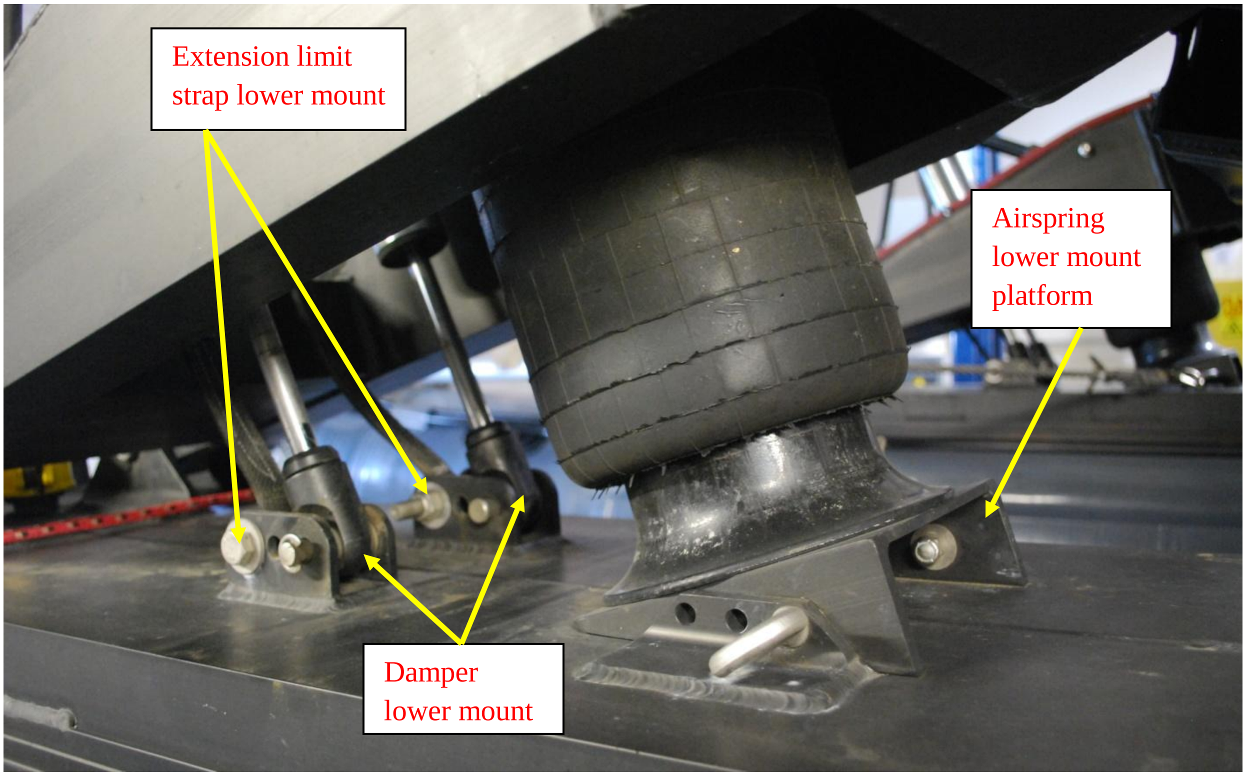

Figure 4-2: Lower mount of airspring, dampers, and limit straps

The upper mounts of the dampers are secured in a raised frame to allow the dampers to travel their full stroke. The raised frame is bolted to the WAM-V at four points, shown in Figure 4-3. The upper mounts of the extension limit straps are also secured in this raised frame.

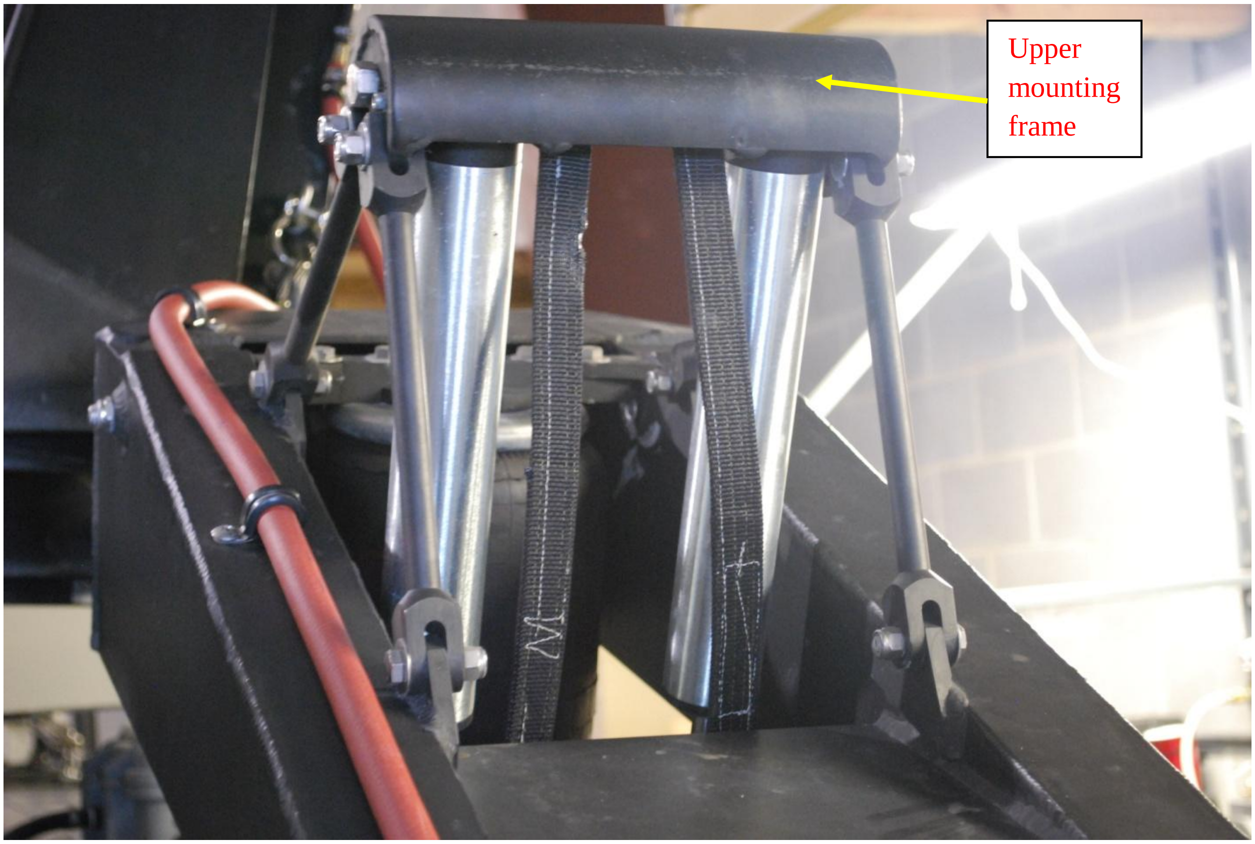

Figure 4-3: Upper mounting frame for stock dampers and extension limit straps

Figure 4-4 shows the underside of the frame. The top of the dampers are mounted like the bottoms, however, instead of one bolt for each damper, one long bolt is used for both dampers and limit straps. Again, cylindrical spacers are used to fill the space in between the flanges and the mounting points of each component.

The spacers installed in the stock suspension allow the dampers to have some deadband. Due to the raised frame around the damper upper mounting points, the spacers cannot be tightened to keep the spherical bearings from rotating. While this was a good design for a compact suspension system, the design for the installation of the new suspension allows the new damper mounts to be tightened, constraining the motion of the dampers to be purely axial.

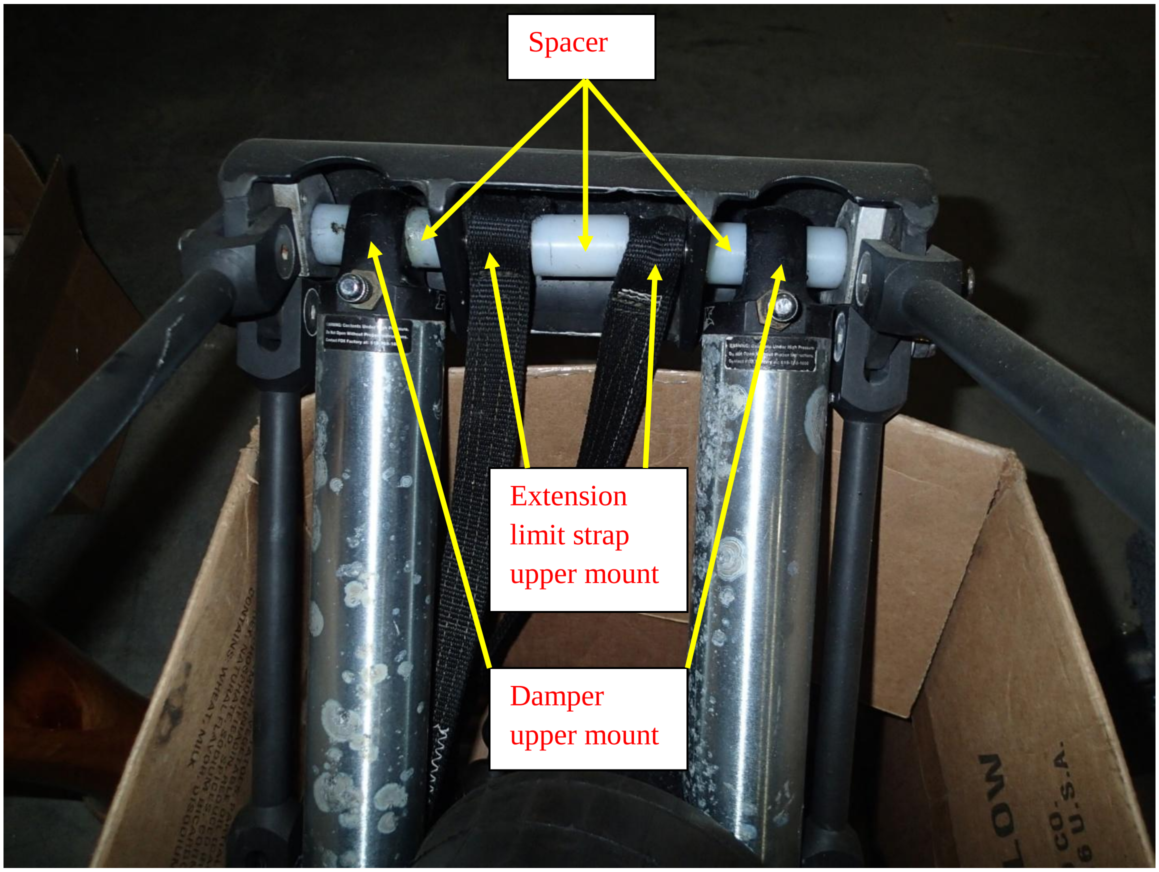

Figure 4-4: Underside of upper mounting frame

The stock dampers are installed and removed with a total of eight bolts: four holding the raised frame to the suspension rocker arm, and four holding the lower mounts of the extension limit straps and dampers. The stock airspring is installed and removed with a total of three bolts: two bolts holding it to the suspension rocker arm, and one to the lower mount platform.

4.1.2 New Suspension

One parameter considered in choosing new suspension components included components that fit into the existing suspension structure of the WAM-V. The new suspension is mounted at the stock damper position to allow the new damper to travel its full stroke.

To accommodate the increased stroke of the new damper, a new raised frame was designed, shown in Figure 4-5. The two sides of the frame are connected with a steel rectangular prism. The external reservoir is secured to this rectangular prism with heavy duty zip ties, keeping it away from any moving parts that may damage it. The top mount of the extension limit strap is mounted to one corner of the raised frame, barely visible in the figure.

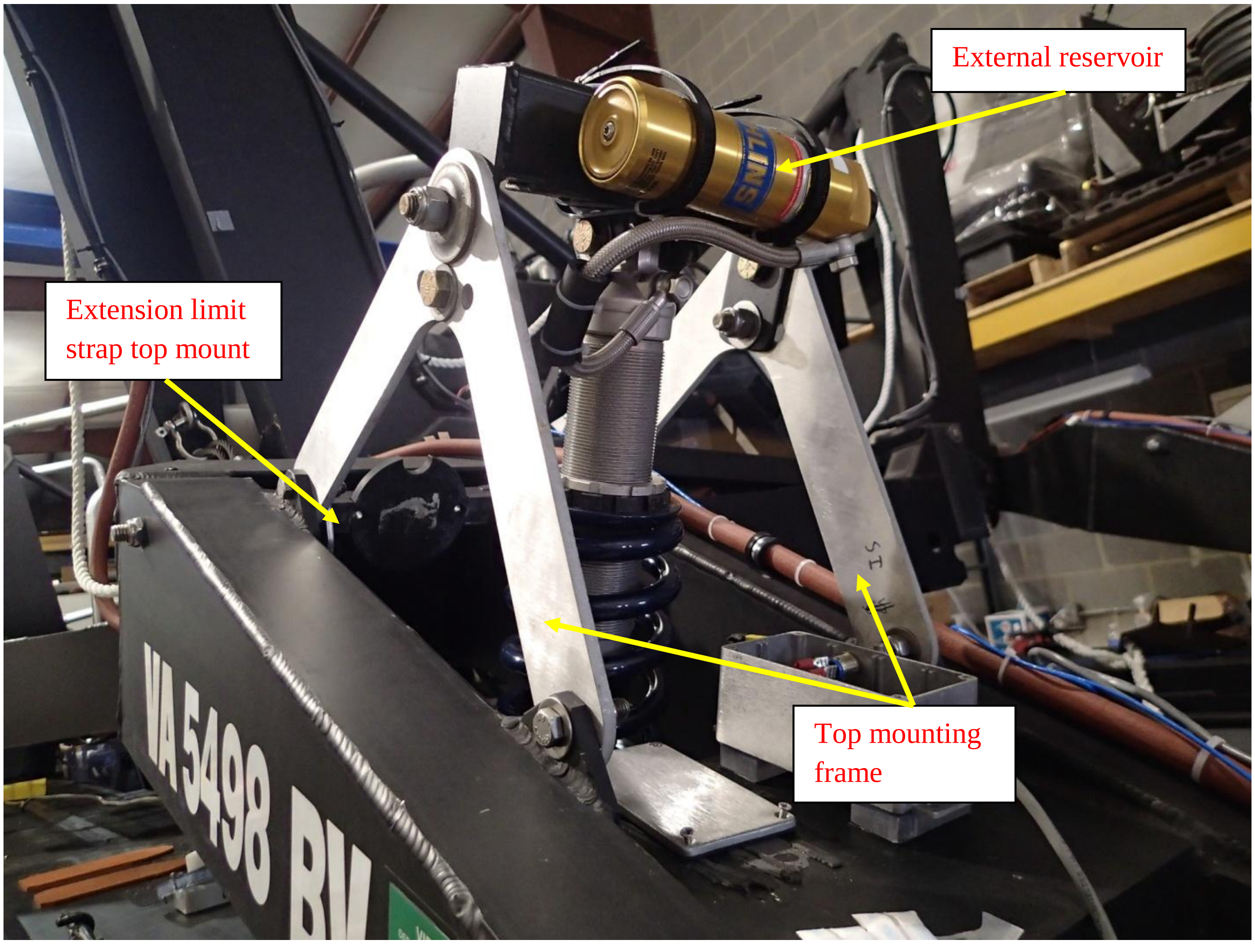

Figure 4-5: Newly designed upper mounting frame for new suspension

Figure 4-6 shows the upper mounting point of the new damper. The spacers used for the new suspension are better sized to fit the space in between the flanges and spherical bearing of the new damper. To better rest against the bearing, one side of the cylindrical spacer is tapered. With the new spacers, the bolt can be tightened to eliminate any deadband.

The lower mount for the damper uses the same principle as the upper mount, using spacers that are tapered at one end to fit against the damper bearing. The new bottom spacers were machined to be a tight fit, leaving the damper no deadband when the installation is complete. Additional flanges are placed under the spacers around the bearing to add support for the bolt and keep it from bending. The lower mount for the new damper is shown in Figure 4-7.

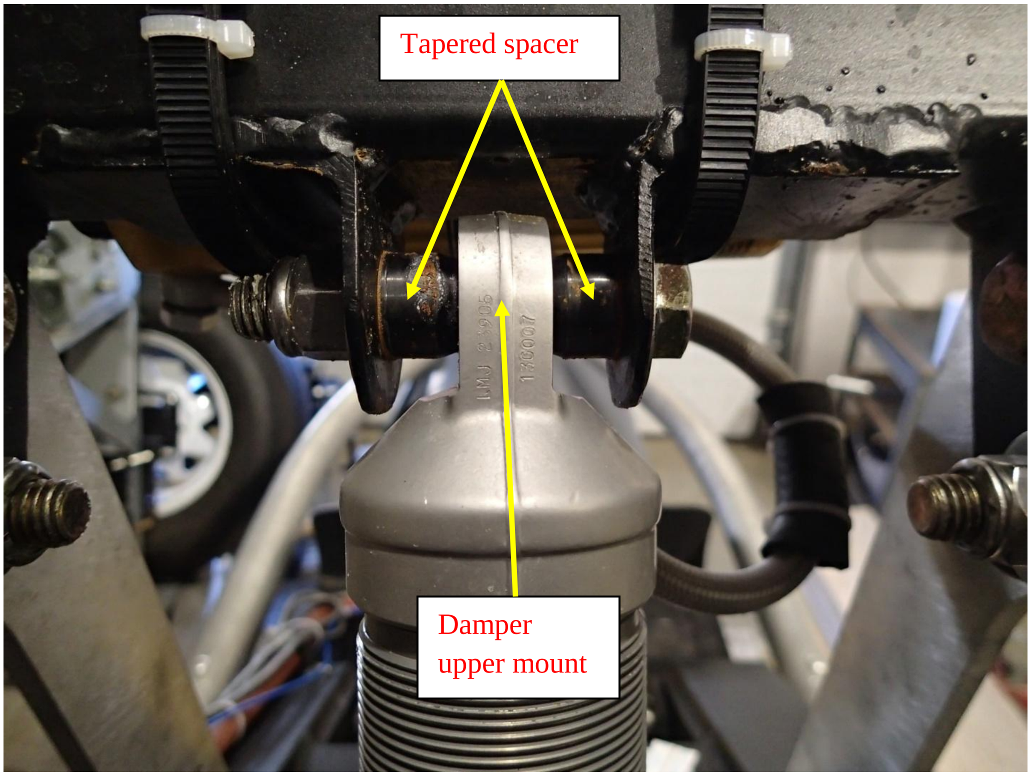

Figure 4-6: Upper mount of new damper

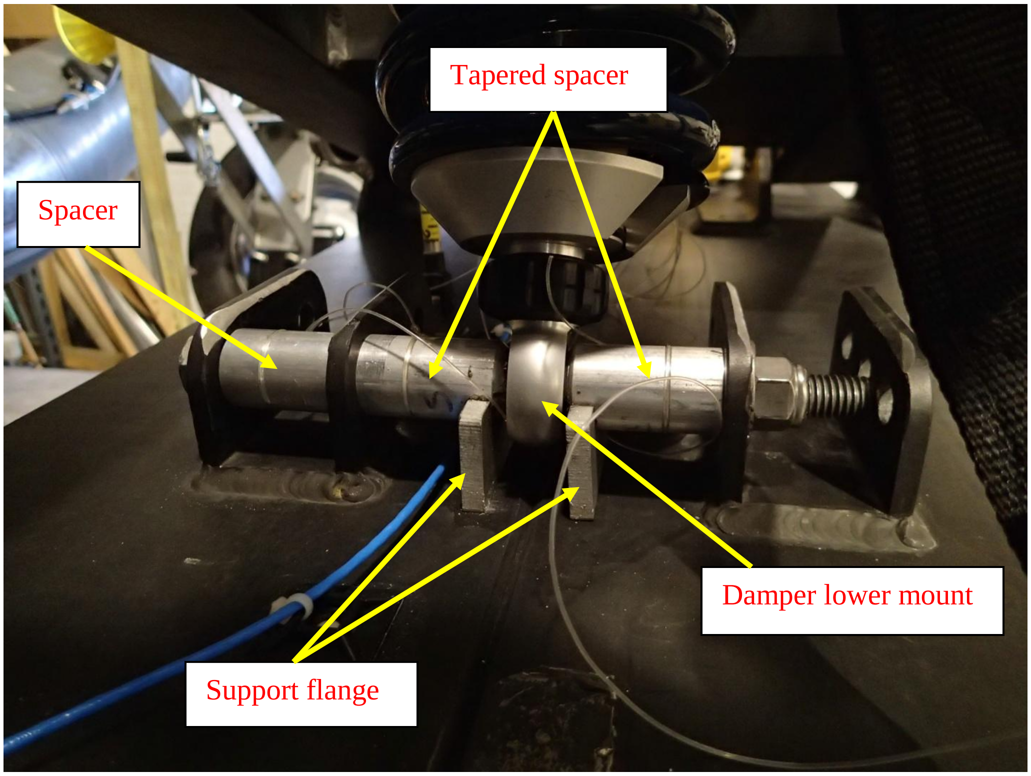

Figure 4-7: Lower mount for new damper

The new suspension is installed and removed with a total of six bolts: four holding the raised frame to the suspension rocker arm, one holding the extension limit strap, and one holding the lower mount for the damper.

4.1.3 Suspension Lifting Tool

In order to switch between the two suspensions during sea testing, a tool had to be constructed to ensure the safety of the personnel. While on the water, the suspension rocker arm will be moving up and down with the waves. A tool is needed to lock out the suspension while the suspension components are being changed. A suspension lifting tool, shown in Figure 4-8, was constructed at CVeSS for the purpose of keeping the suspension from compressing.

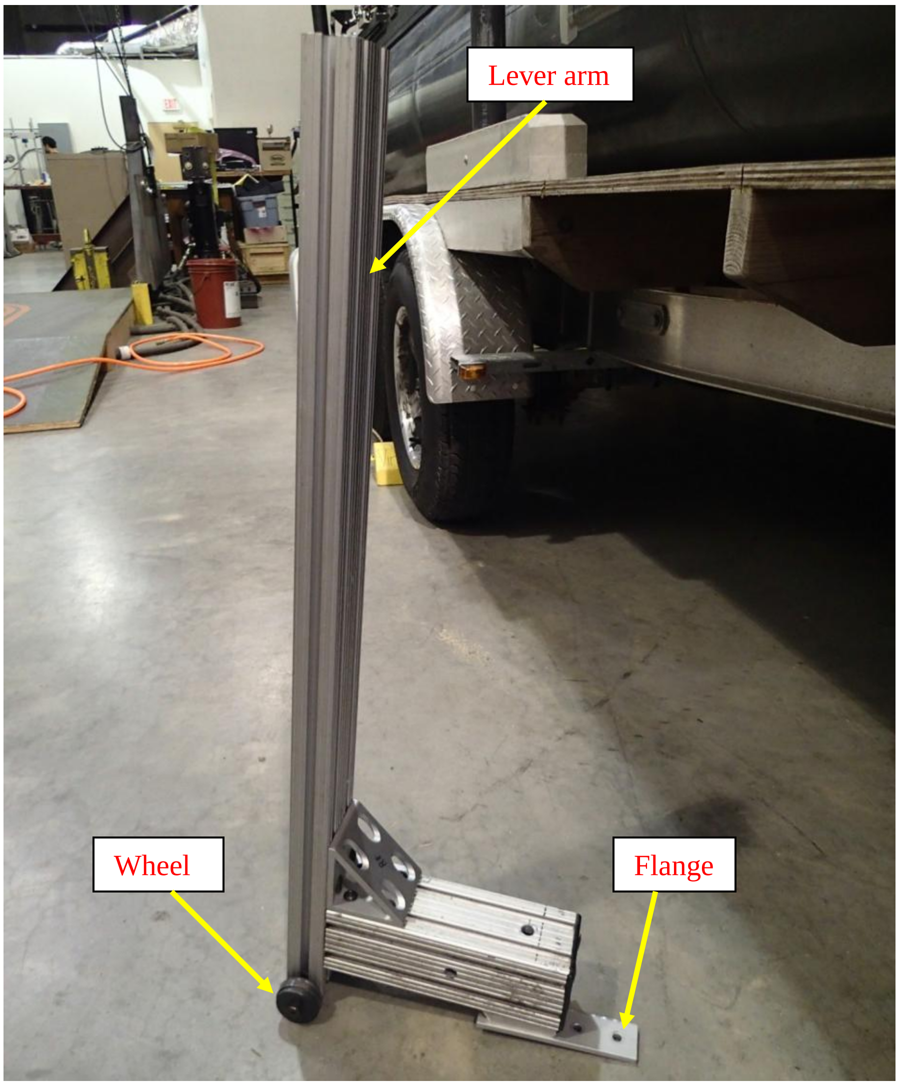

Figure 4-8: Suspension lifting tool

The suspension lifting tool is comprised of a flange to fit into the space in the suspension rocker arm, and a lever arm to push the tool in place. Wheels were installed on one end of the tool to roll the tool into place. Figure 4-9 shows two pictures of the lifting tool in place. The picture on the left shows the tool resting behind the airspring, propping up the suspension rocker arm. The picture on the right shows the flange hooked in the space of the rocker arm, keeping the lifting tool from being pulled out.

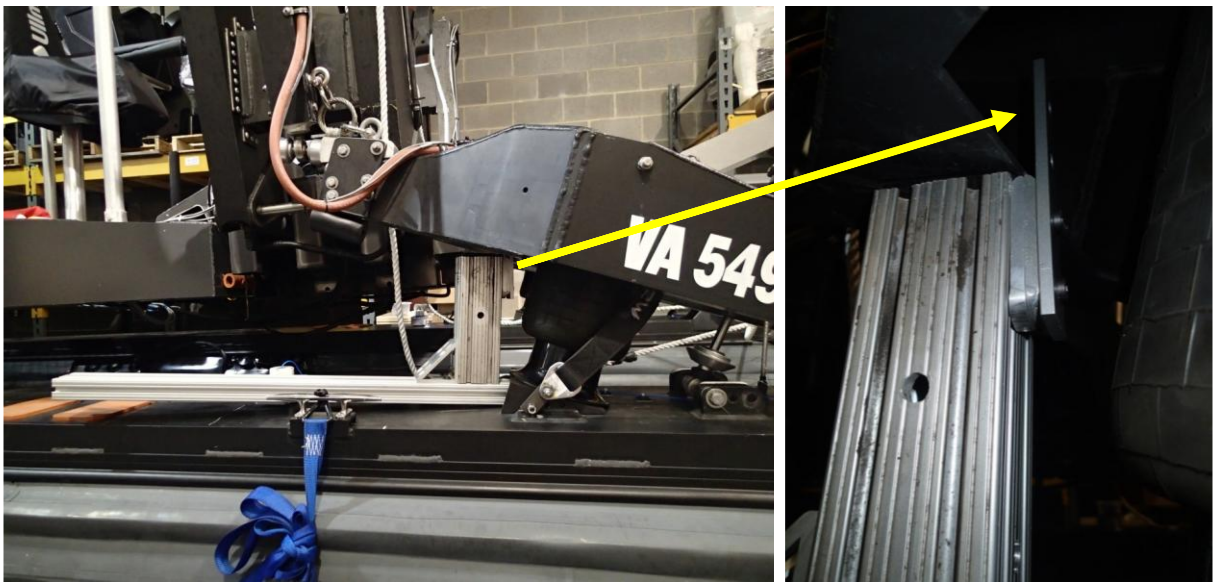

Figure 4-9: Tool props suspension up (left) and flange keeps tool from rolling (right)

Figure 4-10 shows the wheels on the bottom of the tool wedged under the lower mount platform of the airspring, keeping the tool from rolling in either direction.

Since the wheels are wedged in place under the airspring platform, which has a height lower than the wheel diameter, the lever arm does not lay flat on the WAM-V ski. The space that results keeps fingers safe from being injured during placement, shown in Figure 4-11.


Figure 4-10: Wheels of suspension lifting tool wedged under airspring platform

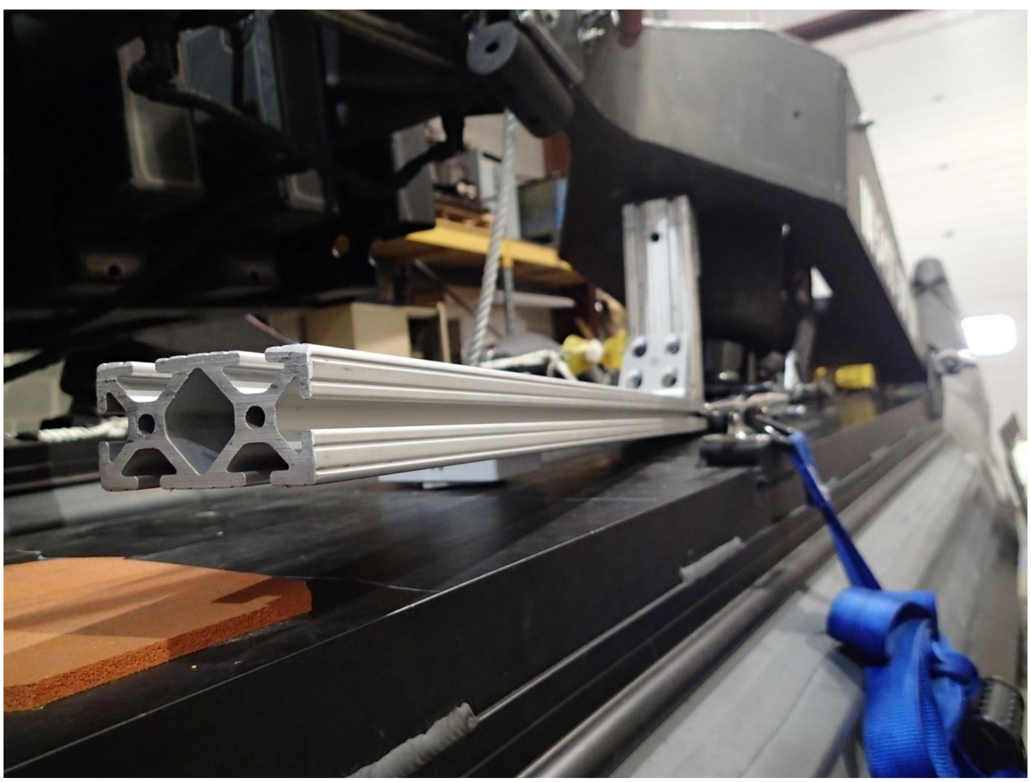
Figure 4-11: Suspension lifting tool does not lay flat on the WAM-V ski

The suspension lifting tool is used to keep the suspension from compressing during a suspension change. To keep the suspension from rising too high and possibly dislodging the lifting tool, a ratchet strap is used, shown in Figure 4-12.

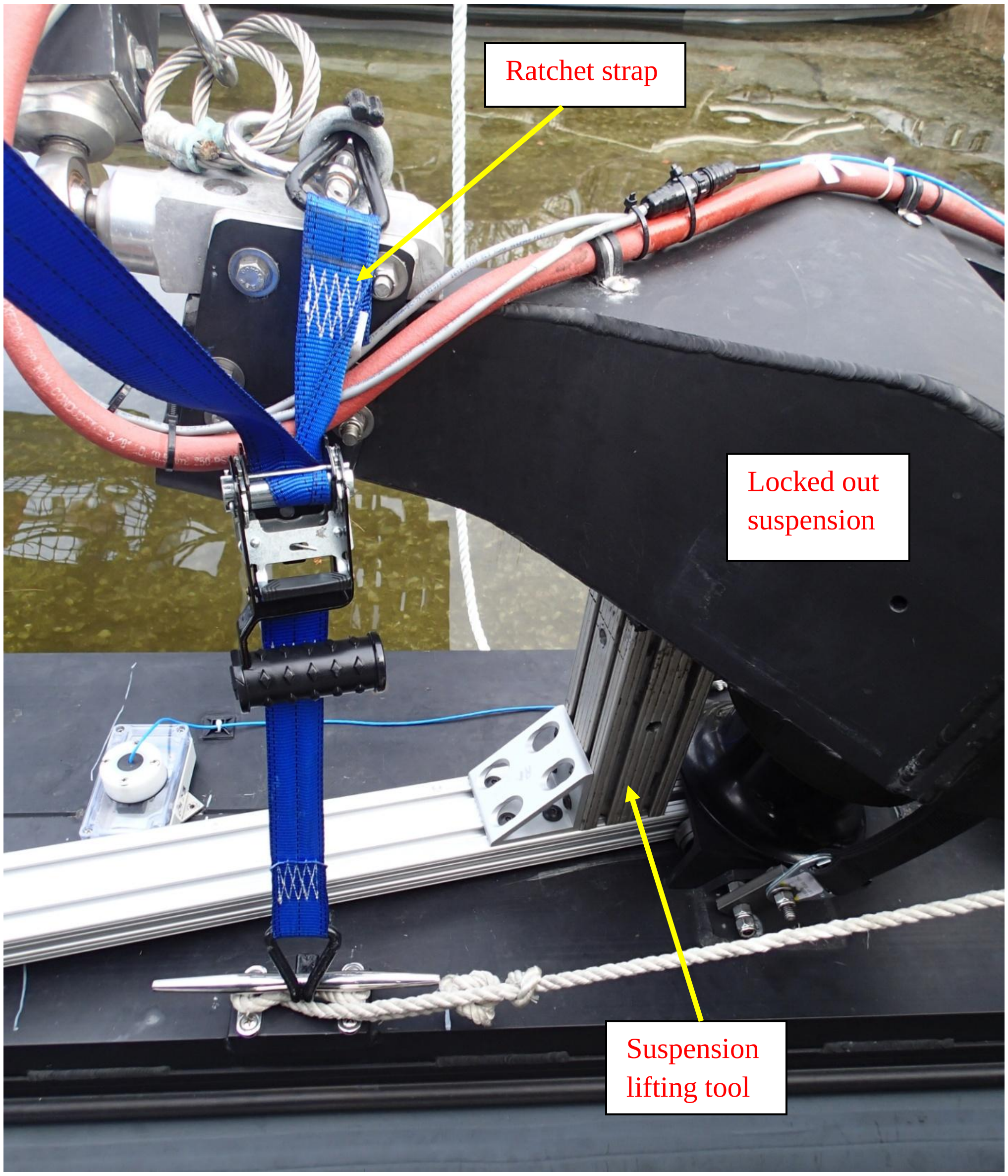

Figure 4-12: Fully locked out suspension with suspension lifting tool and ratchet strap

Once the suspension lifting tool is in place, the ratchet strap is attached to a ring on the suspension and a cleat on the pontoon ski and then tightened. The result is a fully locked out suspension.

4.2 Suspension Sea Trial Setup

The 33ft WAM-V was instrumented with an array of sensors and was tested in two main sea conditions while running predetermined test patterns.

4.2.1 Instrumentation of the 33ft WAM-V

In order to collect data to analyze the 33ft WAM-V dynamics, it is instrumented using accelerometers and potentiometers, their placements shown in Figure 4-13. Accelerometers are used to measure the accelerations at various locations, and potentiometers are used to measure displacements.

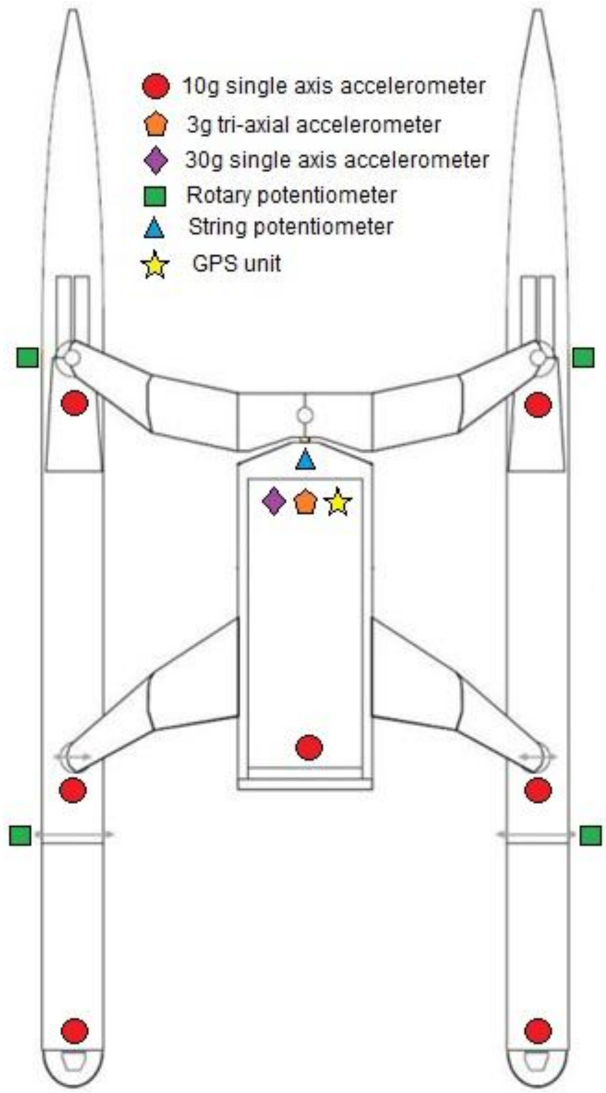

Figure 4-13: Diagram of sensor placement on 33ft WAM-V

The 10g and 30g accelerometers used are PCB Series 3741 MEMS DC Response Accelerometers, manufactured by PCB Piezotronics. Due to a number of sensor failures throughout the course of testing the 33ft WAM-V, each accelerometer is encased in a 4.7 inch x 2.6 inch x 1.6 inch polycarbonate waterproof box, manufactured by Hammond Manufacturing. In addition to the waterproof box, desiccant packs are placed in each box to keep moisture from ruining any sensors. The cable to each accelerometer is passed through a hole drilled into the waterproof box and then through a cable clam to maintain the waterproof properties of the box. The accelerometer box setup is shown in Figure 4-14.

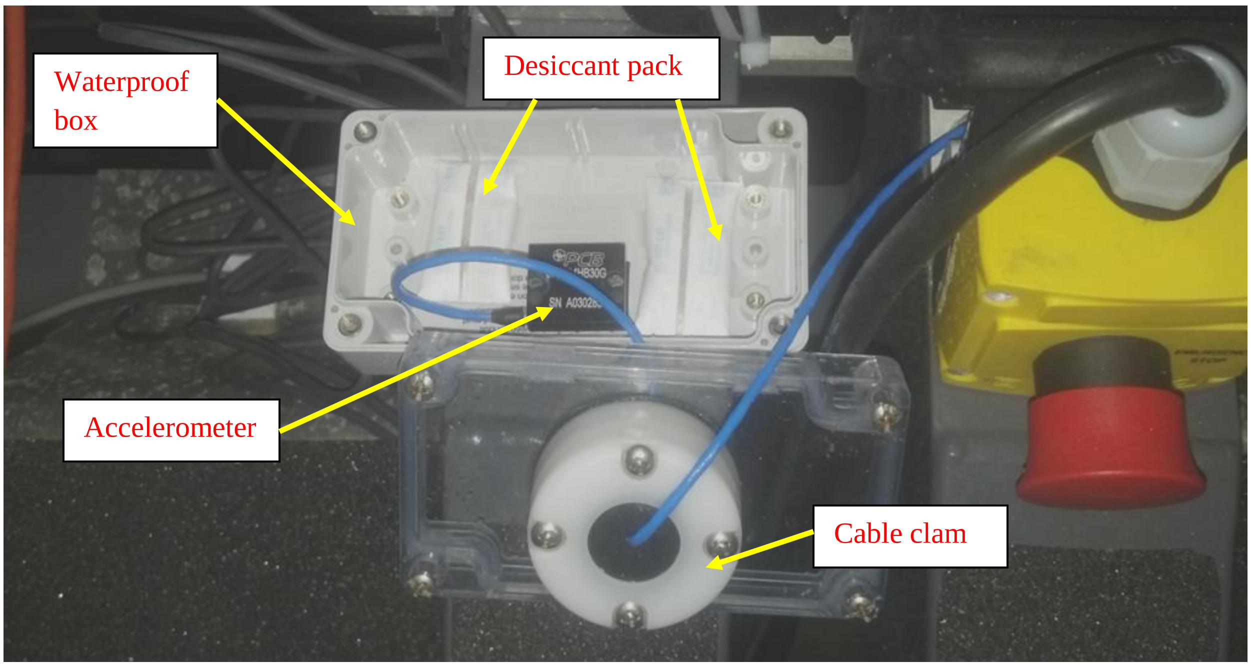

Figure 4-14: Accelerometer box setup

Four of the seven 10g accelerometers, represented by the circles in Figure 4-13, are placed at the four corners of the WAM-V: two at the front of the pontoon and two at the rear. The two accelerometers at the front are placed near the suspensions, and the two at the rear are right under the joints connecting the pontoons to the rear arch. Figures 4-15 and 4-16 show the accelerometers at the front and rear, respectively. The accelerometers shown are housed in a different box than described in Figure 4-14, but their location is the same.

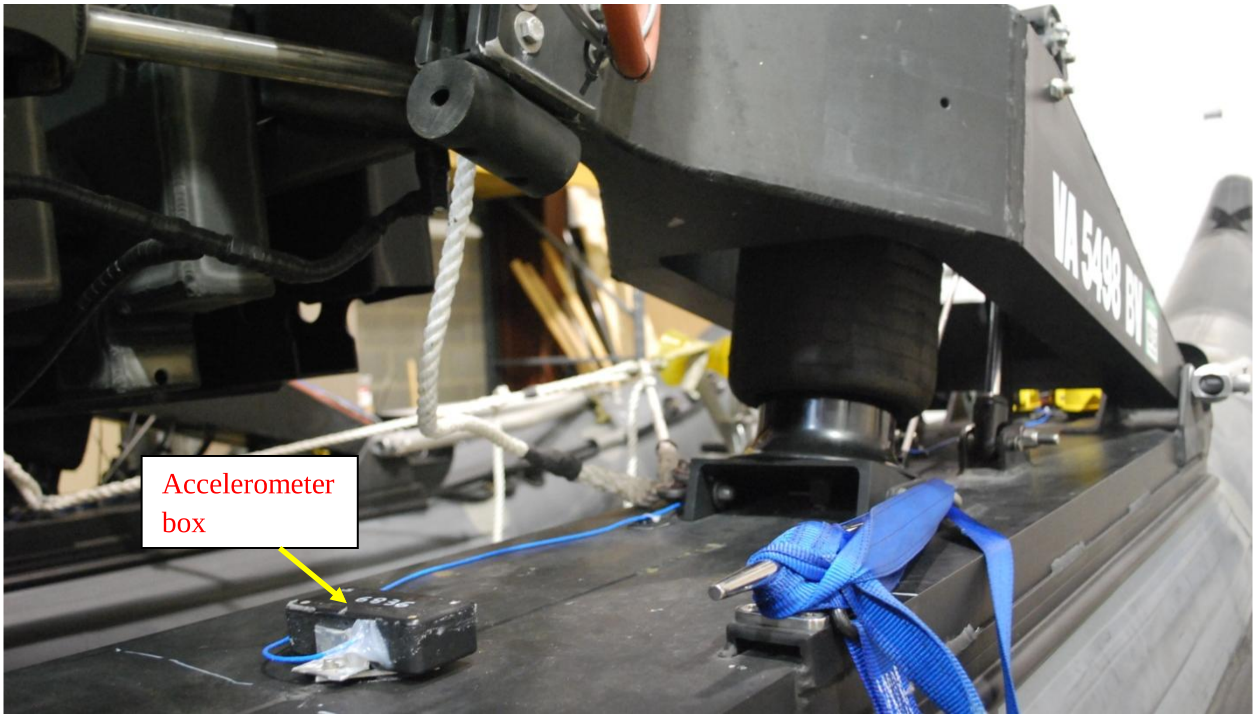

Figure 4-15: Accelerometer located towards pontoon bow near suspension

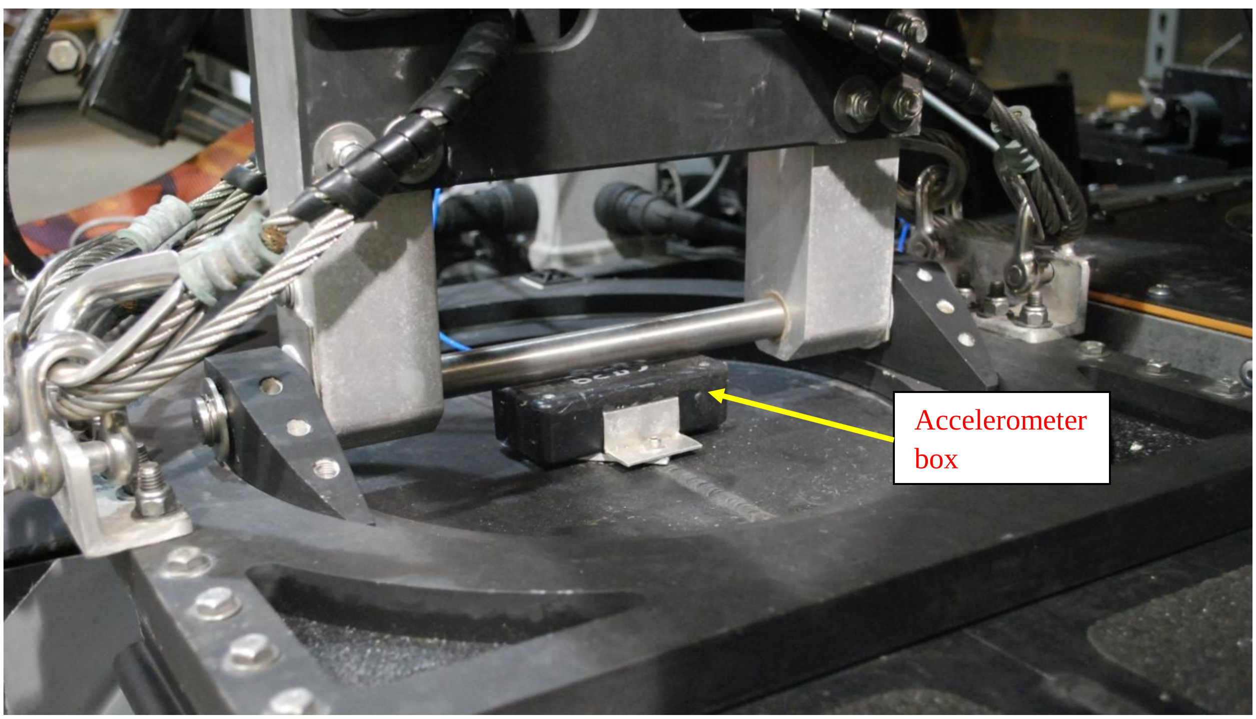

Figure 4-16: Accelerometer located under rear joint

Two additional 10g accelerometers are installed on the back of each engine pod. Originally 30g accelerometers, they were replaced by 10g accelerometers due to early sensor failure. This change in sensors is acceptable because the accelerations seen at the engine pods in previous tests did not exceed 10g. Figure 4-17 shows the accelerometer mounted at the back of the engine pod.

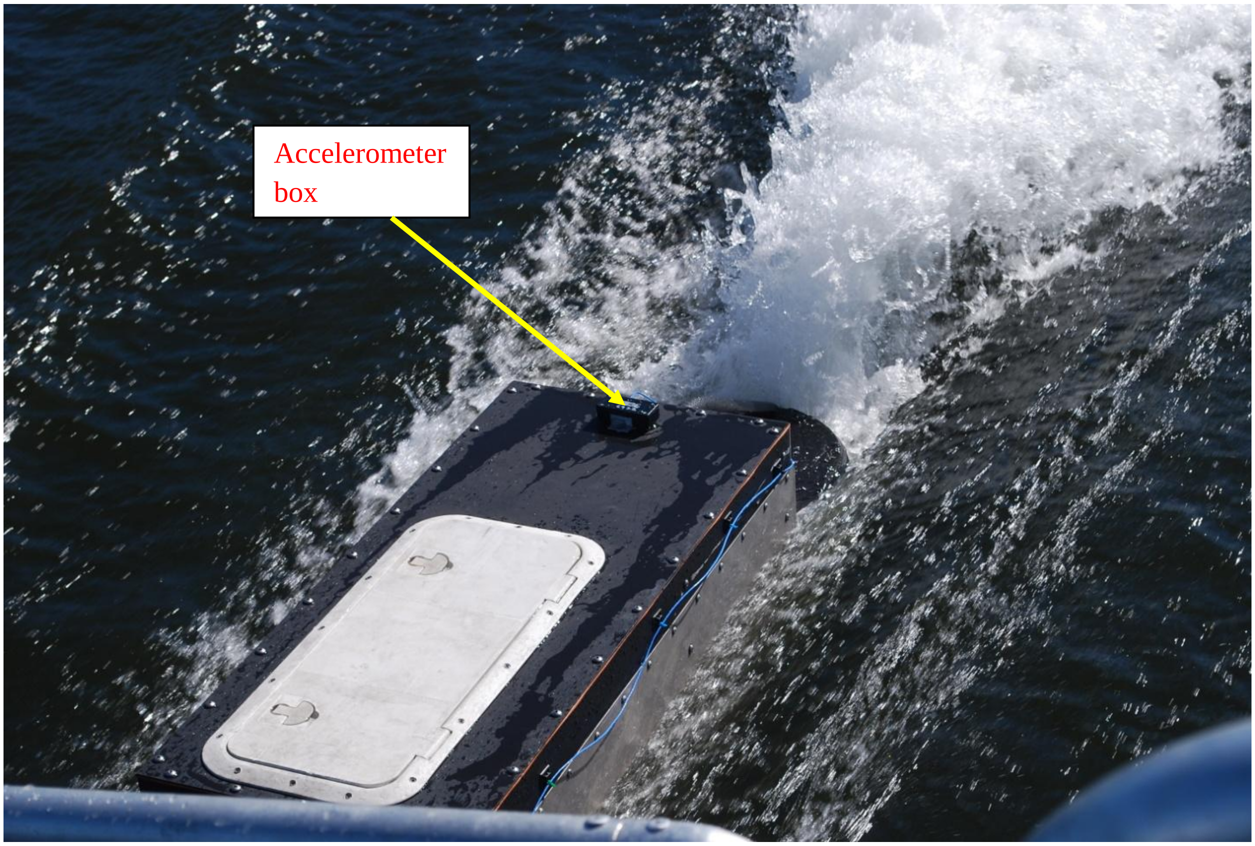

Figure 4-17: Accelerometer located at the back of engine pod

Three accelerometers are mounted on the payload tray: the last 10g accelerometer mounted at the rear, and one 30g accelerometer and one tri-axial 3g accelerometer at the front. The tri-axial 3g accelerometer, represented by the pentagon in Figure 4-13, is located inside the data acquisition box at the front of the payload tray. The 10g and 30g accelerometers at the front and rear of the payload tray capture how much the accelerations at the pontoons are attenuated. The 30g accelerometer is represented by the diamond in Figure 4-13.

A string potentiometer, represented by the triangle in Figure 4-13, is mounted between the front arch and the payload tray to measure the angle between the two. Figure 4-18 shows the string potentiometer at two angles for a better understanding of the setup. A plastic guard, barely visible in the figure, is located in front of the string to ensure that the string potentiometer readings are not influenced by spray during testing.

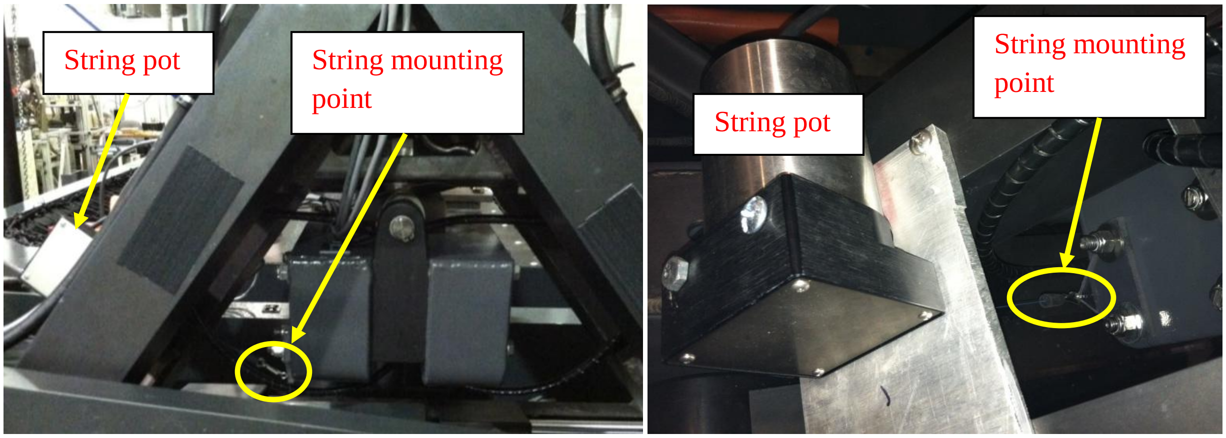

Figure 4-18: String potentiometer between front arch and payload tray

In order to measure the suspension displacements at the front and the engine pod angles at the back, rotary potentiometers, represented by the squares in Figure 4-13, are installed. Each submarine-rated potentiometer is placed in a waterproof metal box along with two desiccant packs. Figure 4-19 shows the potentiometer box setup.

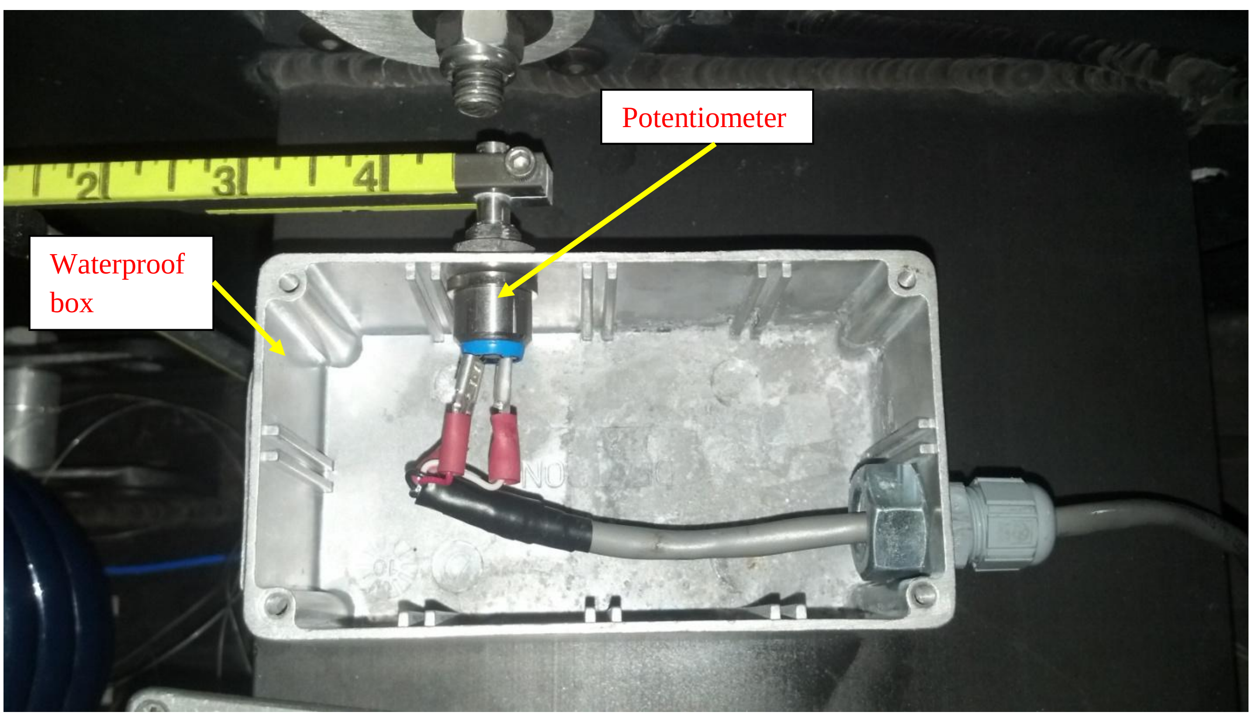

Figure 4-19: Potentiometer box setup

To measure the displacement of the suspension, the potentiometer is mounted between the suspension arm and the ski on top of the pontoon using a series of linkages. Figure 4-20 shows the mounting of the potentiometer at the suspension.

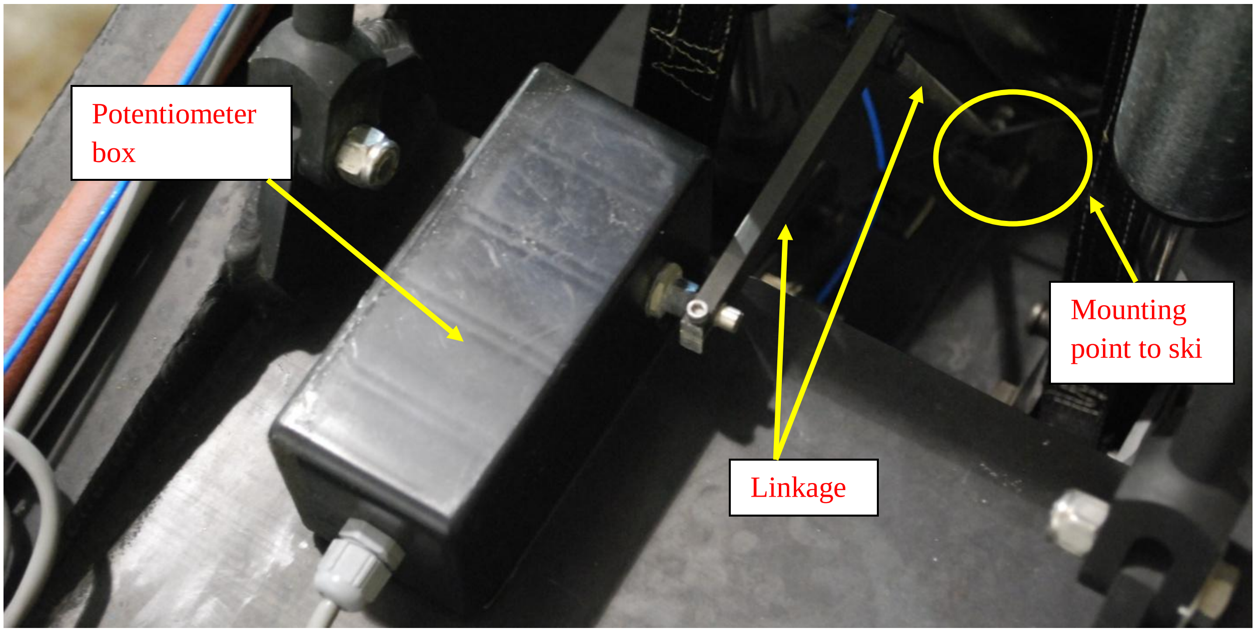

Figure 4-20: Potentiometer at suspension

Rotary potentiometers are mounted between the engine pods and the pontoon skis to measure the angles that are formed by the engine pods in the water. Figure 4-21 shows the mounting of the potentiometer at the engine pod.

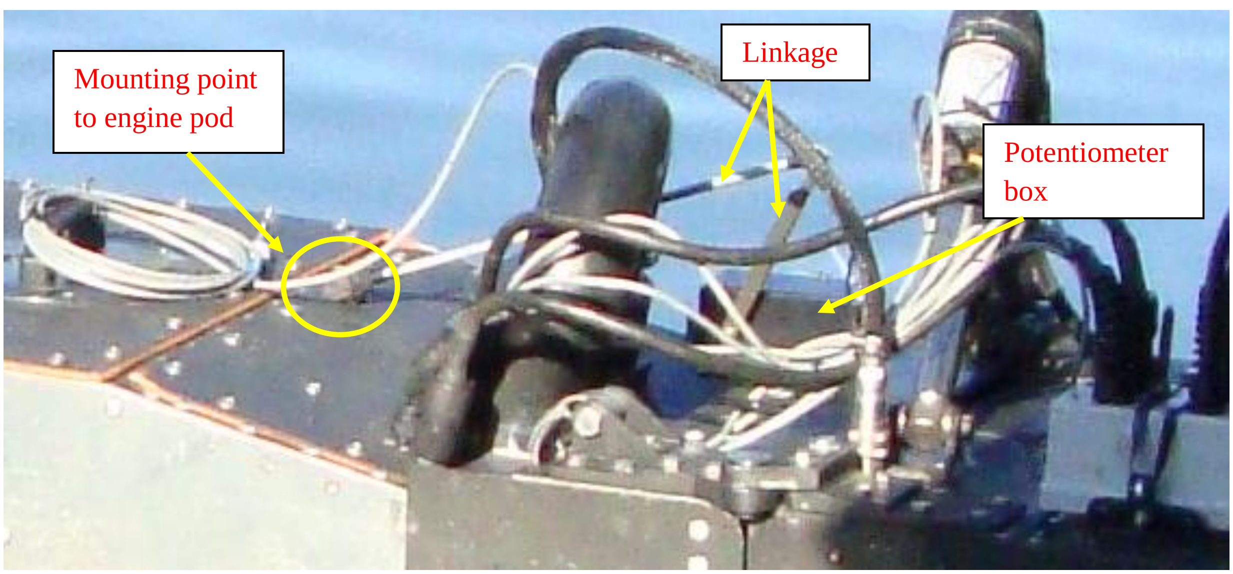

Figure 4-21: Potentiometer at engine pod

To track the 33ft WAM-V on the water, a GPS unit, which is represented by the star in Figure 4-13, is mounted on top of the data acquisition (DAQ) box. The GPS unit, a Garmin 18x-5Hz, transmits data at a rate of 5Hz. The Garmin GPS takes information such as time in Coordinated Universal Time (UTC), longitude and latitude readings in degrees and minutes, speed in knots, and heading in degrees. Figure 4-22 shows the Garmin GPS unit mounted on the lid of the data acquisition box.

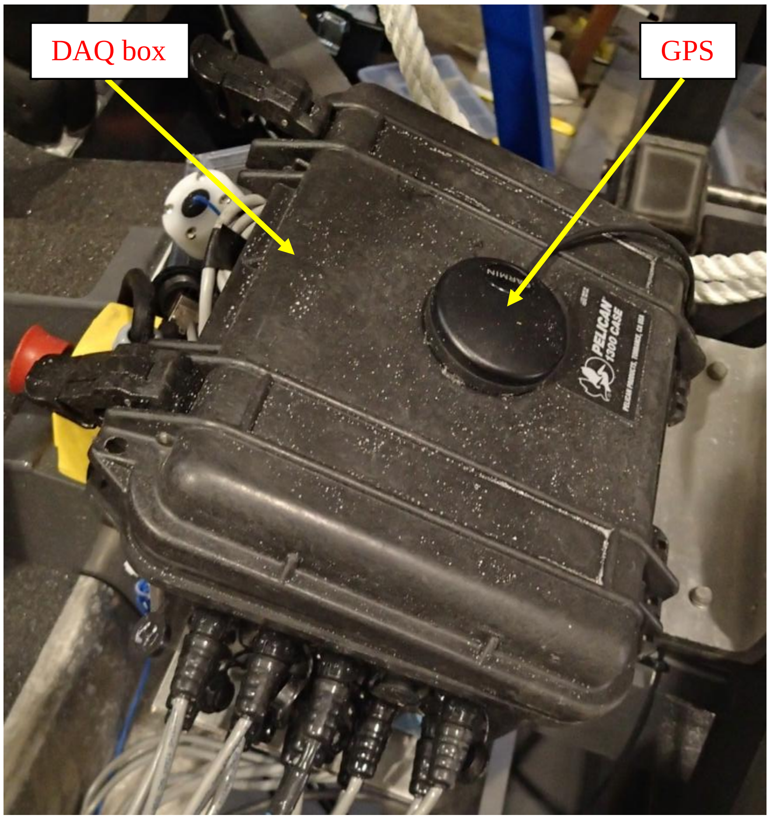

Figure 4-22: GPS unit mounted on top of the data acquisition box

To record all the data being obtained by the accelerometers, string and rotary potentiometers, and GPS unit, a CompactRio data acquisition system is used. The CompactRio, or cRIO, is used with LabVIEW, and both hardware and software are developed by National Instruments. Recording at 500Hz, the cRIO takes data from eighteen sensor channels: eight single-axis accelerometer readings, three accelerometer readings from the tri-axial accelerometer, four readings from the rotary potentiometers, one from the spring potentiometer, one for a radio trigger to mark important sections of data, and one for the battery voltage. The cRIO also records time data, though that is a process computed within the cRIO.

The cRIO, data acquisition battery, and tri-axial 3g accelerometer are all mounted inside a waterproof Pelican box shown in Figure 4-23. The cRIO and tri-axial accelerometer are under the battery and are not visible in the figure.

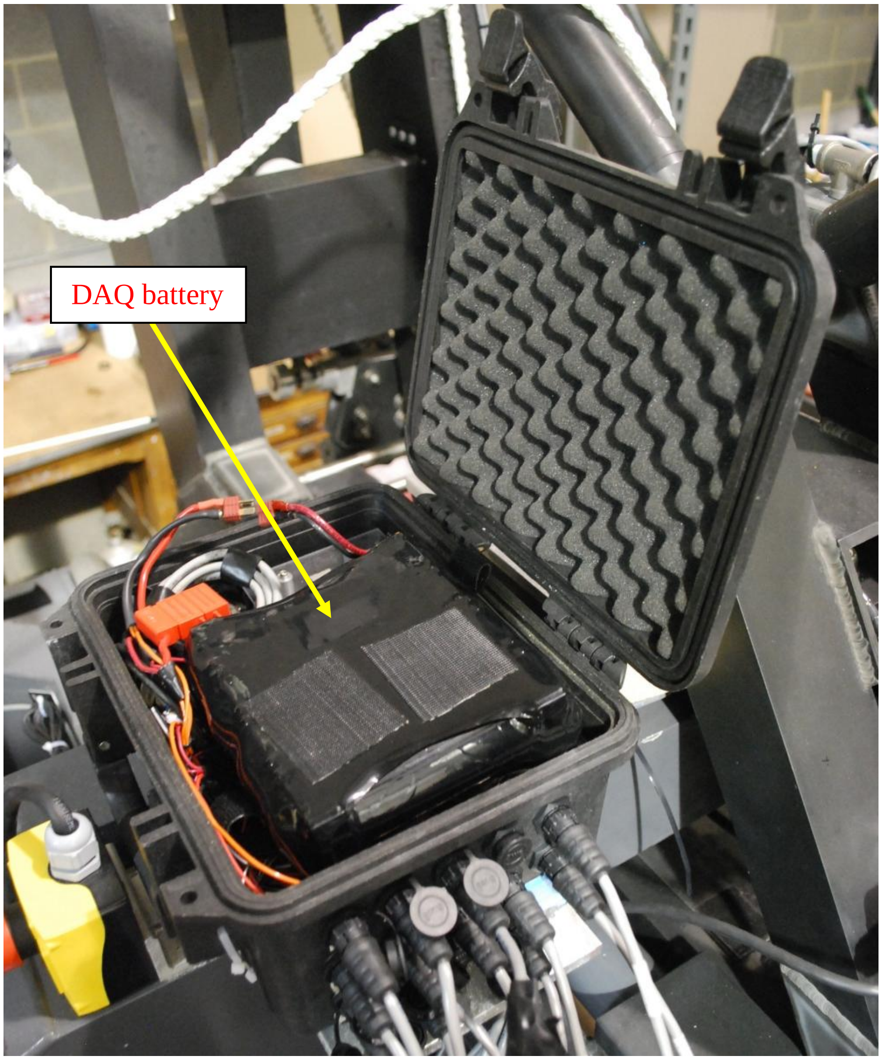

Figure 4-23: DAQ box containing cRIO, tri-axial accelerometer, and DAQ battery

In addition to all the quantitative sensor data being obtained, video cameras are mounted at various positions on the 33ft WAM-V to take qualitative data. Two GoPro cameras are positioned at various locations on the 33ft WAM-V: these include placement near the suspension to capture suspension motions, at the engine pods to capture engine pod motions, and at the string potentiometer to capture the motion of the front arch. Figure 4-24 shows an instance where the GoPro camera was used to capture front arch and string potentiometer motion during testing.

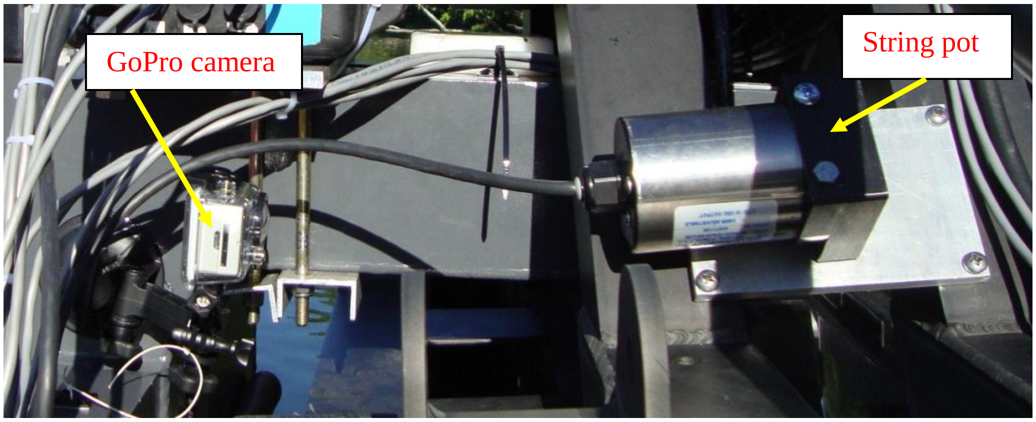

Figure 4-24: GoPro camera capturing motions of string potentiometer

Four additional cameras, provided by CCD, are installed to capture video of the operator and pontoons during testing. These videos are linked with another GPS unit, supplied by CCD, and show time, position, and speed on the video. Figure 4-25 shows three locations of the CCD cameras. The left picture is of the camera located under the payload tray looking forwards at the motion of both pontoons. The middle camera is located at the back of the payload tray to record operator response. The right picture is of the camera that is also located under the payload tray, but only pointing towards one pontoon. The fourth camera is not shown since it is similar to the third camera described, but pointing at the other pontoon.

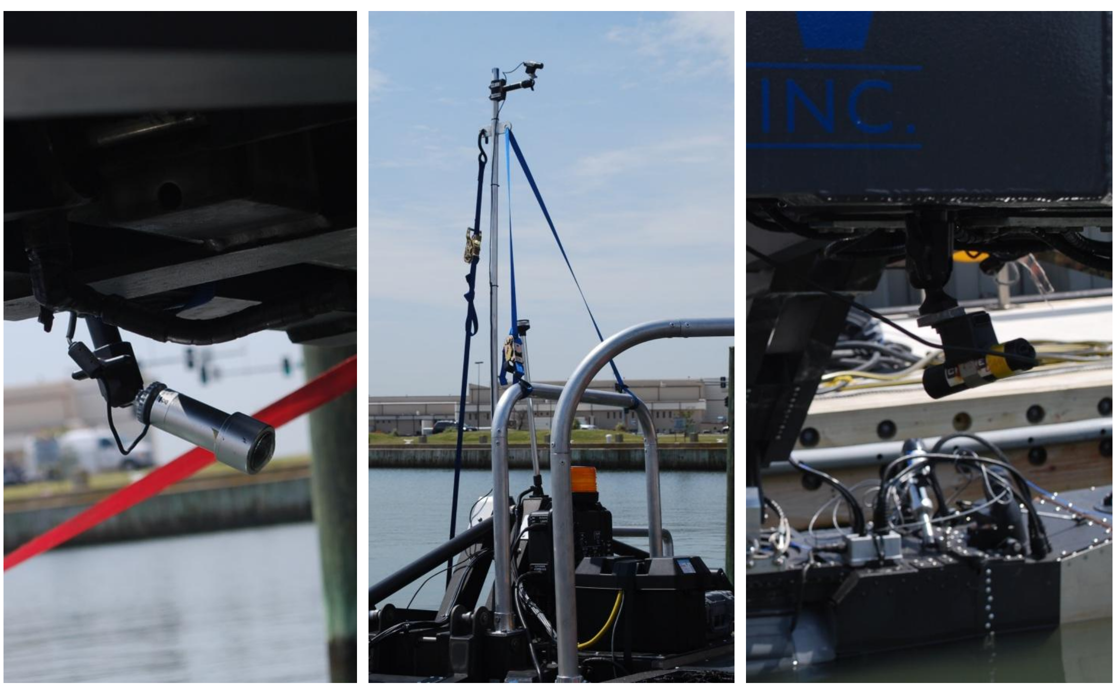

Figure 4-25: Cameras provided by CCD on 33ft WAM-V

For safety purposes, a chase boat is launched with the WAM-V for every test. The chase boat provided by CCD was a 7M rigid inflatable boat (RIB), a standard monohull high speed boat used by the United States Navy.

In order to compare dynamics between the two vessels, a set of video cameras and sensors are implemented on the 7M RIB as well. A camera is stationed behind the pilot to capture the motions seen at the payload deck. A data acquisition system is mounted near the center of mass on the payload tray of the RIB to record data from an accelerometer and from a GPS unit.

4.2.2 Test Patterns

Two types of tests were attempted on the 33ft WAM-V through rough waters at the Naval Station in Norfolk, VA: constant speed runs, and star patterns at constant speeds. The constant speed runs were conducted in two directions, the first being the initial direction of travel, and the second being its reciprocal to cancel out any motions influenced by the currents. The speeds tested were 5 knots, 10 knots, 15 knots, and top speed, which varied with each test.

A star pattern is comprised of five legs: head, aft quartering, beam, bow quartering, and following seas. With this test, the response of the 33ft WAM-V to different wave directions can be evaluated. The legs of the star pattern are depicted in Figure 4-26 and are defined in Table 4-1.

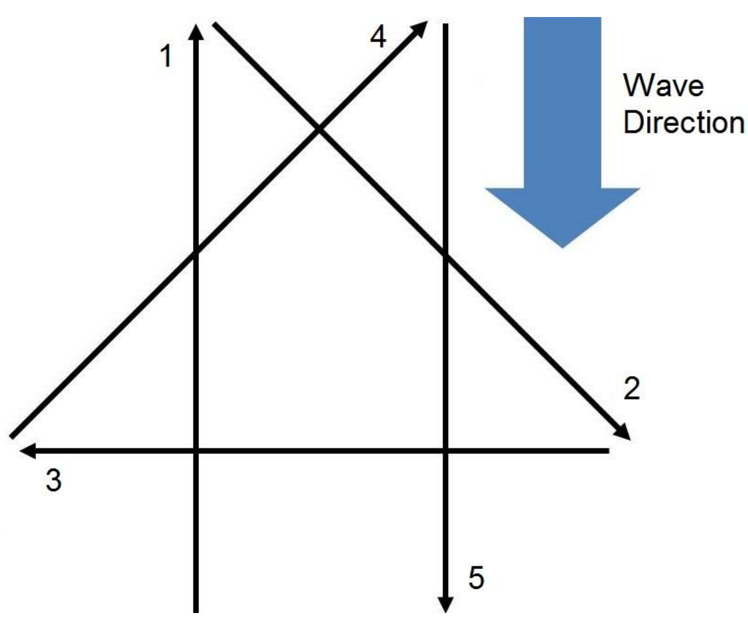

Figure 4-26: Diagram of star pattern

Table 4-1: Legs of Star Pattern

Leg #	Wave
1	Head Seas
2	Aft Quartering Seas
3	Beam Seas
4	Bow Quartering Seas
5	Following Seas

4.2.3 Testing Procedure

Tests were conducted on days that provided the desired sea conditions. Sea conditions were determined by checking the National Digital Forecast Database produced by the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS). The service provides wave height, wind speed, and wind direction [10] that helped in determining whether to put the WAM-V in the water. Figure 4-27 shows two screenshots of the information provided around the Norfolk region. The screenshot on the left is of wave height, and the one on the right is of wind speed and direction.

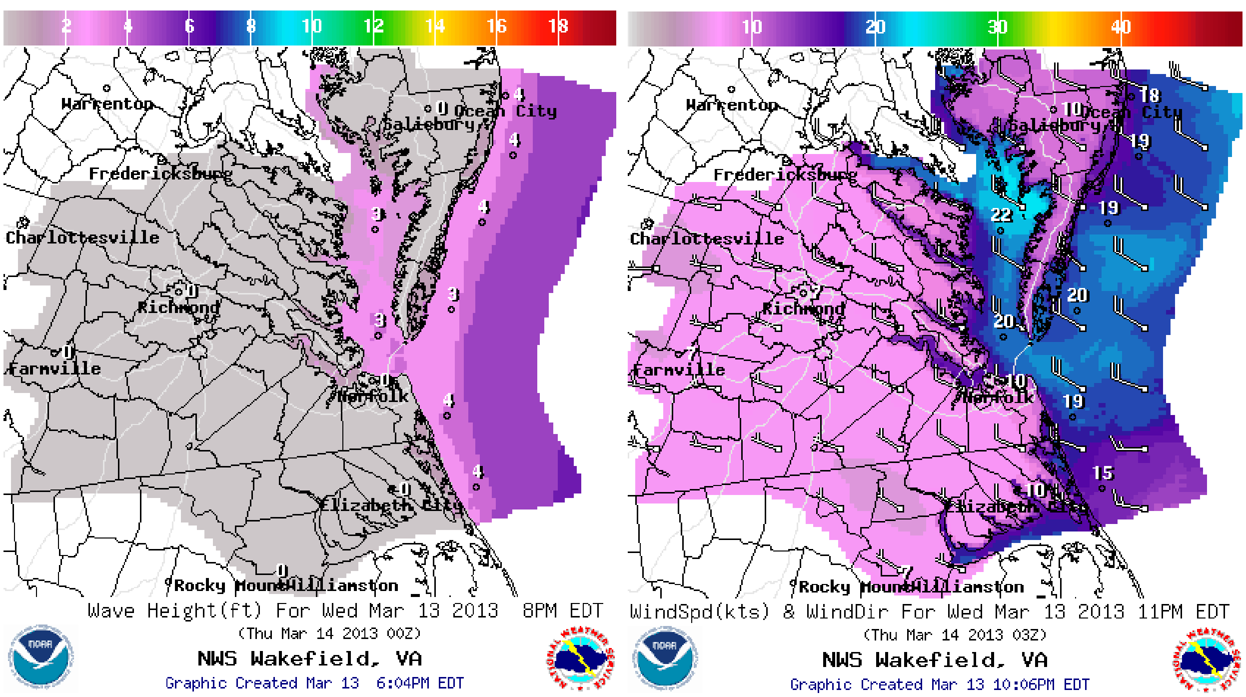

Figure 4-27: Wave heights (left) and wind speed and direction (right) [10]

Once it is decided to test, personnel start preparations for putting the 33ft WAM-V and chase boat into the water. The WAM-V goes through a pre-launch checklist provided by M.A.R. [11].

Items on the pre-launch list include checking that all hatches are secured, that electrical connections are correctly plugged in, and that everything on the payload tray is secure. Another pre-launch check is ensuring all the sensors are functioning, and that the cRIO is correctly taking data.

Everyone involved with the tests was required to wear life jackets for safety. While only life jackets were required in summer testing, during winter testing, dry suits, waterproof gloves, balaclavas, and ski goggles were required in addition to the life jackets for protection against the cold.

Waterproof handheld radios kept the WAM-V operator in constant communication with the chase boat during summer testing. However, due to complications with spray and rough waters in winter testing, the primary means of communication between vessels was replaced with hands-free Piratecom headsets, but the handheld radios were kept as a backup.

During each test, everyone onboard both vessels had responsibilities to ensure safe testing. The operator of the 33ft WAM-V communicated with the 7M RIB via radio to coordinate testing patterns and speeds. A person on the chase boat watched the WAM-V and took notes on anything significant that happened during testing, which included noting any observations seen by the 33ft WAM-V operator that were relayed back to the chase boat. These notes were taken in a waterproof notebook and usually included the observation and the time it occurred. A second person on the chase boat was in charge of operating the safety radio, which cuts the engines of the WAM-V if anything happens to the WAM-V operator causing loss of control. If there were enough people on the RIB, a third person would be in charge of taking pictures and video of the WAM-V for more qualitative data.

After testing, all observations and notes are put into a test report template for distribution and future reference. The data is transferred off the cRIO and analyzed.

Chapter 5 Suspension Testing and Performance Analysis

This chapter starts with an overview of the testing conducted on the 33ft WAM-V. Analysis of the new suspension is performed in Sea State 1 (SS1), followed by comparison analysis between the stock and new suspension in Sea State 2 (SS2). The chapter ends with a comparison between the dynamics of the stock and new suspension during an encounter with a 2- and 4-foot wave.

5.1 Testing Summary

33ft WAM-V testing of the stock and new suspensions was conducted at the Naval Station in Norfolk, VA during the summer of 2012 and again in the winter of 2012.

Summer 2012 testing of the WAM-V was conducted only on the stock suspension since the new suspension components had not yet been chosen. Due to WAM-V reliability issues and lack of desirable sea conditions, a limited amount of data is available with the stock suspension installed.

Winter 2012 testing of the WAM-V was originally meant to test both suspensions in higher sea states. Due to WAM-V reliability issues and sea conditions being too rough, suspension changes were not made during the tests, resulting in only the new suspension being tested in the winter.

Table 5-1 shows the available data from the tests conducted. Within the limited data, only constant speed data are available, as they were conveniently run while heading towards and returning from the testing area.

Table 5-1: Available Data from Testing

	SS1	SS2 / 2-foot wave	4-foot wave
Stock Suspension	n/a	June 26, 2012	June 21, 2012
New Suspension	December 14, 2012	December 11, 2012	December 11, 2012

Sea State 1 (SS1) testing of the stock suspension was conducted early in the summer, however, due to problems with the data acquisition, no SS1 data exists for analysis. However, a brief overview of suspension dynamics seen during winter testing of the new suspension is analyzed in an SS1.

Data was collected for both suspensions operating in an SS2, and analysis of the differences seen between the two is covered in this chapter. Analysis over a longer period of time, about 10 minutes, was conducted to determine the differences in the ride heights of each suspension. Each suspension was then analyzed in detail while traveling over a wave with a height of 2 feet to evaluate the differences in dynamics.

Further analysis was done on the WAM-V when subjected to a wave with a height of about 4 feet. This was an "extreme" case where both pontoons were launched into the air and slammed back down onto the water.

5.2 Sea State 1 Results

SS1 testing occurred during the summer of 2012 as well as during the winter. Due to unusable data from summer testing, only data with the new suspension exists.

SS1 testing of the new suspension was conducted on December 14, 2012. The 500lb/in spring was used and preloaded to raise the suspension ride height to 20.75 inches on the port side, and 20.375 inches on the starboard side. Three damper settings were tested in head and following seas, totaling six runs. The tests were run at a test speed of 20 knots, the maximum speed of the WAM-V, in an attempt to increase the motions seen by the suspension to generate better data. Since the head sea runs were rougher than the following sea runs, only the head sea runs are analyzed.

The damper settings were middle damping, maximum damping, and minimum damping. Run 1 was conducted with the dampers set at their middle setting: six clicks on the main adjustment knob, and maximum damping on the fine adjustment knob. Run 2 was conducted with the dampers at their maximum setting: maximum on both the main knob and the fine knob. Run 3 was conducted with the dampers at their minimum setting: minimum on both the main knob and fine knob.

Probability density functions (PDFs) were generated for the vertical accelerations of the pontoon bows and payload tray while operating through SS1. These plots show the range of accelerations the WAM-V experiences at those locations. Figures 5-1 to 5-3 show the vertical acceleration PDF for the port and starboard pontoon bow, and for the payload tray of Runs 1 through 3, respectively. All the plots have been given the same scale to note the differences between the three runs.

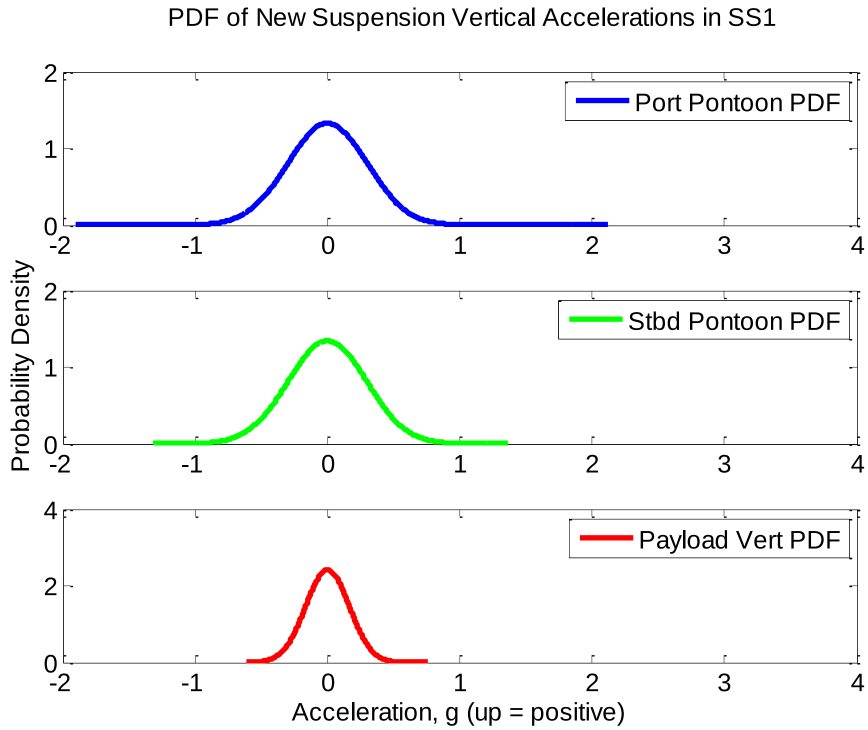

Figure 5-1: PDF of vertical accelerations during Run 1

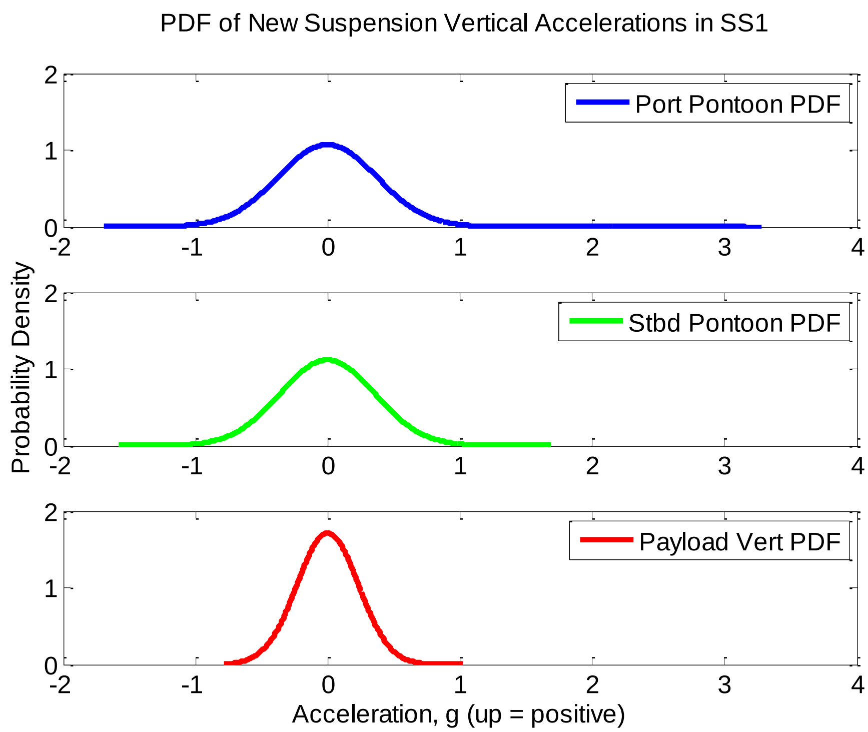

Figure 5-2: PDF of vertical accelerations during Run 2

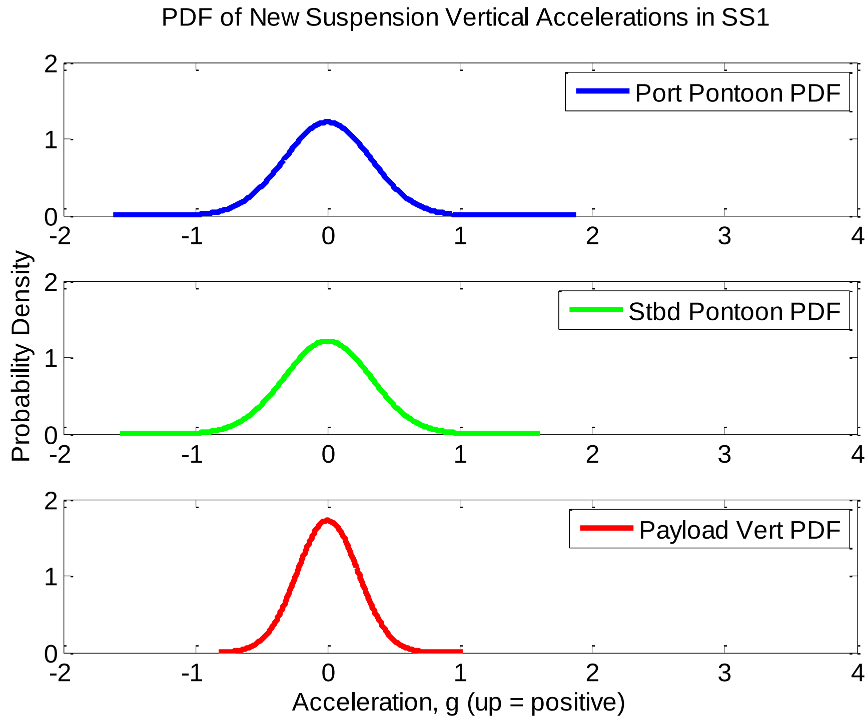

Figure 5-3: PDF of vertical accelerations during Run 3

The figures show that Run 2 was the roughest of the three runs, generating the largest range of accelerations at the pontoons and payload tray, with the port pontoon reaching approximately 3.25g, the starboard pontoon reaching about 2.6g, and the payload tray reaching 1g. The pontoons during Run 1 only reach 2g, while the payload tray reaches 0.8g. Run 3 recorded the same payload acceleration as Run 2, even though the pontoon accelerations are lower during Run 3.

PDFs were also generated for the percent compression of the dampers to establish where the suspension typically operated in SS1 waters during the course of each run. Figures 5-4 to 5-6 show the PDF for the percent the dampers are compressed during Runs 1 through 3, respectively. A value of 0% means a fully extended damper, while 100% is fully compressed. The vertical dotted line in each plot is the height when the damper comes into contact with the compression bumper. The vertical dash-dotted line indicates when the damper contacts the extension limit straps. The solid data line is the PDF of the port damper height, and the dashed data line is the PDF of the starboard damper height.

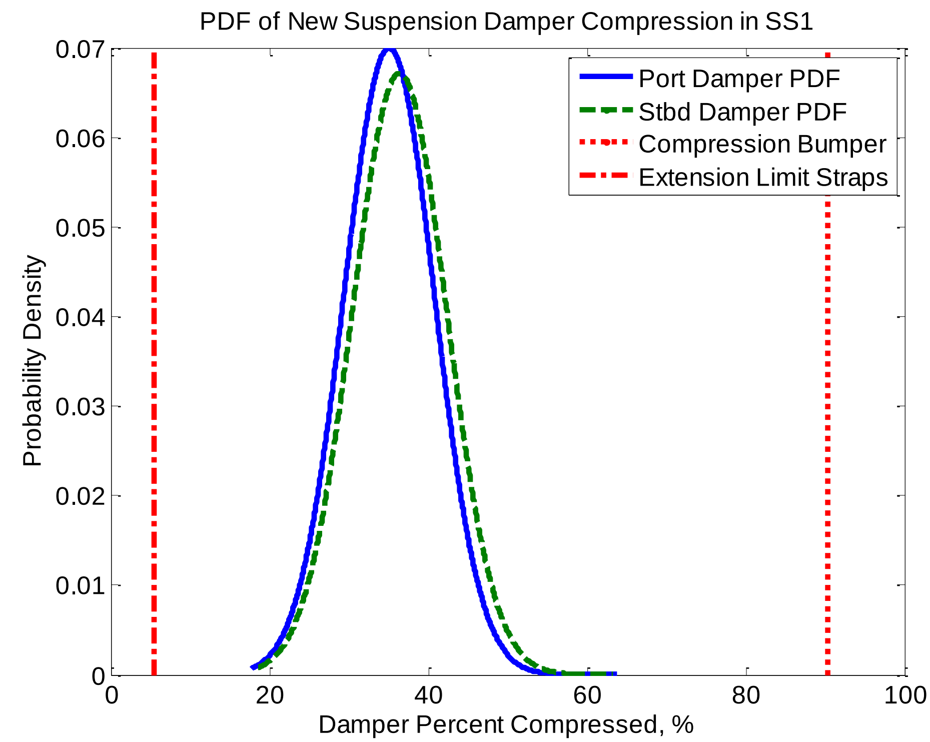

Figure 5-4: PDF of new damper percent compression during Run 1

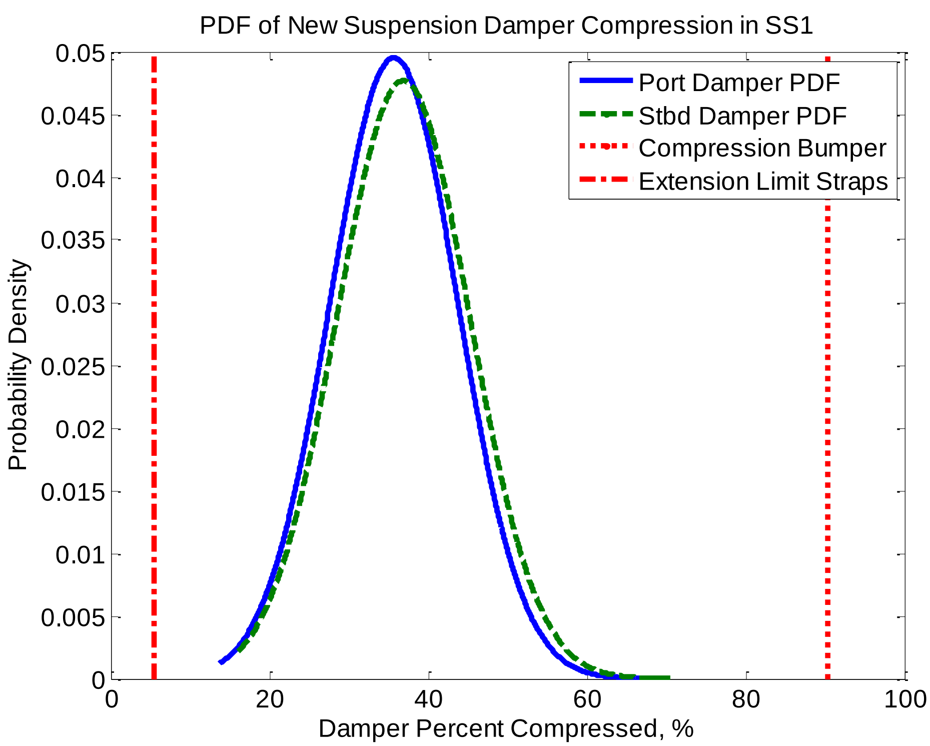

Figure 5-5: PDF of new damper percent compression during Run 2

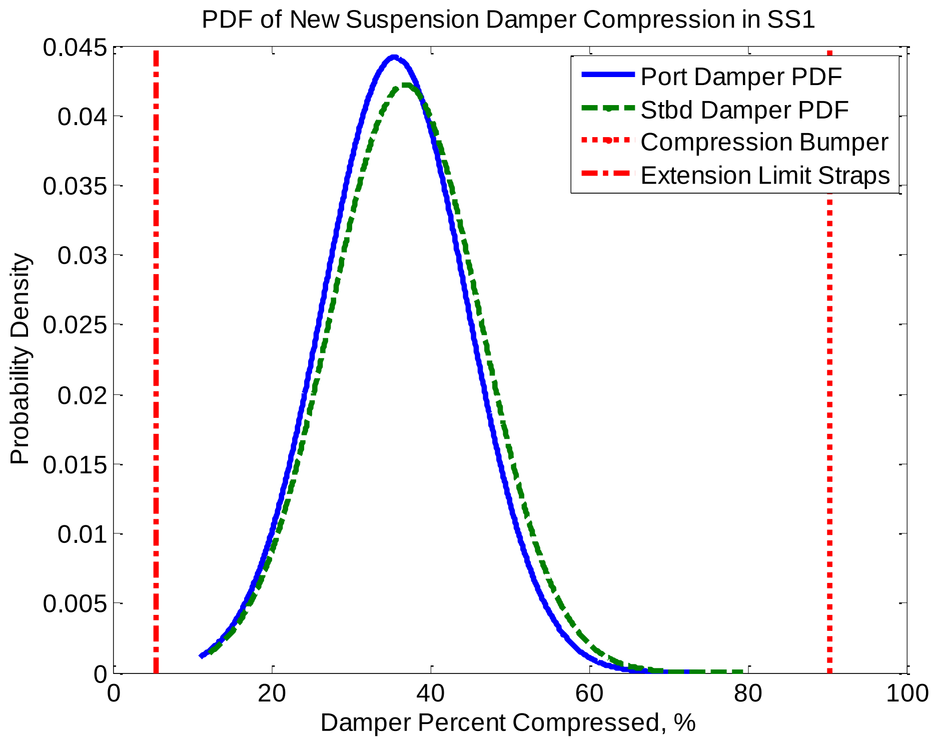

Figure 5-6: PDF of new damper percent compression during Run 3

Throughout the course of SS1 testing of the new suspension, the seas varied slightly from test to test. Table 5-2 shows the average and range that the dampers were compressed for each run, as determined from Figures 5-4 to 5-6.

Table 5-2: Average, Minimum, and Maximum Percent of Damper Compression

Run #	Damper Setting	% Compression of Damper		
		Minimum	Average	Maximum
Run 1	Middle	18	35	63
Run 2	Maximum	13	35	70
Run 3	Minimum	10	35	80

According to Table 5-2, Run 2 was conducted in seas that were slightly rougher than during Run 1. Even with a higher damping rate, Run 2 has more suspension movement than Run 1, proving that the seas during Run 2 were rougher. Video taken from SS1 testing shows that Run 2 was conducted in rougher seas, confirming what is observed in the data.

Figure 5-7 shows the PDF of the suspension ball joint height of Run 2. Since the relationship between ball joint and damper height is linear, the ball joint heights of Runs 1 and 3 follow the trend of their respective PDFs and are not shown.

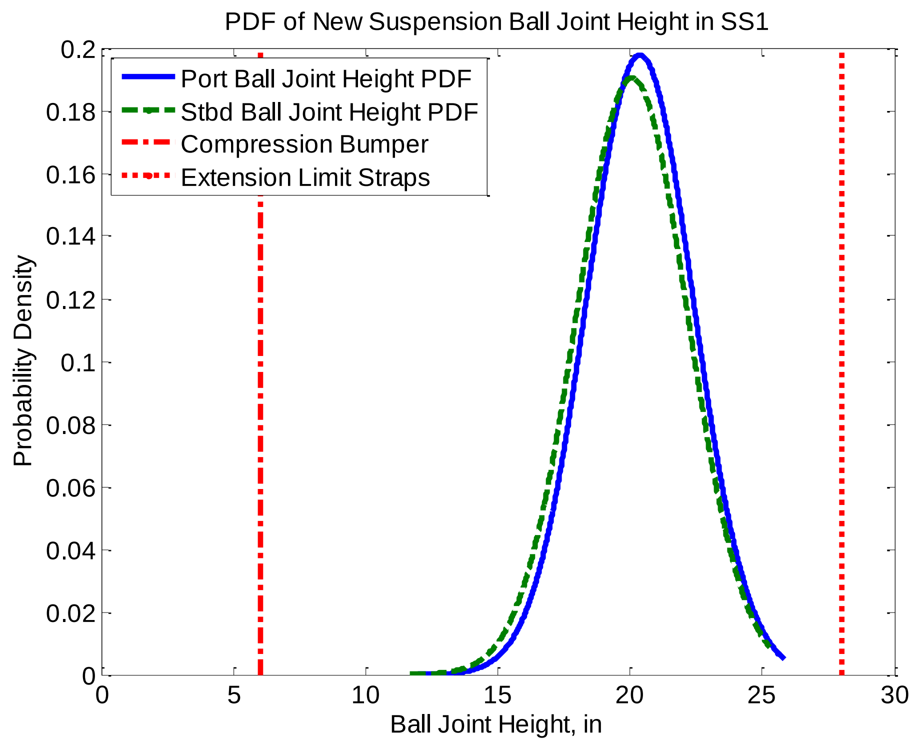

Figure 5-7: PDF of new suspension ball joint height of Run 2

Significant differences could not be determined between damper settings from the SS1 testing of the suspension. Without significant waves to induce suspension movement, the operator was not able to definitively determine which damper setting was optimal for the WAM-V in an SS1.

With preload on the spring, the suspension ride height was at a position that allowed for more compression stroke than extension. The analysis on SS2 suspension testing in the following section will show that the preload during SS1 testing would have been preferred had it been possible. It should be noted that SS1 testing of the new suspension was conducted after SS2, which is why the suspension was not preloaded during SS2 testing.

5.3 Sea State 2 Results

Testing in SS2 waters was conducted at the Naval Station in Norfolk, VA on June 26, 2012 with the stock suspension, and on December 11, 2012 with the new suspension. Both tests were conducted in the Willoughby Bay/Thimble Shoals area near Norfolk, VA. The testing conditions on each day are listed in Table 5-3.

Table 5-3: Testing Conditions in Sea State 2 Waters

	Jun. 26, 2012	**Dec. 11, 2012**
Suspension	Stock	New
Sea state	Hi2/Lo3	2
Wave heights	n/a	2-3+ ft
Wind	SW 10-15 kts	15-20 kts
Ambient temperature	99 degrees F	50 degrees F
Water temperature	75 degrees F	50 degrees F

The setup of the stock suspension during SS2 testing included the airspring at a pressure of 25psi. For SS2 testing of the new suspension, the 500lb/in spring was used with no preload, resulting in a suspension ride height of approximately 19 inches on both sides. Due to the rough sea conditions, a more precise measurement of the ride height could not be taken without risking safety. The new dampers were adjusted to their middle setting: six clicks on the main adjustment knob, and maximum on the fine adjustment knob.

Due to sensor issues during June testing of the stock suspension, only one-half hour of data from that day is usable. The starboard suspension potentiometer slipped and became loose about 15 minutes into the test, and the port suspension potentiometer broke about 30 minutes into the test.

PDFs were generated for the pontoon bows and payload tray vertical accelerations seen throughout both testing days. Figures 5-8 and 5-9 compare the acceleration ranges seen during stock and new suspension testing in SS2, respectively. Approximately 15 minutes of data were used from the stock suspension testing, while 10 minutes of data were used from the new suspension testing. Even though both suspension tests were conducted in SS2, accelerations seen during new suspension testing were about two times greater than accelerations during stock suspension testing.

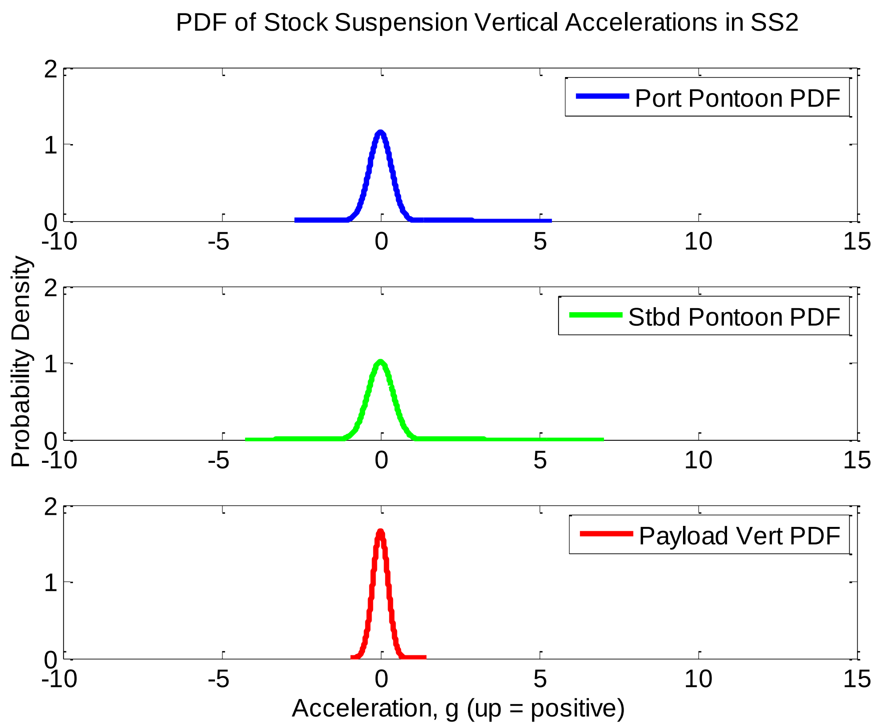

Figure 5-8: PDF of vertical accelerations during stock suspension testing

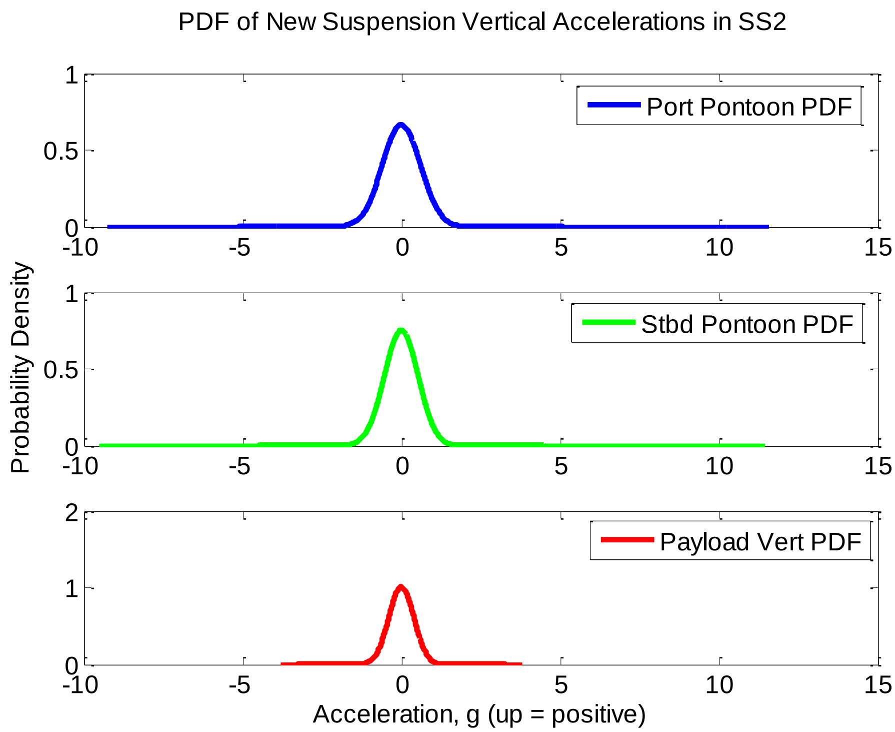

Figure 5-9: PDF of vertical accelerations during new suspension testing

PDFs were generated for the heights of the suspension to see where the suspension was typically operating in SS2 waters over a long period of time. The data chosen from the stock suspension testing was after the starboard suspension potentiometer was broken, so only the port suspension was plotted. Both suspensions were plotted for the new suspension data.

The port stock airspring height PDF is shown in Figure 5-10. The solid data line represents the PDF of the airspring height. The vertical dashed line represents when the airspring comes into contact with the compression bumper. The vertical dotted line indicates when the airspring has crossed the lower limit of the “do not operate” zone recommended by the manufacturer. The vertical solid line is the suggested maximum height of the airspring. The vertical dash-dotted line indicates when the airspring comes into contact with the extension limit straps. SS2 testing of the stock suspension shows that the airspring operated mostly in and over the “do not operate” zone suggested by the manufacturer. Figures 5-11 and 5-12 show the PDF for the percentage that the dampers are compressed during SS2 testing of the stock and new suspensions, respectively. The vertical dash-dotted line on the plots represents the height at which the dampers hit the extension limit straps, and the vertical dotted line indicates when the dampers hit the compression bumper.

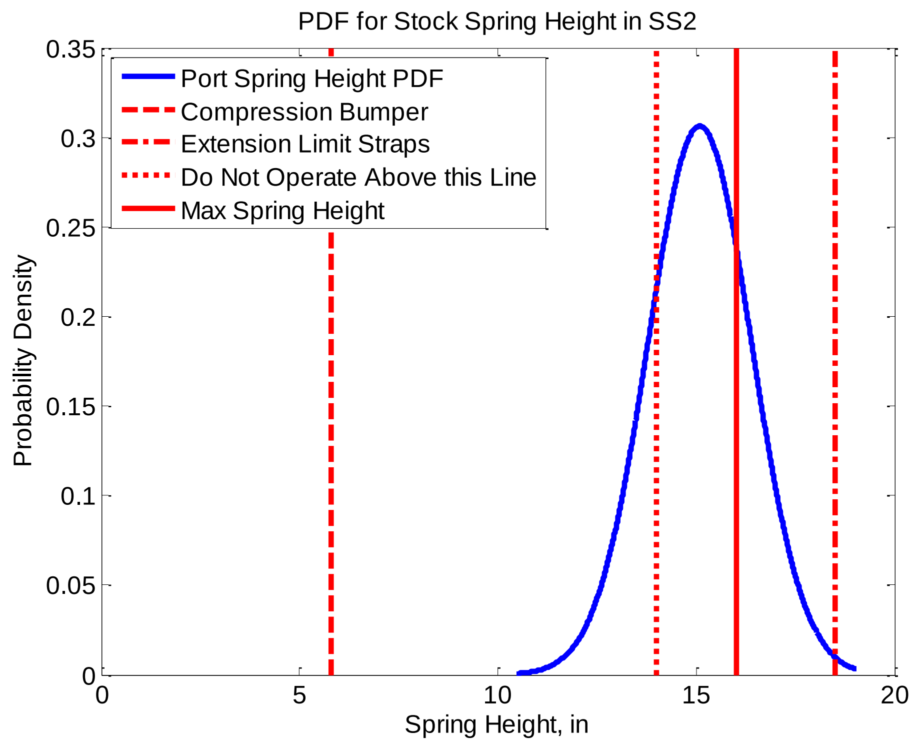

Figure 5-10: PDF of stock airspring height through SS2

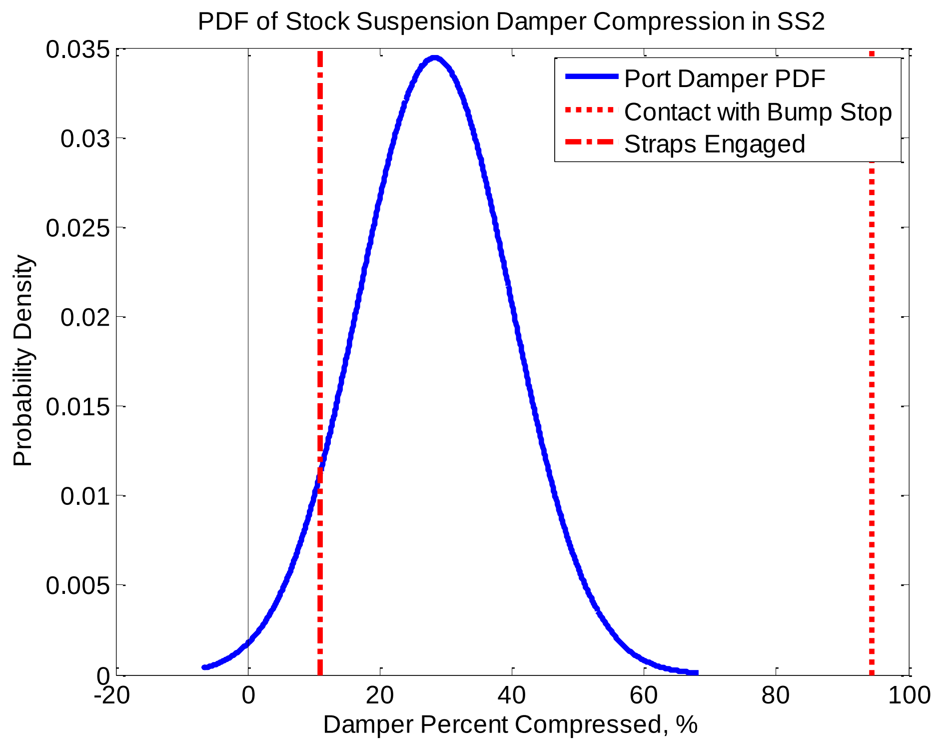

Figure 5-11: PDF of stock damper percent compression through SS2

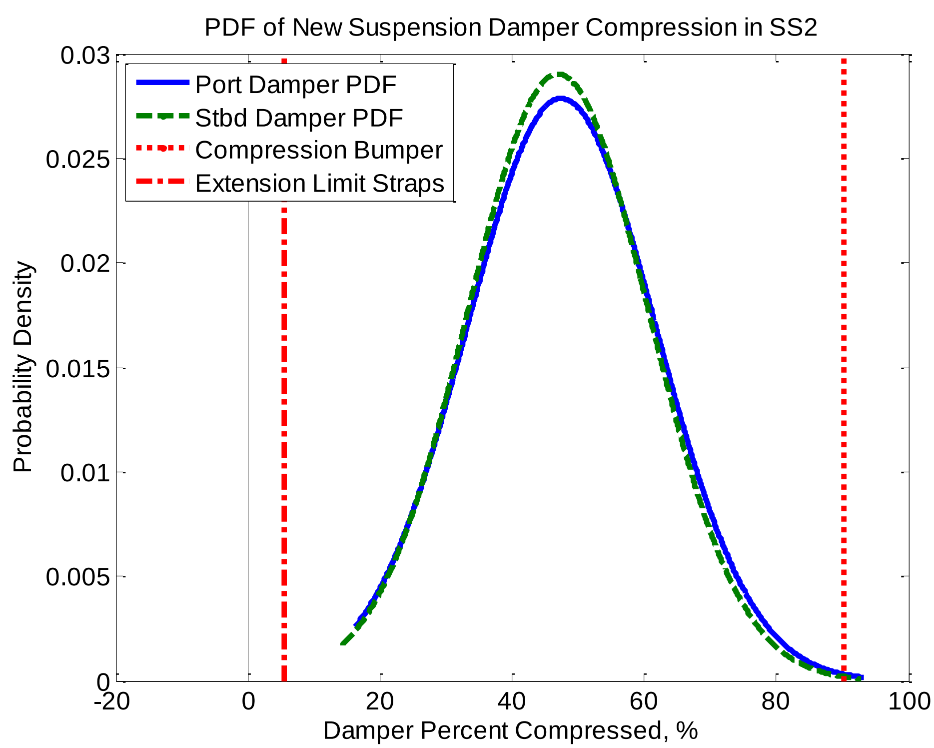

Figure 5-12: PDF of new damper percent compression through SS2

It is easy to see that the dampers chosen for the new suspension are better suited for the 33ft WAM-V. The majority of the test had the new damper at 50% compression whereas the stock dampers were at about 35% compression. The stock dampers engage the extension limit straps multiple times and even extend past its maximum height of 8 inches, which could have damaged the dampers. The new dampers are far from extending to their full stroke of 9 inches. The new dampers do compress to hit the compression bumper, but do not fully compress.

Figures 5-13 and 5-14 show the PDFs for the ball joint heights of the stock suspension and new suspension, respectively, through SS2 testing. The vertical dash-dotted line represents the height at which the ball joint heights contact the compression bumper, and the vertical dotted line indicates when the ball joint heights hit the extension limit straps. The solid and dashed data lines, if applicable, are the PDFs of the port and starboard ball joint heights, respectively.

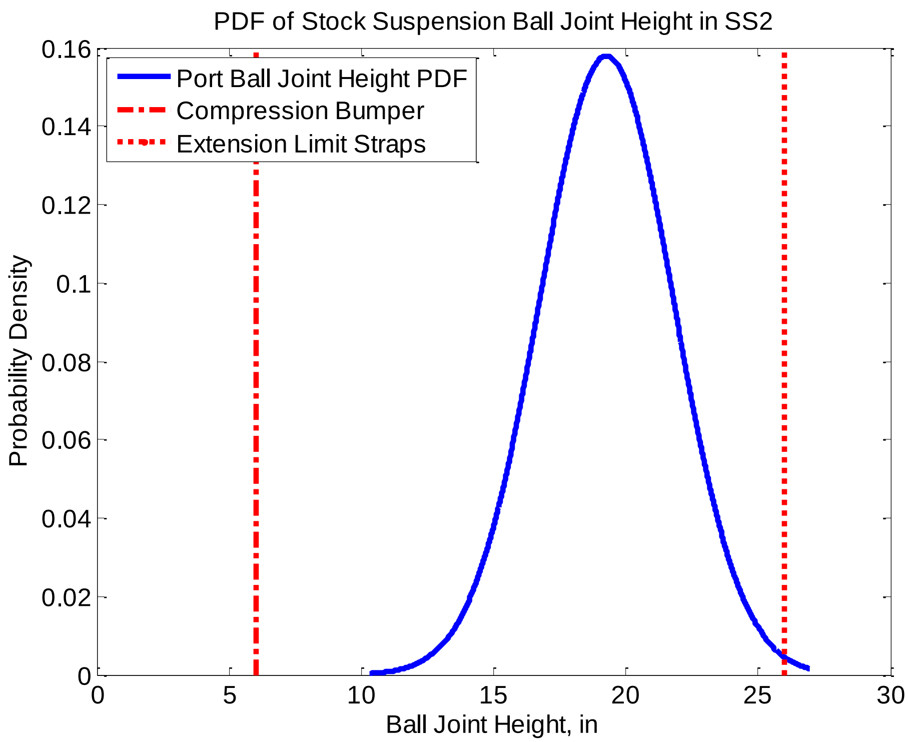

Figure 5-13: PDF of stock suspension ball joint height through SS2

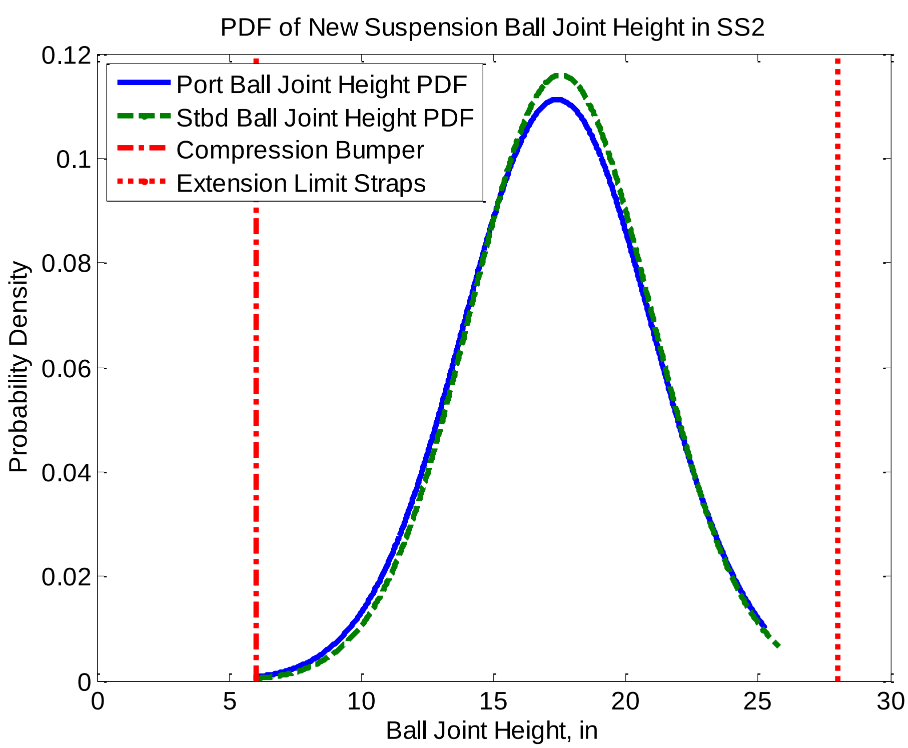

Figure 5-14: PDF of new suspension ball joint height through SS2

The PDFs of the ball joint heights also show that the new suspension is better suited for the WAM-V than the stock suspension, which makes sense because the relationship between ball joint and damper height is linear. The new suspension travels in the middle of the stroke of the ball joint, never engaging the extension limit strap, and only hitting the compression bumper occasionally while never fully bottoming out. The stock suspension does not bottom out either, but that is due to the fact that it rides so close to the fully extended height of the ball joint that it causes it to instead engage the extension limit straps over and over.

The broad overview of the two suspensions shows that the new suspension is better suited for the 33ft WAM-V. The following analysis is of a shorter time period, indicating the performance of the suspension over one wave event.

5.4 Individual Wave Event Analysis

For a more detailed analysis of the differences between each suspension, two wave events for each suspension were utilized for comparison purposes. The first wave event was a 2-foot wave extracted from SS2 testing of each suspension. The second wave event was a 4-foot wave extracted from calm water testing for the stock suspension, and SS2 testing for the new suspension. Detailed descriptions of each wave event are provided in the following sections to explain why these waves are comparable to a certain degree. The 500lb/in spring was installed without preload for the new suspension for both waves.

Each wave event has been broken down into seven phases to analyze the suspension. The seven phases help analyze the dynamics of each suspension as the WAM-V makes its way over the wave. The phases are as follows:

Phase 1: Initial Encounter
Phase 2: Loading
Phase 3: Unloading
Phase 4: Freefall
Phase 5: Initial Impact
Phase 6: Maximum Compression
Phase 7: End

At each phase, both suspensions are discussed to show the differences. Screenshots at each phase show the WAM-V from the chase boat. Zoomed-in pictures of the operator and suspension are overlaid on the WAM-V picture to better identify those components.

Throughout the seven phases of analysis on each wave, certain plots are shown repeatedly. This is done to specifically look at the dynamics during each phase of the wave event. The figures are annotated for the specific phase to point out the key differences between the two suspensions.

5.4.1 Two-Foot Wave Event Analysis

Since the majority of the rougher waves in the June testing of the stock suspension were seen after the two suspension potentiometers malfunctioned, the highest wave encountered in the remaining usable data was about 2 feet. Fortunately, the test in December of the new suspension, though rougher at times, also contained 2-foot waves. Looking through the video footage, a 2-foot wave was found with each suspension that was comparable to each other.

During testing of the stock suspension, the 33ft WAM-V encountered a wave about 2 feet in height while traveling at approximately 12 knots. This wave event caused the port pontoon to be launched into the air while the starboard pontoon maintained contact with the water. In testing of the new suspension, the WAM-V encountered a wave of about the same height while traveling at 10 knots. This time the starboard pontoon was launched into the air as the port pontoon stayed on the water.

For the stock suspension testing, the zoomed-in picture of the operator comes from the CCD camera mounted at the back of the payload tray because the angle of the video from the chase boat does not fully capture the response of the operator.

Phase 1: Initial Encounter occurs before the WAM-V has encountered the wave. Figures 5-15 and 5-16 are screenshots of the stock and new suspension wave event at Phase 1, respectively. Without any waves, the operator is in a normal sitting position with his hands in the controller pouch for both tests.

Figure 5-15: Phase 1 screenshot of stock suspension testing

Figure 5-16: Phase 1 screenshot of new suspension testing

The suspension ball joint heights for both tests are shown in Figure 5-17 to highlight Phase 1. The stock and new suspensions are plotted on the same graph: the port ball joint height for the stock suspension, and the starboard ball joint height for the new suspension. Those specific suspension sides were chosen based on which pontoon was lifted out of the water. Both suspensions are at about their respective ride height before the wave is encountered, with the stock suspension riding higher than the new suspension. The stock suspension height is shown by the solid data line, and the new suspension by the dashed data line. The horizontal dash-dotted line represents the extension limit strap height of the stock suspension, while the horizontal dashed line shows the new suspension extension limit strap height. Differences between the extension limit strap heights are present because the straps themselves are different for each suspension. Also, the new suspension uses one strap while the stock suspension uses two. Both suspensions have the same height when the compression bumper is engaged, indicated by the horizontal dotted line. Vertical dashed lines are overlaid on each graph and marked as the seven phases of each event.

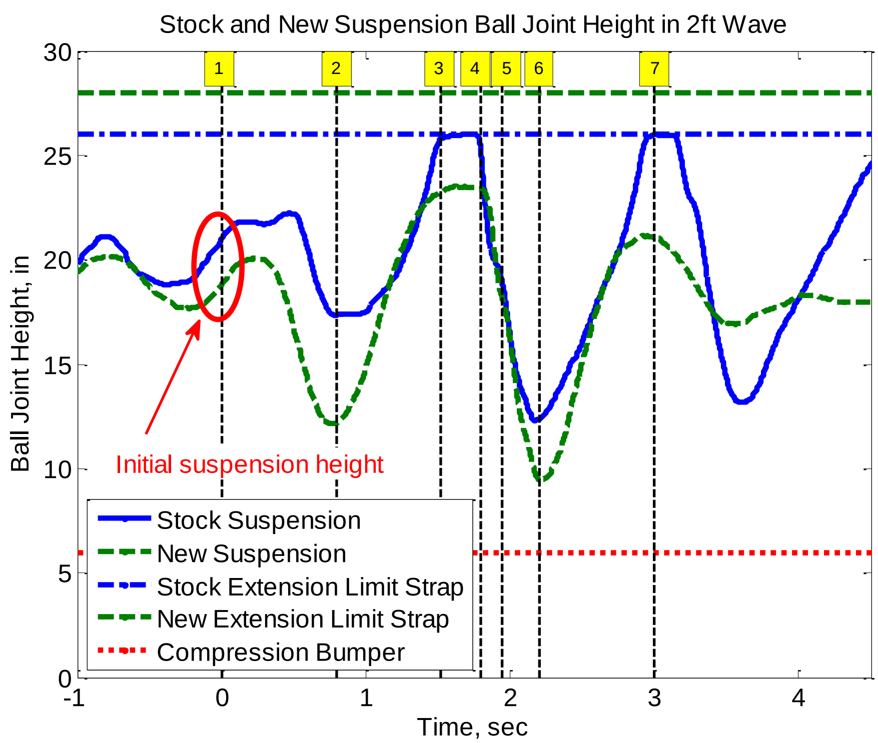

Figure 5-17: Phase 1 ball joint height of stock and new suspensions

Phase 2: Loading occurs when the WAM-V first encounters the wave, causing the pontoons to fold back slightly. Figures 5-18 and 5-19 are screenshots of each suspension at Phase 2. The operator is still seated in a normal position for both tests.

Figure 5-18: Phase 2 screenshot of stock suspension testing

Figure 5-19: Phase 2 screenshot of new suspension testing

Figure 5-20 highlights the suspension ball joint heights of the stock and new suspensions. Both suspensions compress by about 35% of their total stroke. The new suspension has a greater change in height than the stock suspension but, due to its increased amount of total stroke, it compresses about the same percentage of the total stroke as the stock suspension.

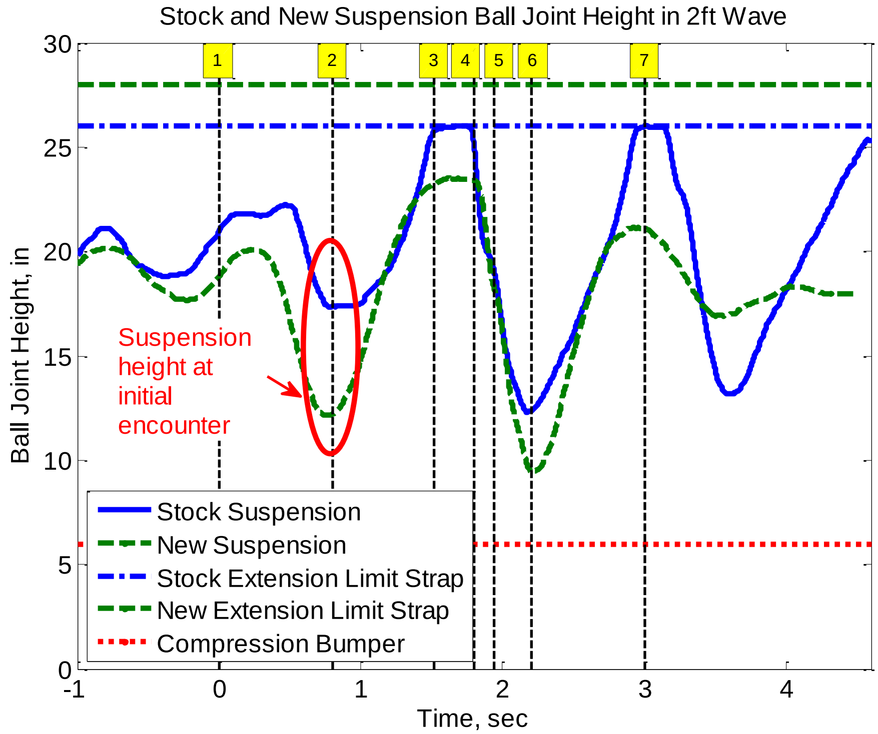

Figure 5-20: Phase 2 ball joint height of stock and new suspensions

Figures 5-21 and 5-22 are pontoon bow and payload tray vertical acceleration plots that highlight Phase 2 with the stock and new suspensions, respectively. With the stock suspension installed, the peak acceleration of the pontoon bow (solid data line) is 0.7g, while the peak acceleration of the payload tray vertical acceleration (dashed data line) is 0.4g, showing 42% attenuation between the pontoon and payload tray. With the new suspension installed, the peak vertical acceleration of both the pontoon bow and payload tray is 0.7g, showing no attenuation between the two.

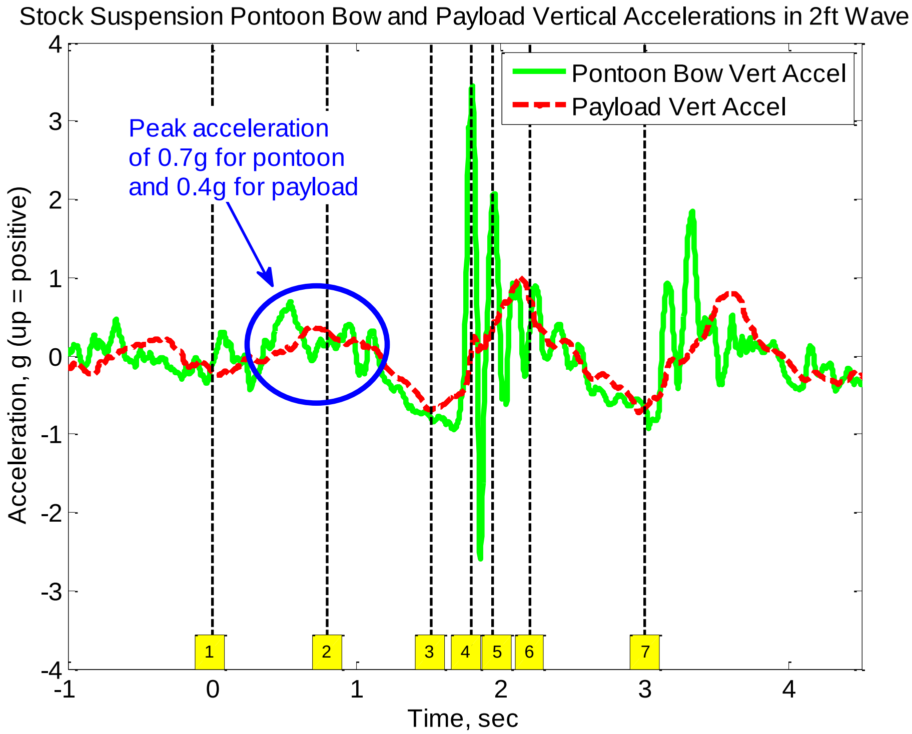

Figure 5-21: Phase 2 pontoon and payload vertical accelerations with stock suspension

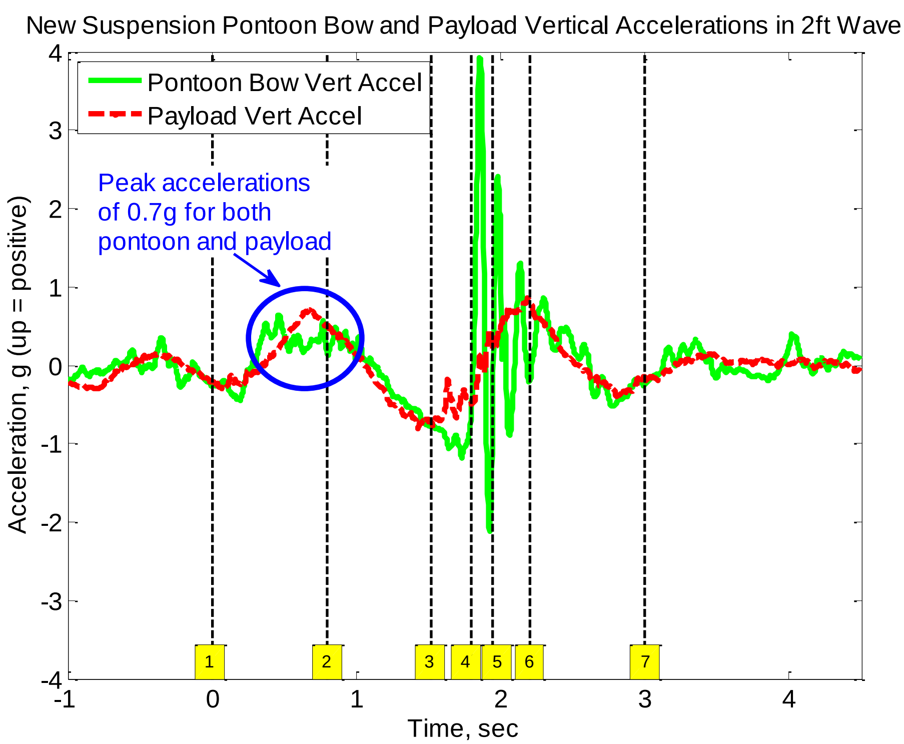

Figure 5-22: Phase 2 pontoon and payload vertical accelerations with new suspension

Phase 3: Unloading of the wave events has one of the pontoons launched into the air while the other maintains contact with the water. Figure 5-23 shows the port pontoon being launched into the air to reach its maximum height off the water during the stock suspension test. Figure 5-24 shows the starboard pontoon being launched into the air to reach its maximum height off the water during the new suspension test. In both instances, the operator is still seated.

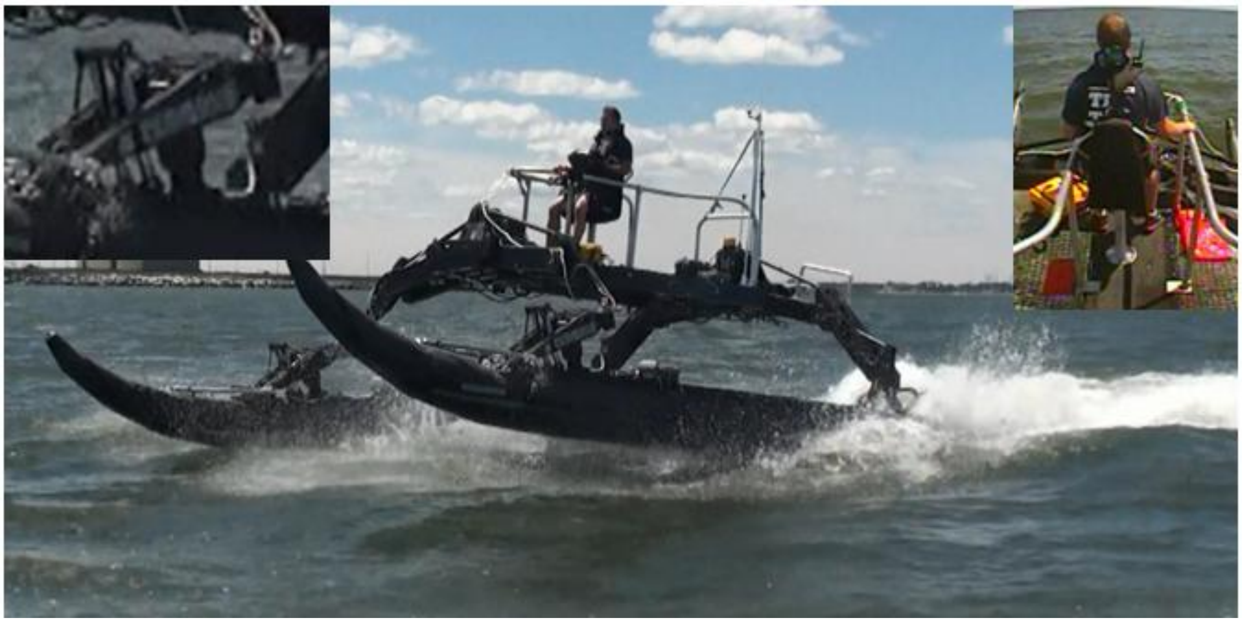

Figure 5-23: Phase 3 screenshot of stock suspension testing

Figure 5-24: Phase 3 screenshot of new suspension testing

Figure 5-25 shows the suspension ball joint height of the stock and new suspensions. With the stock suspension setup, the suspension hits its maximum height and pulls on the extension limit straps. The height of the stock suspension extension limit strap is indicated by the horizontal dash-dotted line. The new suspension also reaches its maximum height but does not engage the extension limit straps. The height of the new suspension extension limit strap is indicated by the horizontal dashed line.

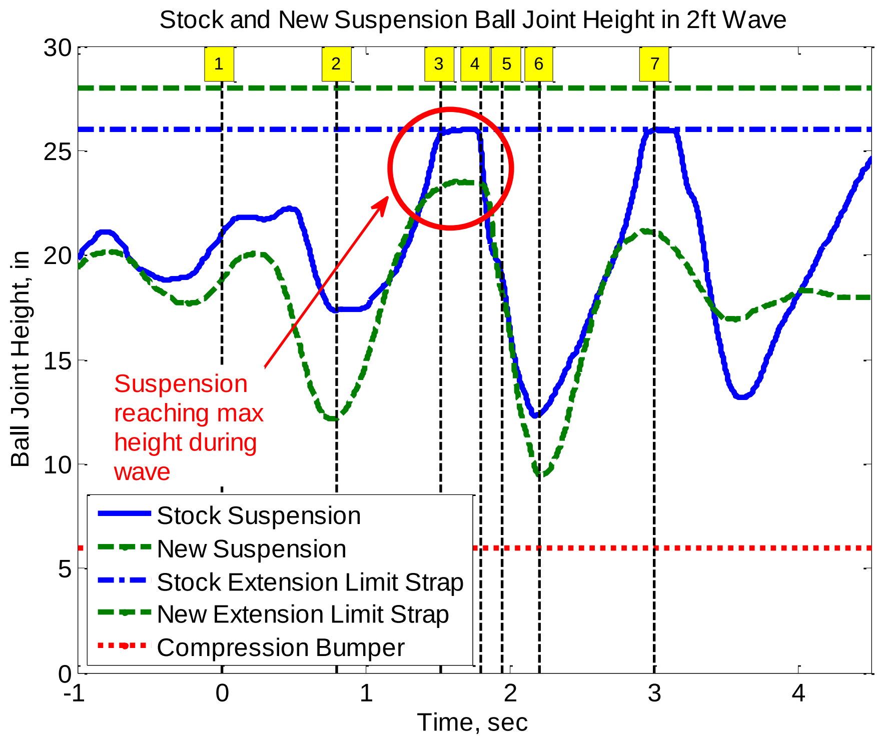

Figure 5-25: Phase 3 ball joint height of stock and new suspensions

Figure 5-26 shows the vertical accelerations of the pontoon bow and payload tray during Phase 3 of the stock suspension test, while Figure 5-27 shows the same plot for the new suspension test. During the stock suspension test, the suspension pulls on the limit straps due to the motion of the WAM-V being launched and from the force generated by the airspring from Phase 2, causing both the pontoon and payload tray to see a vertical acceleration of -0.7g. The new suspension, without pulling on the limit straps, also sees a vertical acceleration of -0.7g at the pontoon and payload tray.

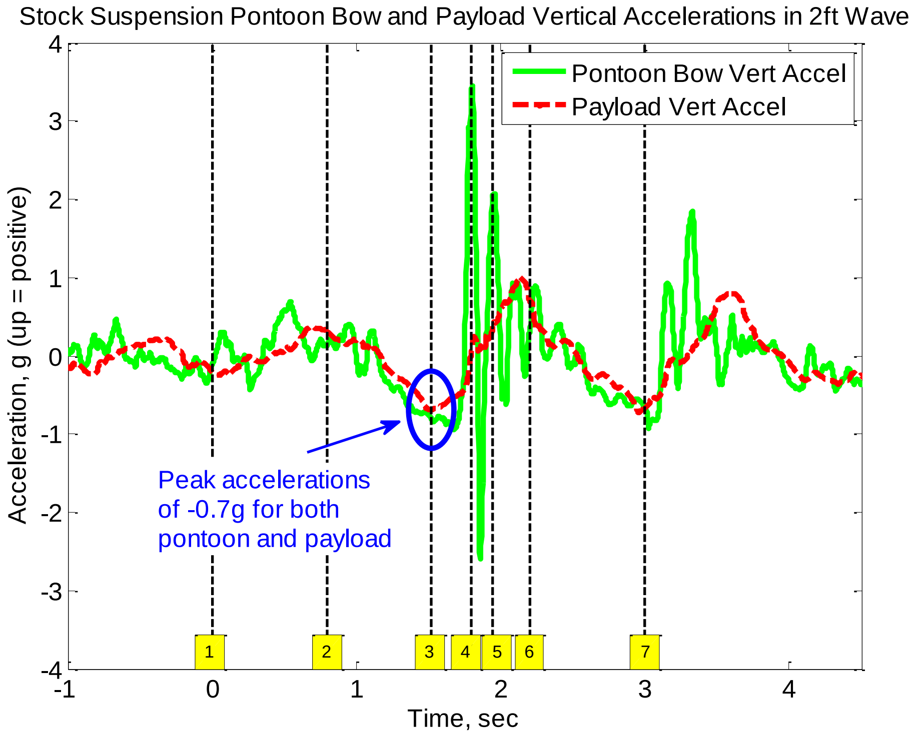

Figure 5-26: Phase 3 pontoon and payload vertical accelerations with stock suspension

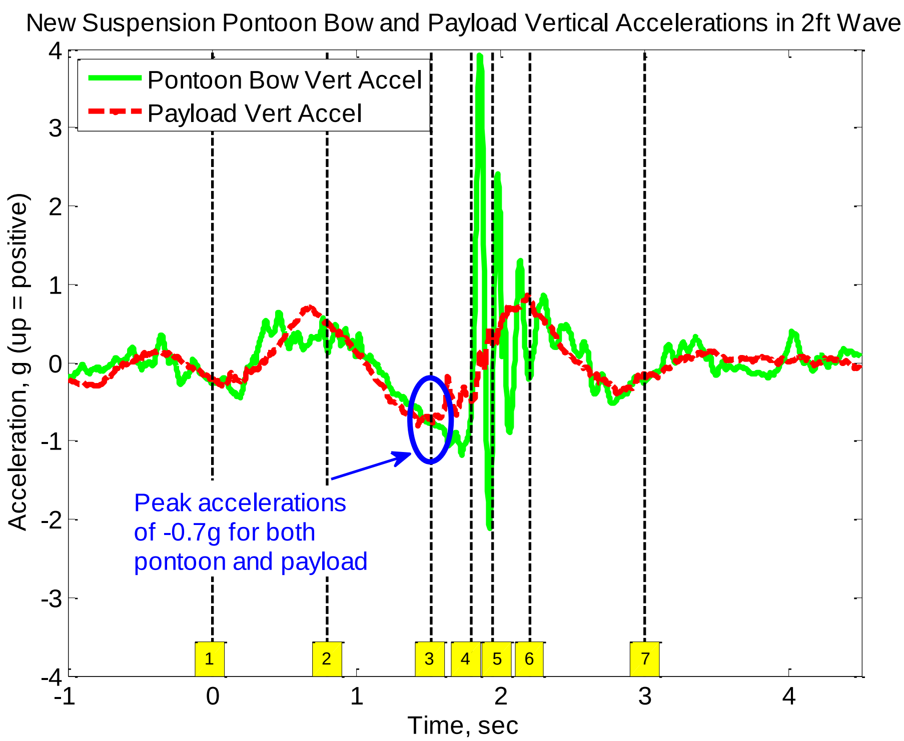

Figure 5-27: Phase 3 pontoon and payload vertical accelerations with new suspension

Phase 4: Freefall is when the pontoon is in freefall after traveling over the wave. In Figures 5-28 and 5-29, the motion of the operator is captured for the stock and new suspension tests, respectively. During stock suspension testing, the operator is lifted slightly out of the seat, causing the operator to straighten his arm to keep hold of the railing. During the new suspension testing, however, the operator is still seated normally as in previous phases.

Figures 5-30 and 5-31 show the vertical accelerations seen by the pontoon and the payload tray during stock and new suspension testing, respectively. In stock suspension testing, as the WAM-V goes from rising to falling, the suspension hits the extension limit straps and pulls the payload tray down with it, causing spikes in the payload vertical acceleration. The operator is lifted into the air due to the payload tray being pulled away from the operator. In the new suspension testing, as the suspension reaches its maximum height, the payload tray starts to fall without the suspension pulling it down via limit straps. The plot shows a smooth transition of the payload tray from rising to falling. The operator is able to remain seated because the suspension does not reach the extension limit straps.

Figure 5-28: Phase 4 screenshot of stock suspension testing

Figure 5-29: Phase 4 screenshot of new suspension testing

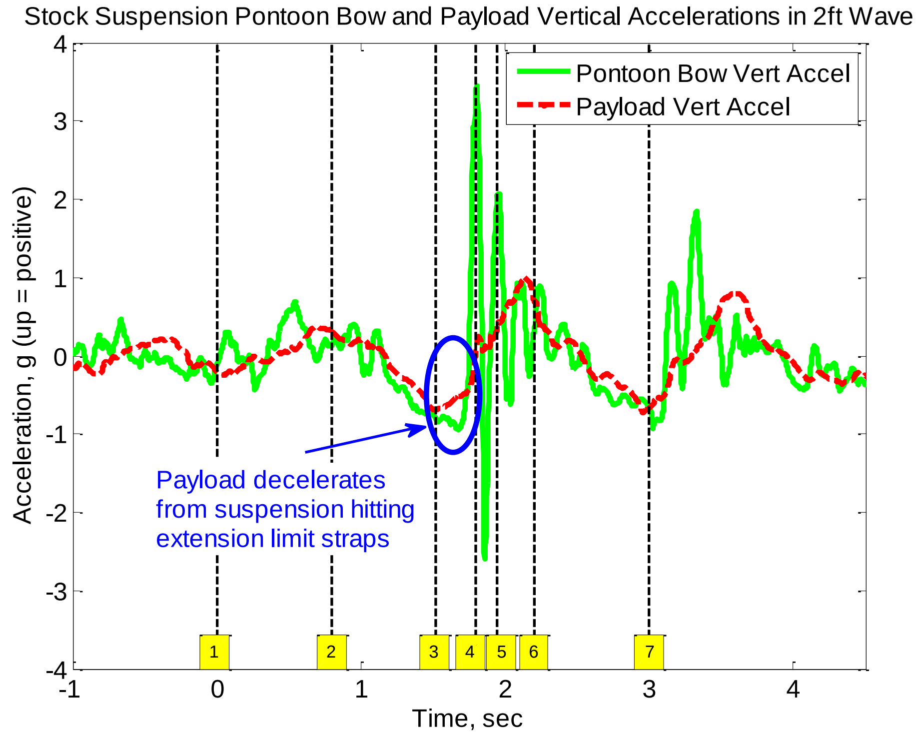

Figure 5-30: Phase 4 pontoon and payload vertical accelerations with stock suspension

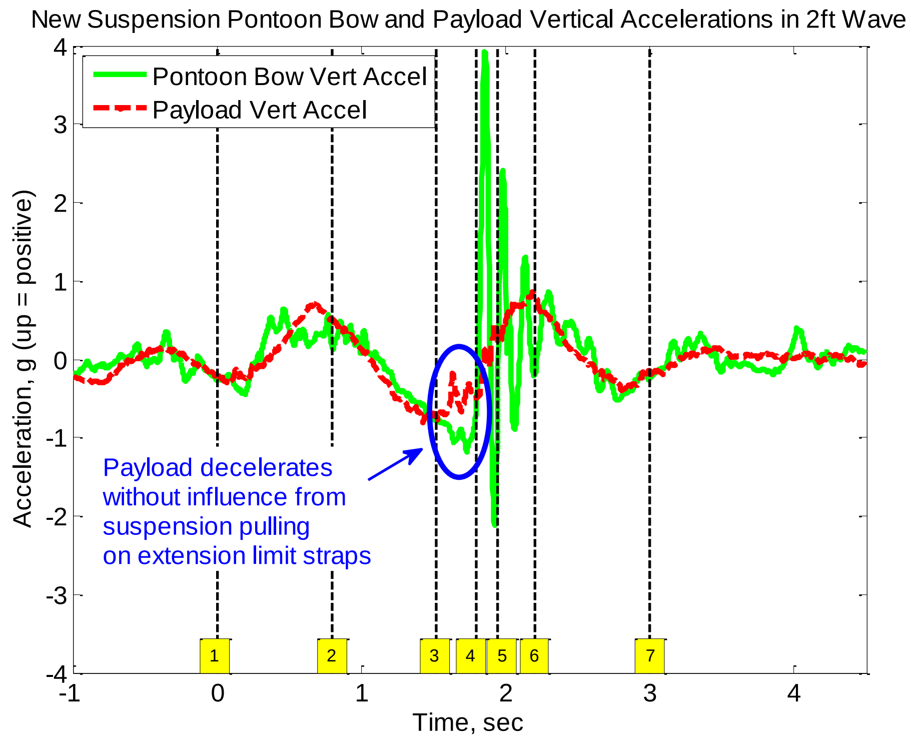

Figure 5-31: Phase 4 pontoon and payload vertical accelerations with new suspension

Phase 5: Initial Impact is when the pontoon comes back into contact with the water, but has not yet fully compressed the suspension. Figures 5-32 and 5-33 show the relevant pontoon coming into contact with the water once again in the stock and new suspension tests, respectively. In stock suspension testing, the operator is coming back into contact with the seat, while in new suspension testing, the operator is still in the same seated position as seen in previous phases.

Figure 5-32: Phase 5 screenshot of stock suspension testing

Figure 5-33: Phase 5 screenshot of new suspension testing

Figures 5-34 and 5-35 show the vertical accelerations seen by the pontoon bow and pontoon stern for the stock and new suspension tests, respectively. The pontoon bow acceleration is represented by the solid data line, and the stern acceleration by the dash-dotted data line. The minimum and maximum accelerations seen at both ends of the pontoon are listed in Table 5-4.

Table 5-4: Pontoon Maximum and Minimum Accelerations

	Pontoon Bow Acceleration, g		**Pontoon Stern Acceleration, g**	
	Maximum	Minimum	Maximum	Minimum
Stock Suspension	3.5	-2.6	0.7	-0.7
New Suspension	3.9	-2.1	0.6	-0.9

The impact of the pontoon stern occurs after the bow hits the water. The accelerations the stern of the pontoon experiences are not as high as the bow because the pontoon stern does not come out of the water as far.

Figures 5-36 and 5-37 show the degree to which the suspension attenuates the motion from pontoon bow to payload tray during the stock and new suspension tests, respectively. The pontoon bow and payload tray peak accelerations are shown in Table 5-5, along with the amount of attenuation that is seen between the two. The new suspension is able to attenuate slightly more than the stock suspension.

Table 5-5: Attenuation between Pontoon and Payload Tray

	Pontoon Bow Acceleration, g	**Payload Tray Acceleration, g**	**Attenuation, %**
Stock Suspension	3.5	1	71
New Suspension	3.9	0.9	76

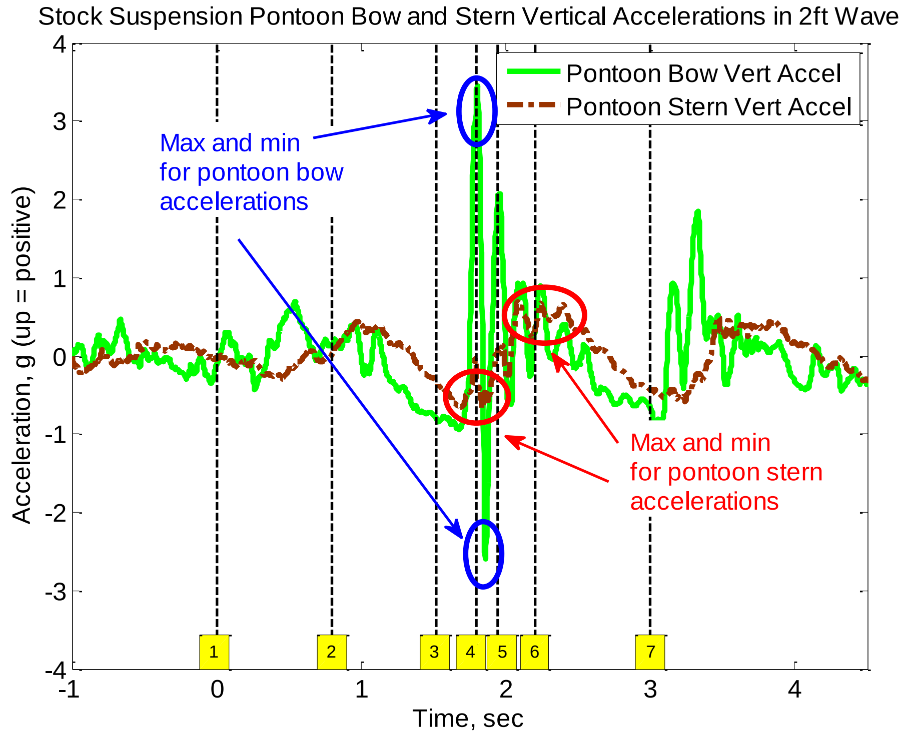

Figure 5-34: Phase 5 pontoon bow and stern vertical accelerations with stock suspension

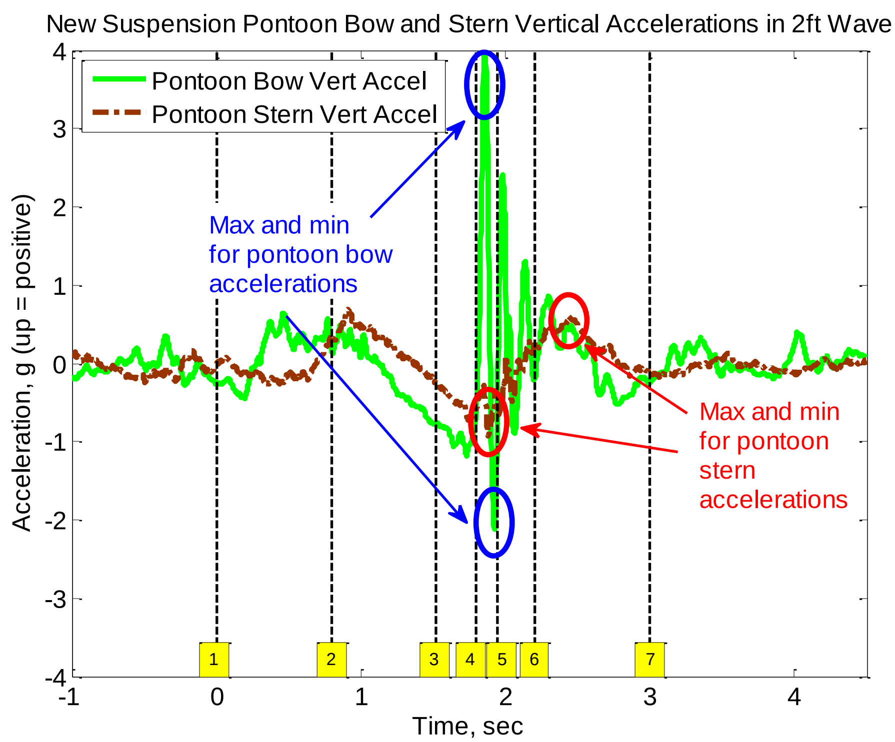

Figure 5-35: Phase 5 pontoon bow and stern vertical accelerations with new suspension

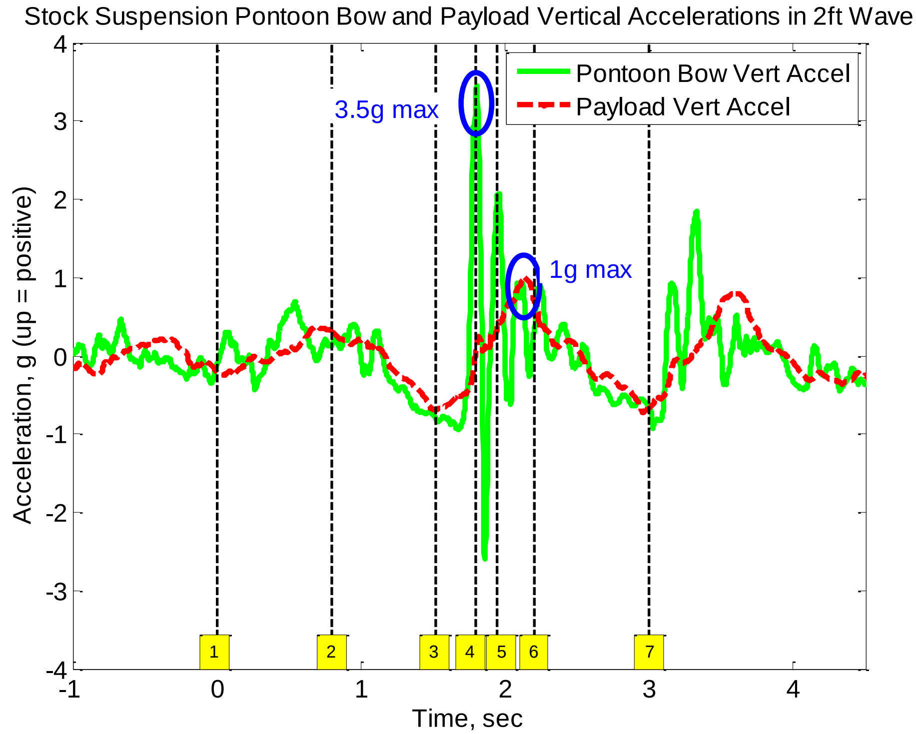

Figure 5-36: Phase 5 pontoon and payload vertical accelerations with stock suspension

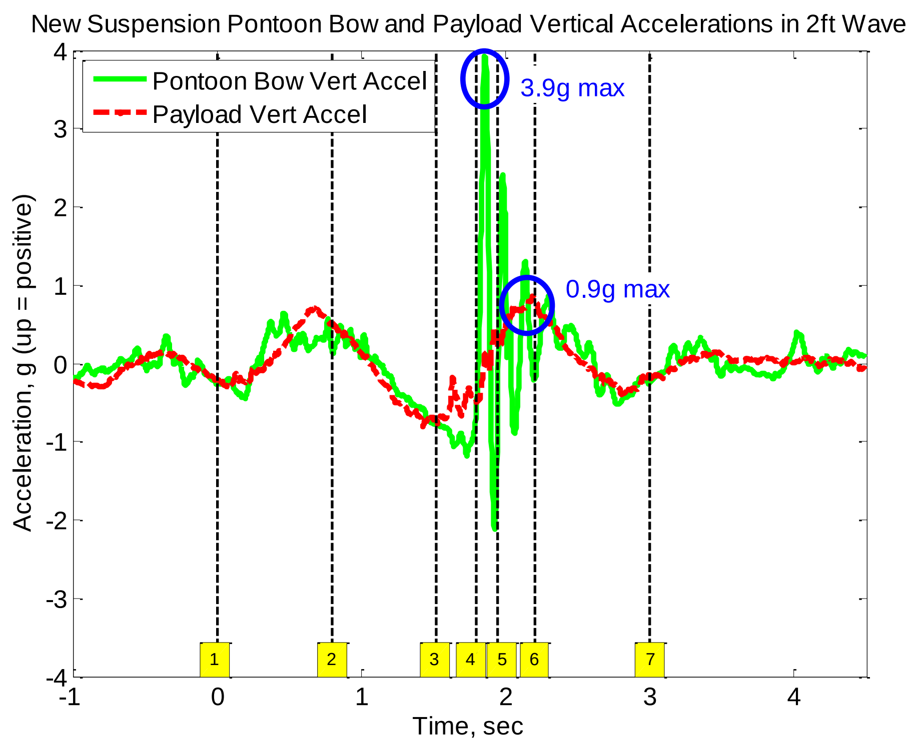

Figure 5-37: Phase 5 pontoon and payload vertical accelerations with new suspension

Phase 6: Maximum Compression is when the suspension compresses to its minimum height. Figures 5-38 and 5-39 show the motion of the operator as the suspension is compressed during the stock and new suspension tests, respectively. The operator is out of the seat and leaning forward as the stock suspension is subjected to the maximum compression of the wave event. With the new suspension setup, however, the operator remains seated and is slightly leaning forward.

Figure 5-38: Phase 6 screenshot of stock suspension testing

Figure 5-39: Phase 6 screenshot of new suspension testing

Figure 5-40 shows that both suspensions reach their minimum height during Phase 6 without reaching the minimum height of the suspension. Both suspensions, however, travel about the same distance. As the new suspension travels within the middle of the suspension stroke, the stock suspension starts its compression at the extension limit straps.

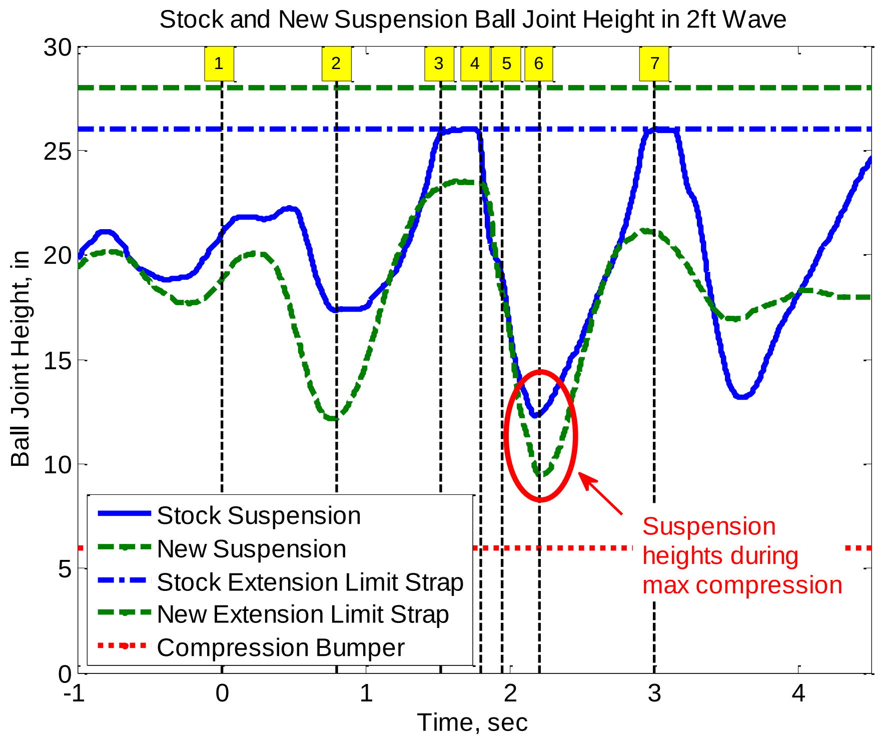

Figure 5-40: Phase 6 ball joint height of stock and new suspensions

Figures 5-41 and 5-42 show the vertical accelerations of the pontoon bow and payload tray of the stock and new suspensions, respectively. With the stock suspension, the operator bounces in his seat and is launched forward and up when the payload tray is subjected to a deceleration of 0.4g in the longitudinal direction, represented by the dotted data line. With the new suspension installed, even though the operator is subjected to the same deceleration value of 0.4g in the longitudinal direction, he only leans forward slightly in the seat. Without the suspension pulling on the limit straps, the operator has not been lifted into the air and is not launched from the seat.

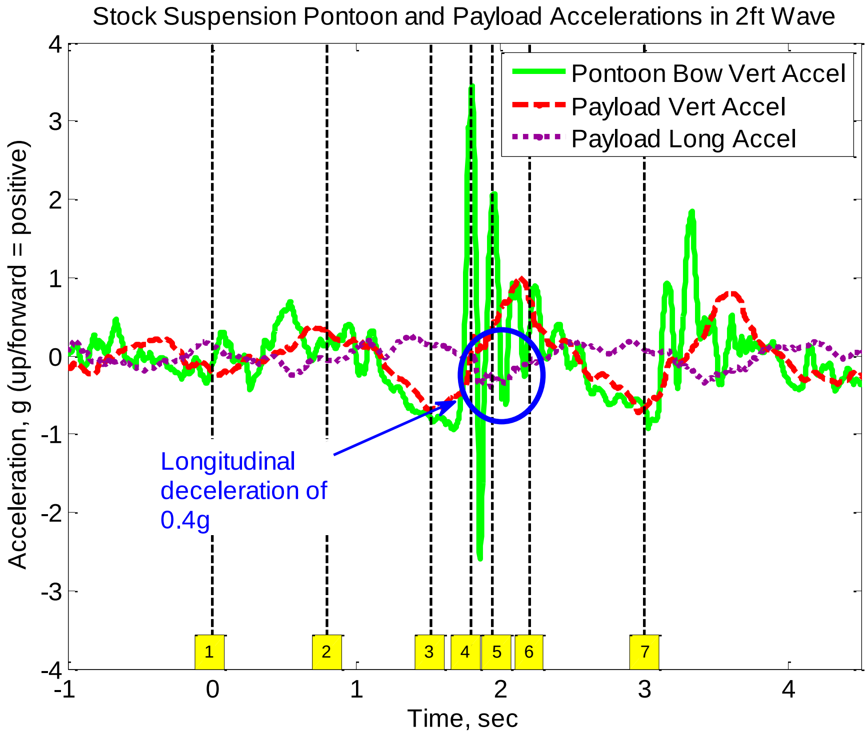

Figure 5-41: Phase 6 pontoon and payload accelerations with stock suspension

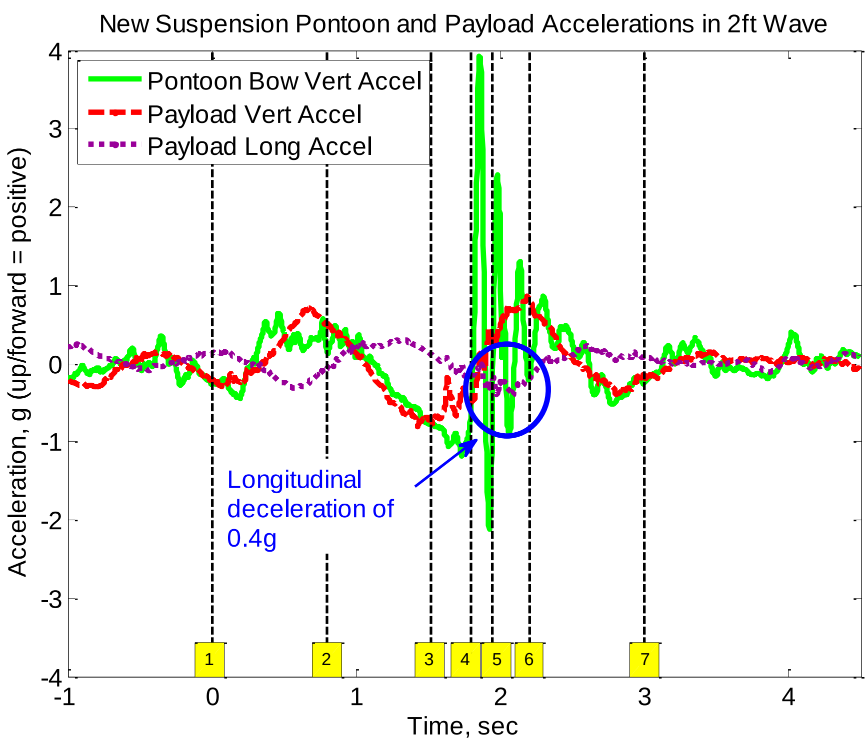

Figure 5-42: Phase 6 pontoon and payload accelerations with new suspension

Phase 7: End is the end of the event. In both cases, the operator is back in the seat and continues SS2 testing, as depicted in Figures 5-43 and 5-44, for the stock and new suspensions, respectively.

Figure 5-43: Phase 7 screenshot of stock suspension testing

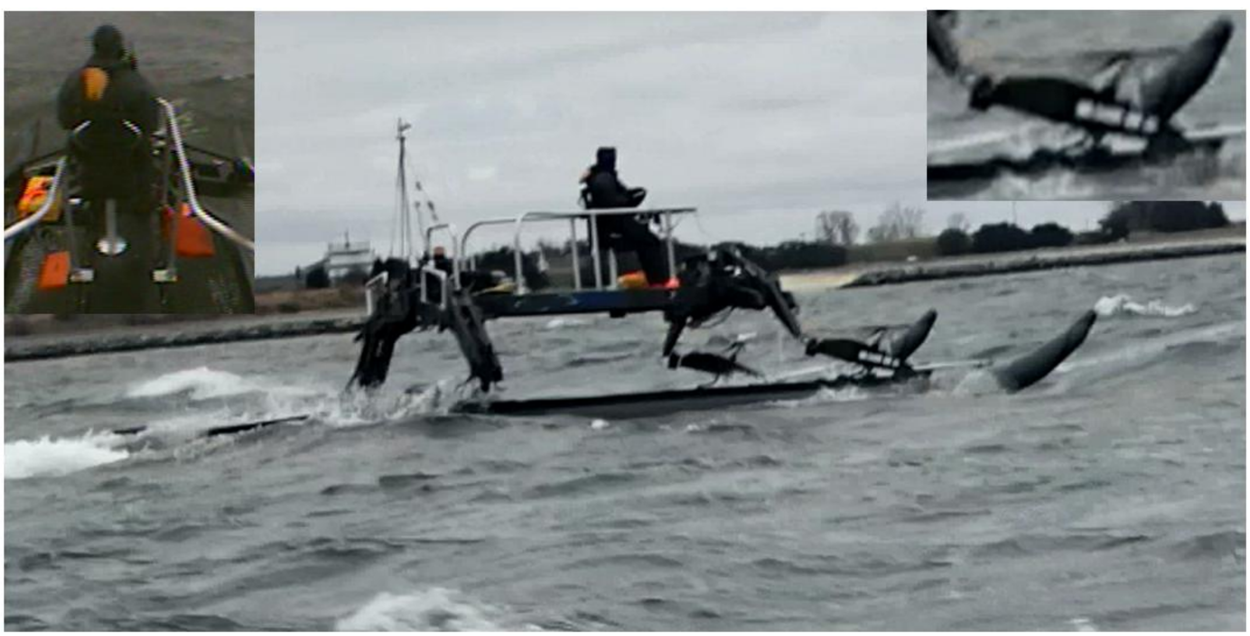

Figure 5-44: Phase 7 screenshot of new suspension testing

Performance improved from switching the stock suspension to the new suspension. The stock suspension sat too closely to the fully extended side, leaving a lot of room for compression but not enough for extension. This caused the suspension to constantly hit the limit straps on the extension side. The new suspension had a more equal amount of compression and extension stroke, leading to the suspension never hitting the extension limit straps. The new suspension did contact the compression bumper several times during SS2 testing due to the ride height being lower than desired, which allowed for slightly more extension stroke than compression. The following statement is the WAM-V operator's observations on the new suspension:

> "Suspension operation was improved over the original setup. The linear spring and damper performed well. It did not feel as though the suspension topped out at all. This was the dominant perception of the original suspension.
>
> Suspension did bottom out once or twice in compression; the bottoming out was not severe and was due to not setting the ride height at the optimal point.
>
> Slight bottoming out was not as detrimental as I thought it would be.
>
> There was no hard crashing sensation at any time on the WAM-V."

If possible, the new suspension would have been adjusted on the water to change the amount of preload on the spring and damping values of the damper. However, due to the water being too rough, it was not possible to make these changes on the water. More preload and a different damping value for the new suspension could have improved WAM-V dynamic performance even more.

5.4.2 Four-Foot Wave Event Analysis

Where the SS2 suspension comparison analyzed the differences between the stock and new suspension systems over a 2-foot wave, the following analysis will look at the performance of each suspension over a wave with a height of 4 feet. Analyzing this more extreme case can help further compare the differences in the suspension systems.

During the first day of testing, on June 21, 2012 in Norfolk, VA, the WAM-V encountered a stern wake of a freighter ship with the stock suspension installed. The ship produced a single wave with a height of approximately 4 feet. The WAM-V was piloted over this wave at a speed of 10 knots. Traveling at 10 knots over a wave of 4 feet was enough to launch the WAM-V into the air. Before the wake, the sea conditions were very calm and smooth, so the single wave was isolated since no other waves were present. This event was later named the Single Wave Input.

Since the Single Wave Input was generated in a very special manner, it was very difficult to find an instance like it in order to test the new suspension for comparison purposes. However, a wave similar to the Single Wave Input in height was found during December 11, 2012 testing. The sea conditions prior to and after the wave were relatively calm for an SS2 day, but nowhere near as calm as during the Single Wave Input. The wave height was also approximately 4 feet, with the WAM-V traveling at about 10 knots.

Similar to the SS2 wave breakdown, the Single Wave Input and its counterpart have been broken down into seven phases for suspension analysis.

Phase 1: Initial Encounter is shown in Figures 5-45 and 5-46, capturing the screenshots of each encounter before the WAM-V hits the wave. The test with the stock suspension, Figure 5-45, shows the WAM-V traveling across very calm and flat waters. The test with the new suspension, Figure 5-46, is relatively calm but rougher than the stock suspension test. In both tests the operator is in a normal seated position.

Figure 5-45: Phase 1 screenshot of stock suspension testing

Figure 5-46: Phase 1 screenshot of new suspension testing

Figure 5-47 shows the suspension height of each wave. The solid data line is the stock suspension height, and the dashed data line is the new suspension height. The horizontal lines represent the height of the extension limit strap with the stock suspension (dash-dotted) and new suspension (dashed). The compression bumper contact height for both suspensions is the same, indicated by the horizontal dotted line. With the stock suspension installed, the suspension starts off at a height very close to full extension. The new suspension test shows that the suspension starts off closer to the mid-stroke of the suspension.

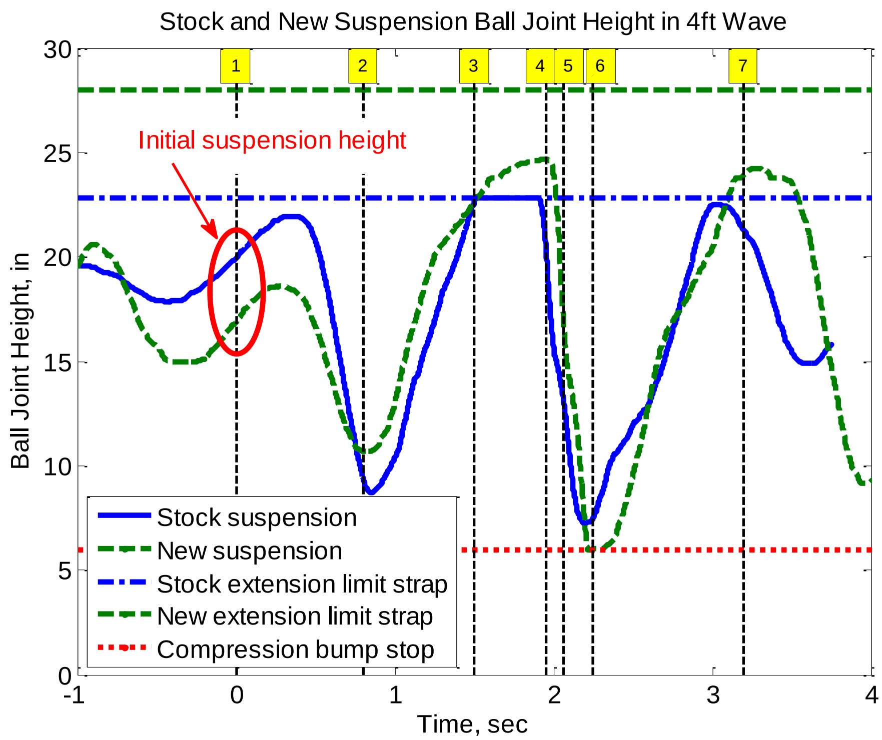

Figure 5-47: Phase 1 ball joint height of stock and new suspensions

Phase 2: Loading occurs as the WAM-V encounters the wave, which is shown in the screenshots in Figures 5-48 and 5-49. Figure 5-48, with the stock suspension installed, shows that the bows of the pontoons are bent backwards as the WAM-V encounters the wave. In Figure 5-49, with the new suspension installed, the pontoons do not bend backwards. This can be explained by the fact that the pontoons were set at different pressures between the two tests. During the stock suspension test, the pontoons were filled to 4psi. Due to malfunction of the air pumps, the pontoons were filled to a pressure closer to 5psi during the new suspension test. However, in both cases, the operator is in a seated position.

Figure 5-48: Phase 2 screenshot of stock suspension testing

Figure 5-49: Phase 2 screenshot of new suspension testing

Figure 5-50 shows the suspension movement while highlighting Phase One. With the stock suspension installed, the suspension travels through 85% of its entire stroke, while the new suspension only travels through about 40% of its entire stroke. This occurs because the way in which the WAM-V hits each wave is different. During the stock suspension test, the WAM-V is traveling in flat waters when it suddenly hits the wave. In the new suspension test, the WAM-V has some momentum from previous waves, and so it does not hit the wave as suddenly as it did with the stock suspension.

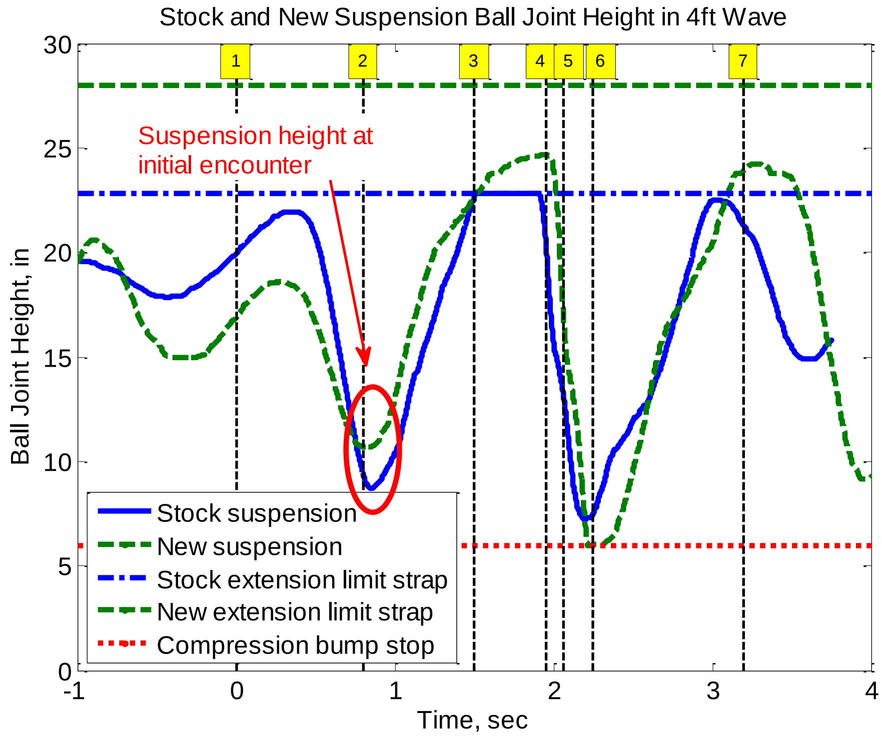

Figure 5-50: Phase 2 ball joint height of stock and new suspensions

Figures 5-51 and 5-52 plot the vertical accelerations of the pontoon bow and payload during stock and new suspension testing, respectively. During the test with the stock suspension, the pontoon experiences a peak acceleration of 0.5g, while the payload experiences 1.5g of vertical acceleration. Not only does the suspension not attenuate the acceleration, but the payload actually experiences a higher acceleration than the pontoon. The new suspension test shows that the peak vertical acceleration of both the pontoon and the payload is 0.7g and again, no attenuation occurs.

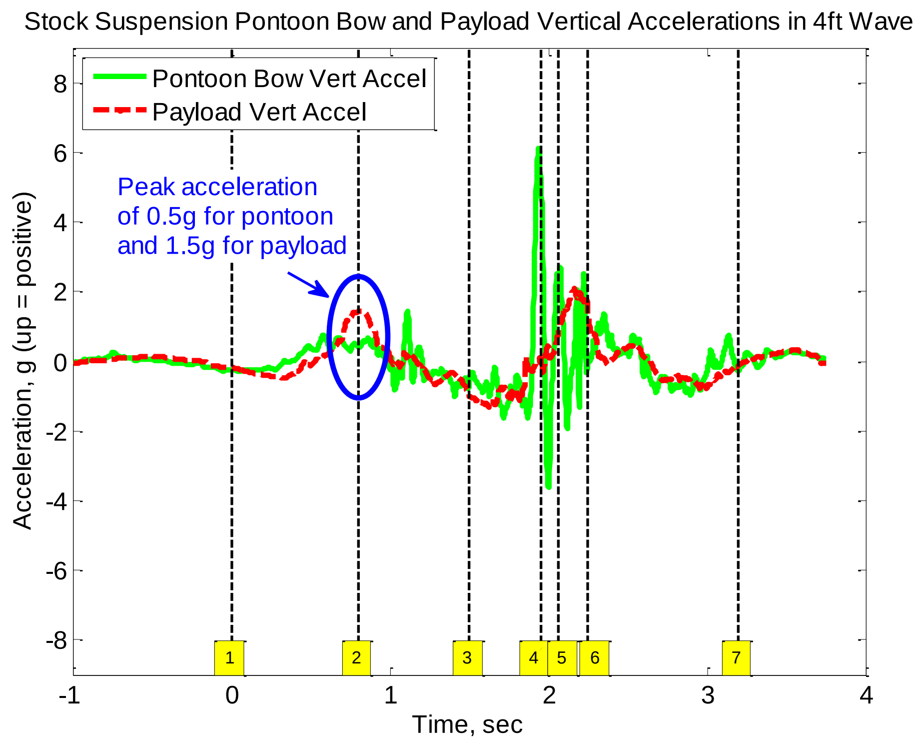

Figure 5-51: Phase 2 pontoon and payload vertical accelerations with stock suspension

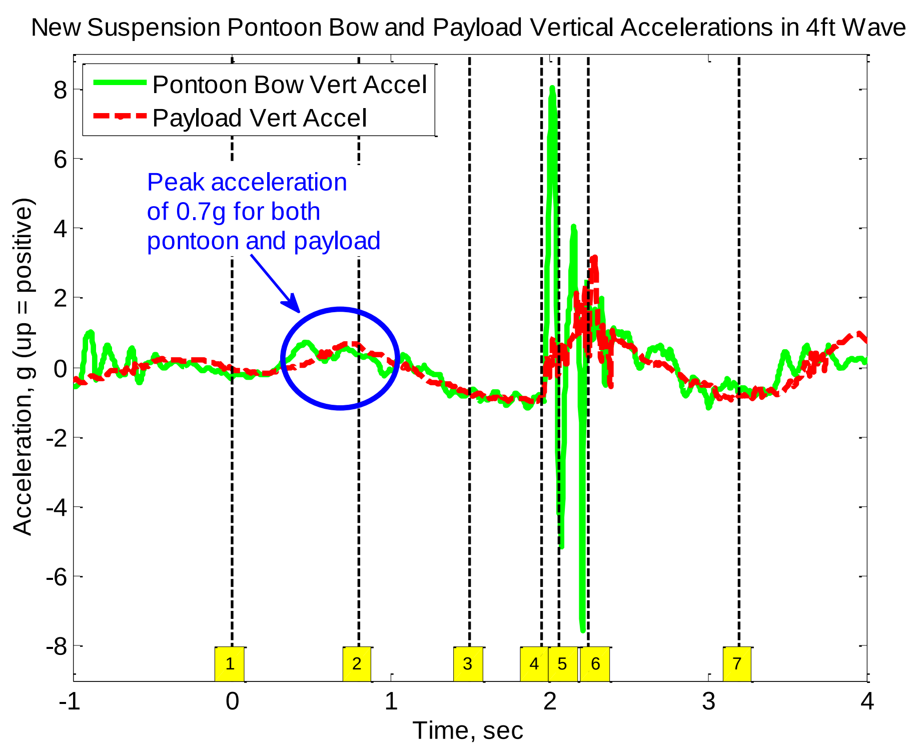

Figure 5-52: Phase 2 pontoon and payload vertical accelerations with new suspension

Phase 3: Unloading occurs as the WAM-V is launched into the air and the suspension reaches its maximum height. Figures 5-53 and 5-54 show the WAM-V being launched into the air during stock and new suspension testing, respectively. The operator remains seated in both cases. The pontoons during the new suspension test are launched slightly higher out of the water due to the momentum generated from previous waves.

Figure 5-53: Phase 3 screenshot of stock suspension testing

Figure 5-54: Phase 3 screenshot of new suspension testing

Figure 5-55 highlights the suspension ball joint heights of Phase 3 for each event. For the testing of the stock suspension, the suspension reaches its maximum height, pulling on the extension limit straps due to the forces seen by the momentum of the payload tray and the forces of the airspring. The new suspension also reaches its maximum height, but does not engage the extension limit strap.

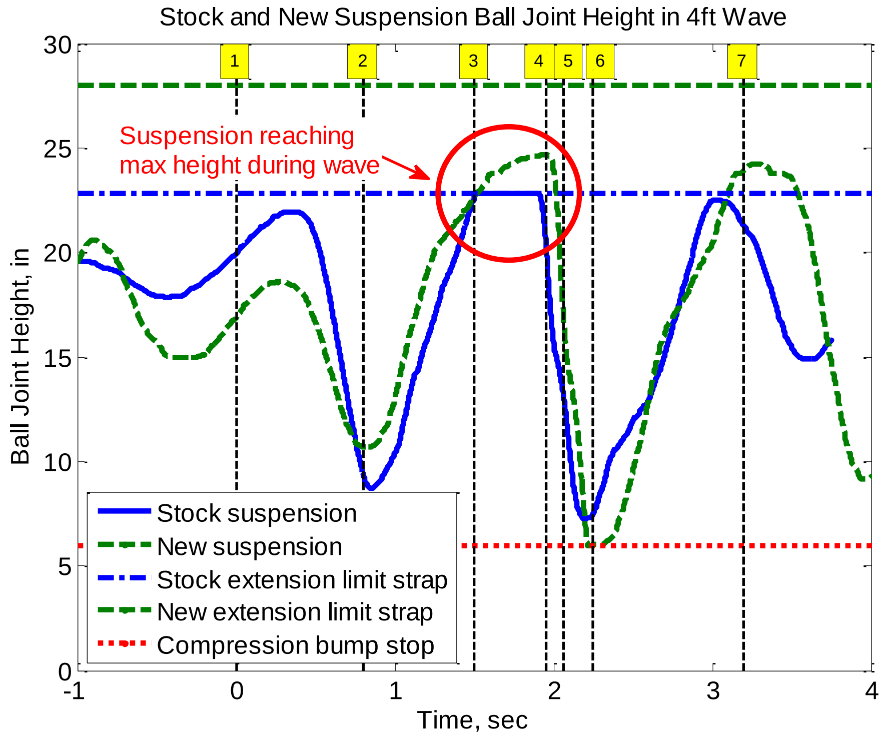

Figure 5-55: Phase 3 ball joint height of stock and new suspensions

Figures 5-56 and 5-57 show the vertical acceleration of the pontoon bow and payload tray during testing of the stock and new suspensions, respectively. With the stock suspension, both the pontoon and payload tray are subjected to a vertical acceleration of -1g. During the new suspension testing, the pontoon and payload tray are subjected to a vertical acceleration of -1g as well.

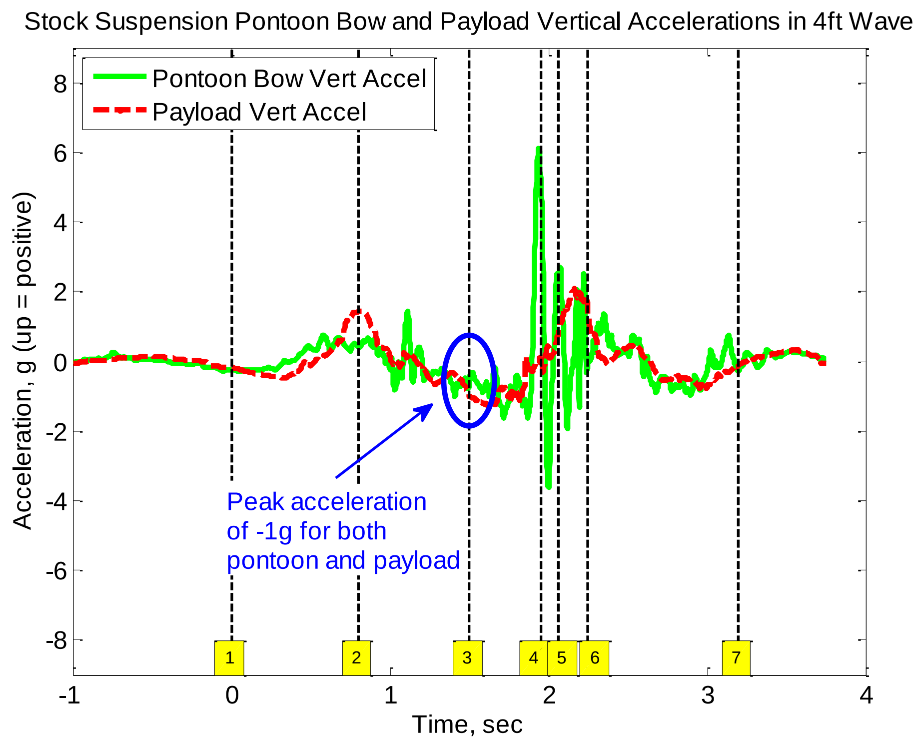

Figure 5-56: Phase 3 pontoon and payload vertical accelerations with stock suspension

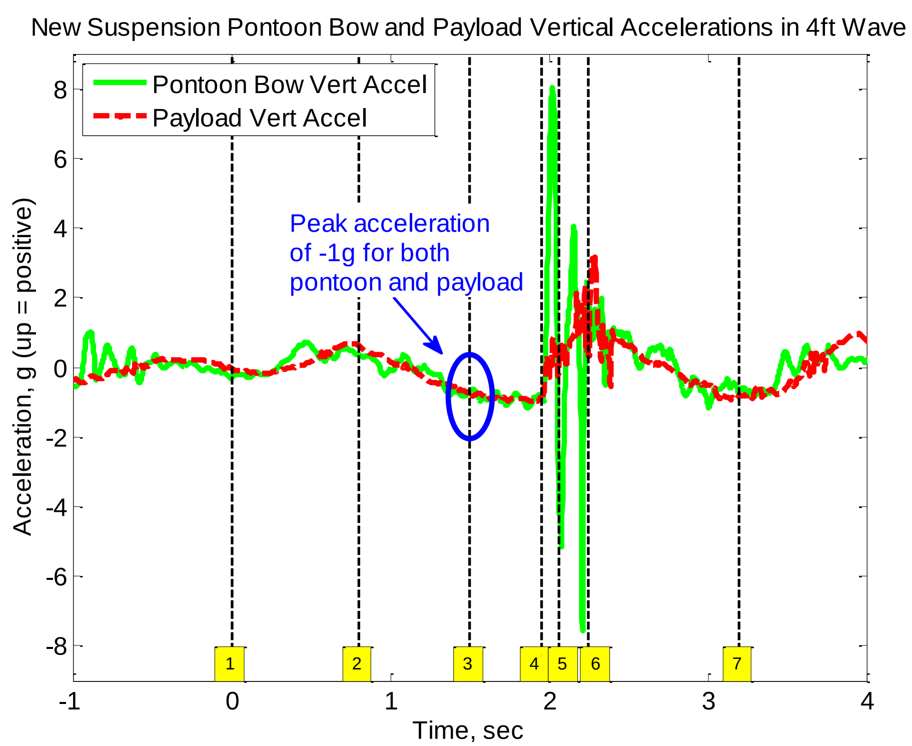

Figure 5-57: Phase 3 pontoon and payload vertical accelerations with new suspension

Phase 4: Freefall takes place as the WAM-V has reached its maximum height off the water and starts falling back down. Figures 5-58 and 5-59 show the WAM-V during freefall for both events. With the stock suspension installed, shown in Figure 5-58, the payload tray is pulled downwards while the operator's momentum continues to carry him up, causing him to leave the seat, similar to what was seen in the 2-foot wave analysis but more exaggerated. The test with the new suspension installed, shown in Figure 5-59, shows that the operator remains in the seat.

The data from Figures 5-60 and 5-61 illustrate why the operator was lifted from the seat during the stock suspension test while remained in the seat during the new suspension test. By plotting the vertical accelerations of the pontoon and payload tray on the same plot, the interaction between the two can be seen.

During the stock suspension test, Figure 5-60, the pontoon reaches a peak vertical acceleration of -1.75g as the payload tray reaches -1.5g. By pulling on the limit straps, the suspension causes the payload tray to fall faster than it naturally would. This causes the payload tray to fall down while the operator continues to travel up, pulling the payload tray and seat away from the operator. During the new suspension test, Figure 5-61, the vertical accelerations of the pontoon and payload tray are very similar: both components travel at the same rate and follow the same trend, reaching a vertical acceleration peak of -1g. Since there is no relative acceleration between the pontoon and payload tray, the operator is not separated from the seat.

Figure 5-58: Phase 4 screenshot of stock suspension testing

Figure 5-59: Phase 4 screenshot of new suspension testing

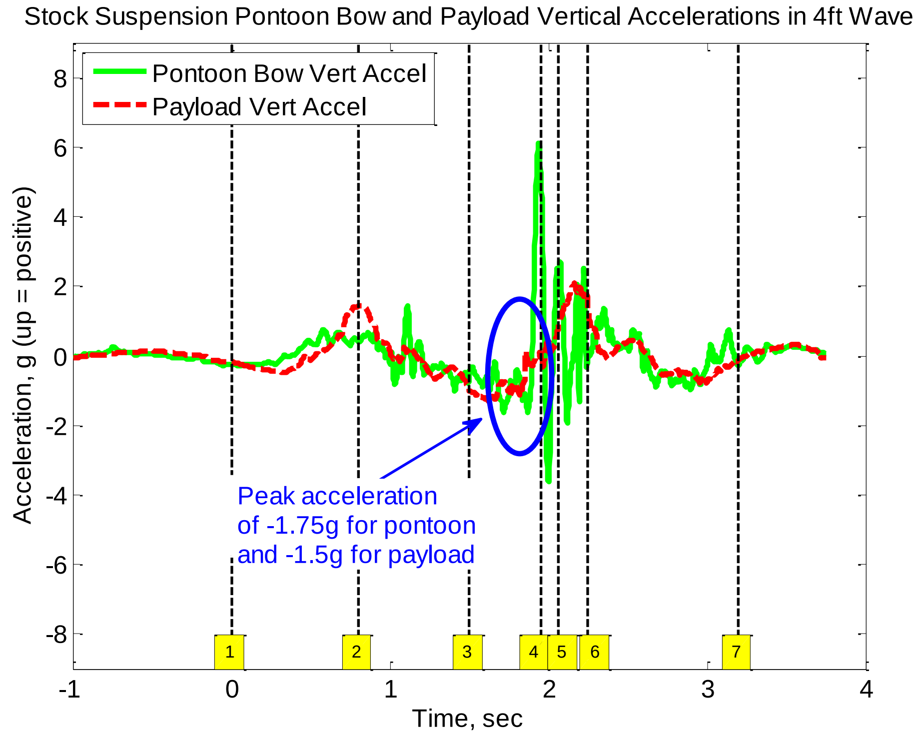

Figure 5-60: Phase 4 pontoon and payload vertical accelerations with stock suspension

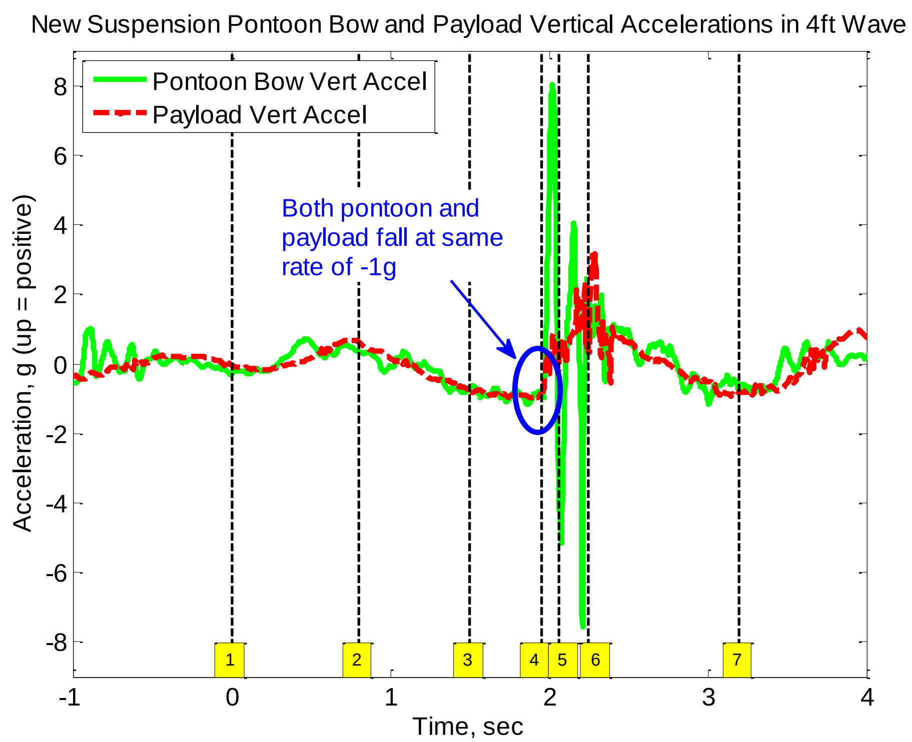

Figure 5-61: Phase 4 pontoon and payload vertical accelerations with new suspension

Phase 5: Initial Impact is when the pontoon bows contact the water, while the pontoon sterns start to come out of the water. As the WAM-V contacts the water during the stock suspension test, the operator is still out of the seat, shown in Figure 5-62. During the new suspension test, Figure 5-63, the operator remains seated as in previous phases.

Figure 5-62: Phase 5 screenshot of stock suspension testing

Figure 5-63: Phase 5 screenshot of new suspension testing

Figures 5-64 and 5-65 show the vertical accelerations of the bow and stern of the pontoon during the impact of the stock and new suspensions, respectively. The minimum and maximum accelerations of both ends of the pontoon are shown in Table 5-6.

Table 5-6: Pontoon Maximum and Minimum Accelerations

	Pontoon Bow Acceleration, g		**Pontoon Stern Acceleration, g**	
	Maximum	Minimum	Maximum	Minimum
Stock Suspension	6	4	5.5	-2.5
New Suspension	8	-7.6	2.3	-2.2

Although the two waves are close to the same height, since the WAM-V was launched higher in the air during Phase 3 of the new suspension test, the accelerations at the bow are higher than those encountered during the stock suspension test.

Figures 5-66 and 5-67 show the amount of attenuation seen from the pontoon to the payload tray during the stock and new suspension tests, respectively. The pontoon and payload tray peak accelerations are listed in Table 5-7, along with the amount of attenuation between the two.

Table 5-7: Attenuation between Pontoon and Payload Tray

	Pontoon Bow Acceleration, g	**Payload Tray Acceleration, g**	**Attenuation, %**
Stock Suspension	6	2	66
New Suspension	8	3.2	60

The new suspension attenuates less than the stock suspension due to the fact that the new suspension compresses to the point of contacting the compression bumper. The 3.2g at the payload tray is a result of the impact between the compression bumper and the top of the pontoon during the new suspension test.

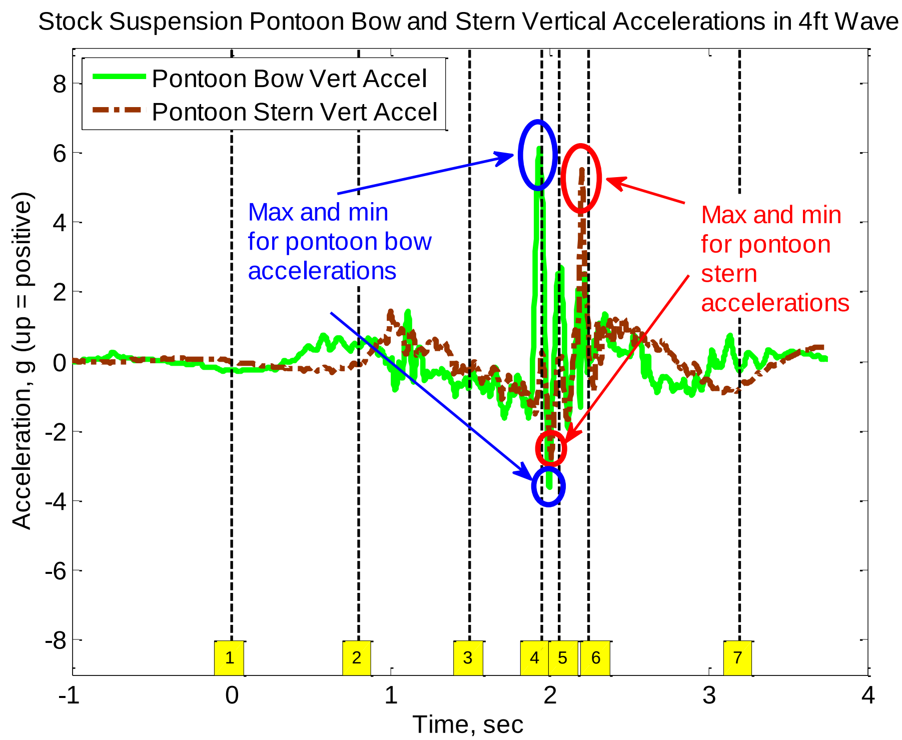

Figure 5-64: Phase 5 pontoon bow and stern vertical accelerations with stock suspension

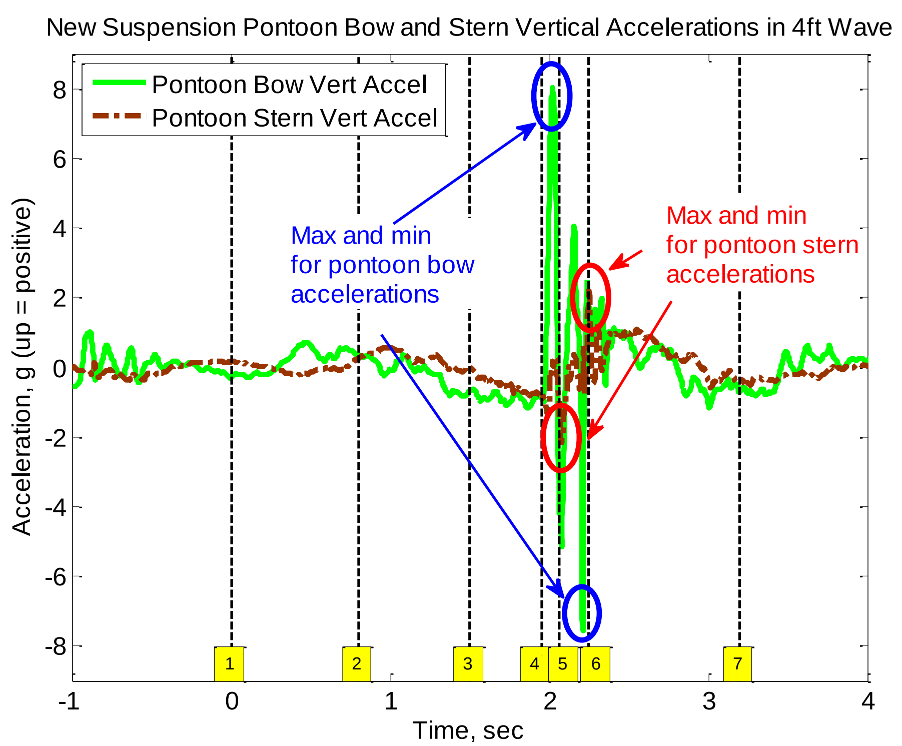

Figure 5-65: Phase 5 pontoon bow and stern vertical accelerations with new suspension

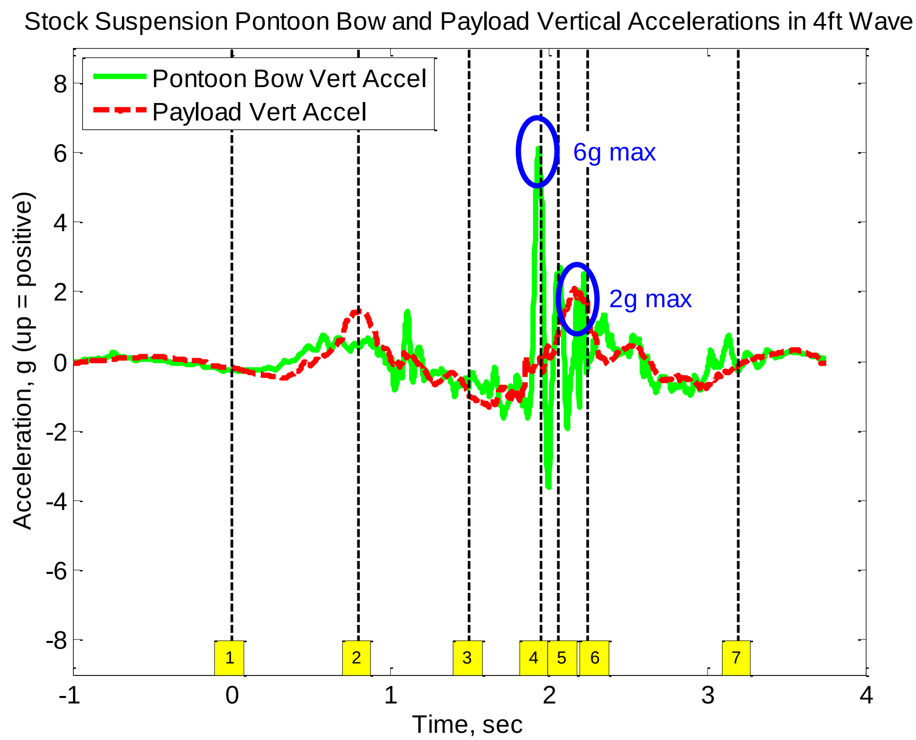

Figure 5-66: Phase 5 pontoon and payload vertical accelerations with stock suspension

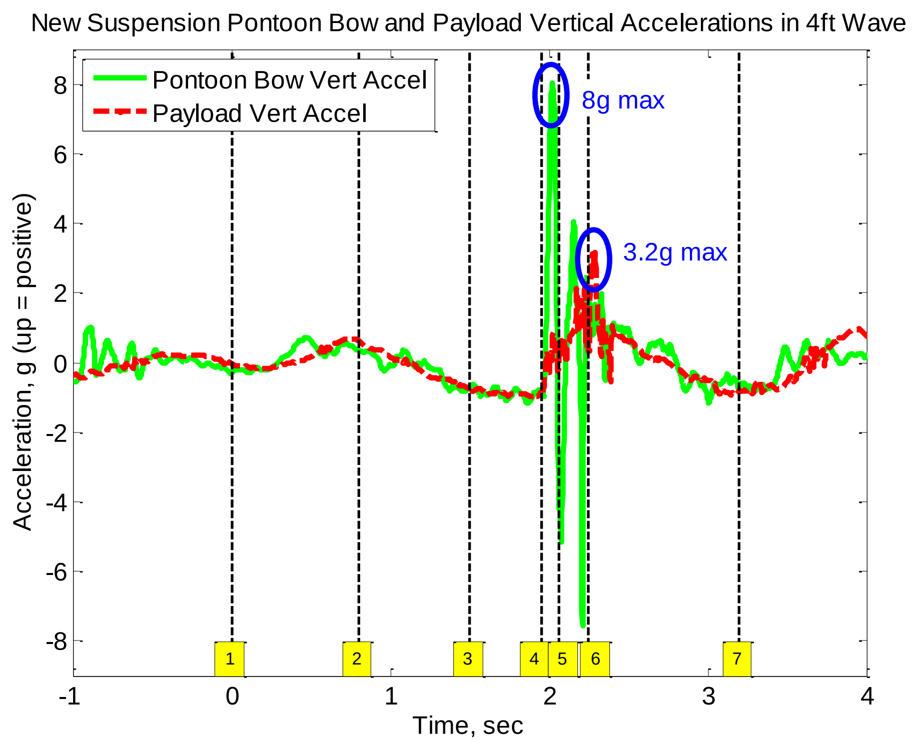

Figure 5-67: Phase 5 pontoon and payload vertical accelerations with new suspension

Phase 6: Maximum Compression is when the suspension is compressed to its minimum height. Figure 5-68 shows that as the stock suspension fully compresses, the operator is launched forward. Since he was already out of the seat from Phase 5, adding the longitudinal deceleration subjected the operator to a whiplash motion. Figure 5-69 shows that as the new suspension reaches its fully compressed position, the operator is leaning forward from the impact. The impact, although greater than that seen with the stock suspension, has a lesser effect on the operator since he remained in contact with the seat from the previous phases.

Figure 5-68: Phase 6 screenshot of stock suspension testing

Figure 5-69: Phase 6 screenshot of new suspension testing

Although a very hard impact occurred, Figure 5-70 shows that the stock suspension is not fully compressed, whereas the new suspension contacts the compression bumper. The stock suspension travels about 90% of its total stroke during the maximum compression phase, while the new suspension travels about 80% of its total stroke. Because the new suspension can be tuned for slightly more compression stroke, it can be less prone to bottoming out when the WAM-V encounters a large wave.

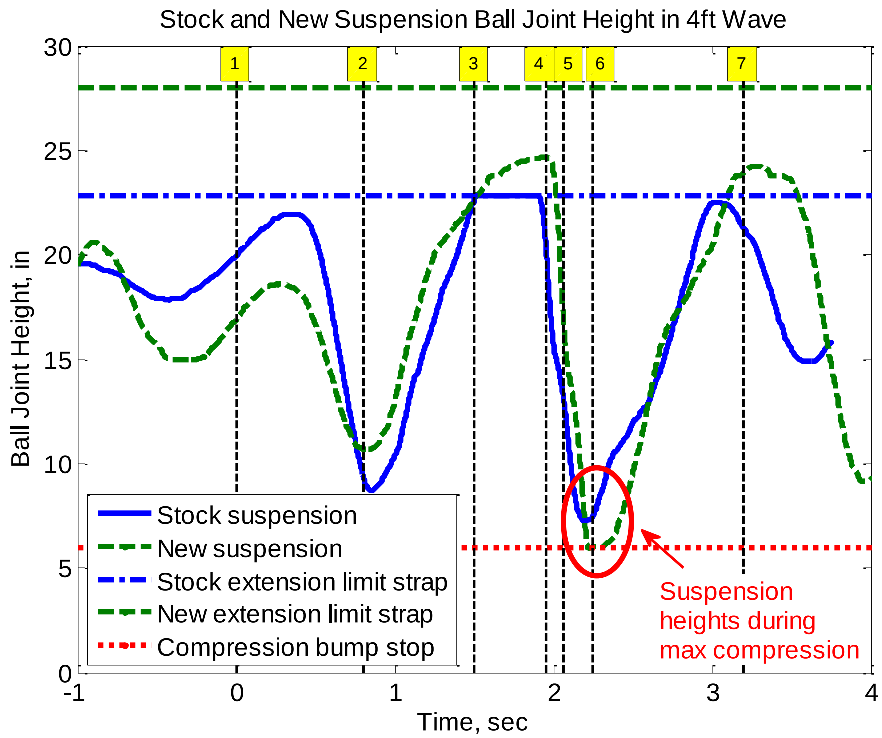

Figure 5-70: Phase 6 ball joint height of stock and new suspensions

Figures 5-71 and 5-72 show why the operator was launched forward during the stock and new suspension testing, respectively. As the WAM-V impacted the water to maximum compression, a longitudinal deceleration of 1.25g was recorded for the stock suspension test. This deceleration, paired with the fact that the operator was already out of the seat from previous phases, caused the operator to be launched forward. Although the longitudinal deceleration for the new suspension test was greater (3.1g), the operator was not launched from the seat because he was properly seated through the previous phases.

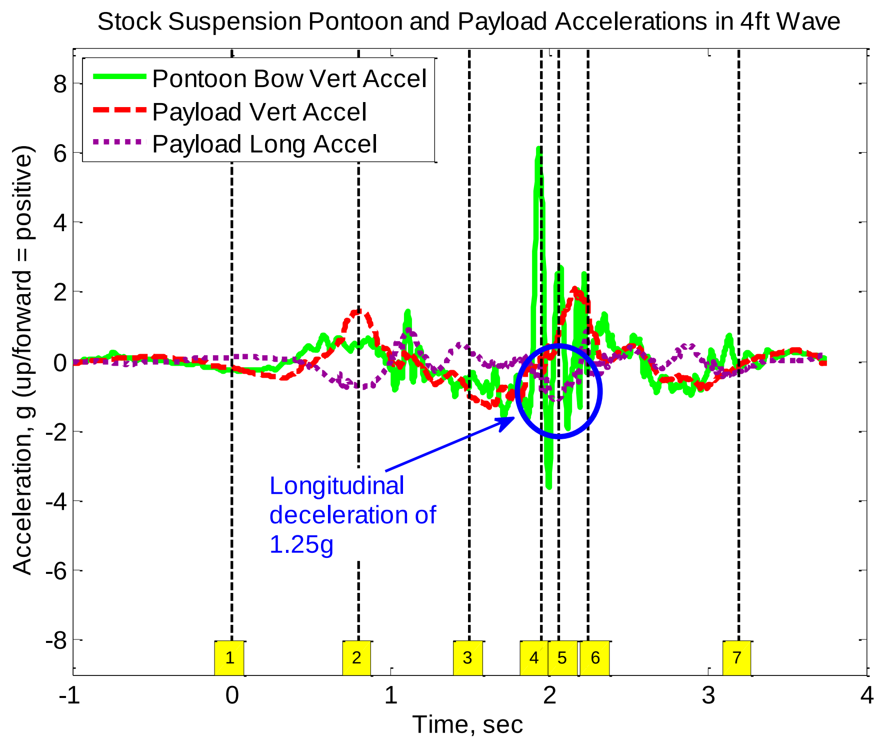

Figure 5-71: Phase 6 pontoon and payload accelerations with stock suspension

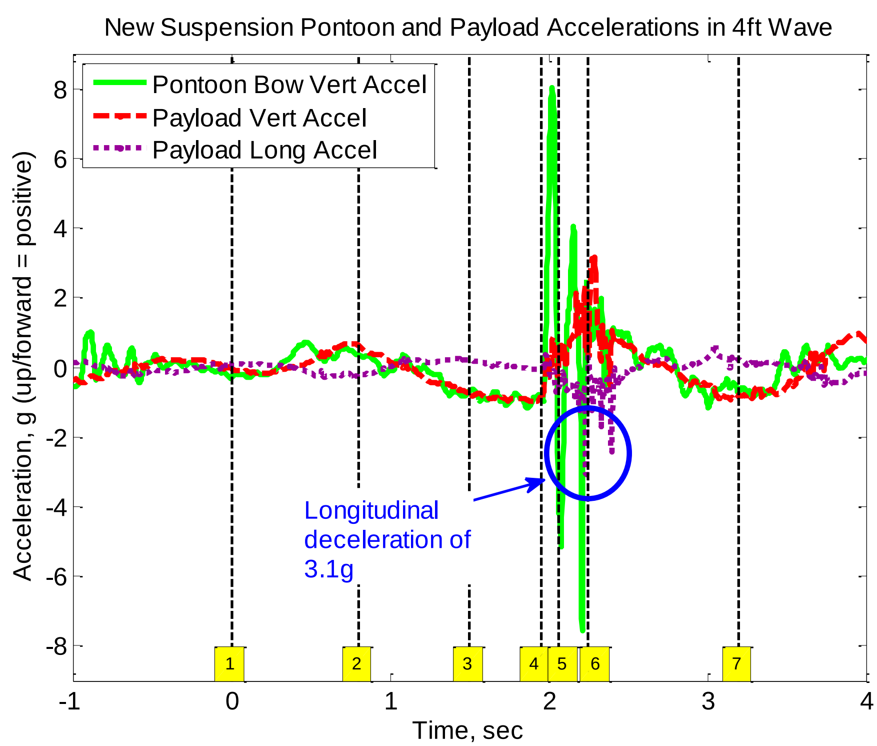

Figure 5-72: Phase 6 pontoon and payload accelerations with new suspension

Phase 7: End is the end of the event. The operator regains his seat during the stock suspension test, Figure 5-73, while the operator sits up during the new suspension test, Figure 5-74.

Figure 5-73: Phase 7 screenshot of stock suspension testing

Figure 5-74: Phase 7 screenshot of new suspension testing

Overall, performance is improved from switching the stock suspension to the new suspension. Even though the stock suspension was able to attenuate more shock from the pontoon to the payload tray, the new suspension provided an overall steadier ride for the operator, keeping him in, rather than separating him, from the seat.

In this more extreme 4-foot wave case, it is easily seen that the operator would have been thrown in and out of his seat during a test of higher sea state with the stock suspension installed. The stock suspension simply rode too close to being fully extended. Preloading the spring, which was done in SS1 testing on December 14, would have raised the ride height by 1.5 inches, allowing more compression stroke. If SS1 testing had taken place before SS2 testing of the new suspension, this preload would have been implemented.

Chapter 6 Conclusions and Recommendations

This chapter discusses the findings of this research and provides recommendations for future testing of the 33ft WAM-V.

6.1 Conclusions

By replacing the stock suspension of the 33ft WAM-V with a new suspension comprised of components more suitable for the size of the vessel, the performance of the WAM-V was improved. Improvements were demonstrated quantitatively in the dynamics of the suspension, and qualitatively in the way the operator responded to the wave-induced impacts during testing.

The stock suspension components were not best suited for the characteristics of the 33ft WAM-V. The stock airspring was intended for commercial buses and provided too much spring force, causing the suspension ride height (21 inches) to be near its total stroke (23 inches). Such a high ride height caused the suspension to frequently reach its extension limit straps, leading to large acceleration peaks at the payload tray and a very harsh ride for the operator.

New suspension components were chosen from analyzing the stock suspension dynamics during tests, and by determining weight values of the sprung and unsprung masses. As a result, a new coil-over-spring suspension was chosen to replace the stock suspension. The new suspension includes a more appropriately-sized spring rate for the weight of the WAM-V, and an adjustable damper that provides a wide range of damping values.

Testing of each suspension in Sea State 2 (SS2) provided data that determined the effectiveness of the new suspension. A comparison of the ride heights over a period of time while the vessel was in SS2 conditions showed that the stock suspension had a 70/30 compression-to-extension stroke ratio, while the new suspension has a more desirable 50/50 ratio.

Direct comparisons of the two suspension systems were made by evaluating similar occurrences from different days of testing, in particular, for single wave events of nearly identical amplitudes. The new suspension proved to be more appropriate than the stock suspension. The ride height of the new suspension was closer to the mid-stroke of the suspension, while the stock suspension was closer to the extension limit, often overextending the suspension and engaging the extension limit straps. When the extension limit straps are engaged, the suspension is disabled and the impact at the pontoons passes through to the payload tray. During a 2-foot wave encounter, the new suspension did not hit the compression bumper or the extension limit straps, allowing the suspension to fully function and not jolting the operator out of his seat for the entire wave event. The stock suspension, however, reached the extension limit straps multiple times, causing the operator to be jolted out of the seat.

Each suspension system was also analyzed when the WAM-V encountered an extreme wave of 4 feet. While the stock suspension engaged the extension limit straps, the new suspension was fully compressed and hit the compression bumper. The operator of the WAM-V during both events stated that full compression of the new suspension was much less harsh than the full extension of the stock suspension. The operator was lifted from his seat and jolted forward when the suspension fully extended with the stock suspension, but remained in the seat during the entire event with the new suspension.

The overall conclusion is that the new suspension design not only provides a better ride height that utilizes the most of the total suspension stroke, it also provides a more stable response in which the operator and the onboard payload are less likely to experience harsh impacts or be jolted around.

6.2 Recommendations

Further testing of the WAM-V is needed to optimize the performance of the new suspension. Tests under the same input conditions would provide the best comparisons between different suspensions and settings.

A recommendation for future testing of the 33ft WAM-V is to conduct tests in a repeatable situation. In the case of the SS2 analysis, finding waves of similar height and dynamic intensity was quite difficult, particularly as the tests are often performed in different seasons and sea conditions. The random sea conditions do not allow for repeatable tests that can be easily compared with each other, making the task of evaluating different components nearly impossible. Therefore, a repeatable and accessible test environment that can be used for design of experiments in evaluating various WAM-V components is highly desirable.

Due to the varying conditions during sea trails, the operator and data do not agree on which suspension is the better of the two. The preferred suspension of the operator is the new suspension, due to the fact that hitting the extension limit straps causes a much harsher response than hitting the compression bumper. Rather than being pushed up and forward out of the seat, which occurs when the extension limit straps are engaged, the operator remains in the seat, a result of the suspension contacting the compression bumper.

Despite the operator's preference, the data does not definitively show that the new suspension is the better choice. When analyzing the suspension ride height, the new suspension provides a better result. However, when analyzing the accelerations seen by the pontoons and payload tray, the data is inconclusive. During the 2-foot individual wave event, the data shows the new suspension being the better suspension, attenuating 76% of the acceleration from the pontoon to the payload tray, while the stock suspension attenuated 71%. However, during the 4-foot individual wave event, the data shows the stock suspension being the better suspension, attenuating 66% of the acceleration from pontoon to payload tray, while the new suspension attenuated 60%.

A two-post test rig would be beneficial by providing the ability to run multiple tests with the same external inputs. In this way, more comparable suspension data can be generated with identical external inputs to determine which suspension is better suited for the 33ft WAM-V. The test rig can also significantly assist with tuning the suspensions for improved operator comfort and boat stability.

The two-post rig that is under construction at CVeSS will be able to test WAM-V designs (both existing and future) under the same input parameters repeatedly. A more accurate comparison of the vessel's components can be made with the boat undergoing the same external inputs. Tests can be run to determine the response of the boat to various dynamic events, and the results can be evaluated both objectively, through analyzing the test data, and subjectively, through riding the boat while being shaken.

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