# U.S. Coast Guard Boat Recovery Simulation at NASA Ames Vertical Motion Simulator


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**The Boat Recovery Simulation was a collaboration between the U.S. Coast Guard and NASA. The experiment was conducted at the NASA Ames Vertical Motion Simulator (VMS). The goals were to (1) design a VMS experiment that can accurately simulate the motion of high sea conditions and to (2) collect data for the U.S. Coast Guard on human performance related to small boat recovery operations. The experiment setup included a software operation model designed around empirical boat position data; a replica boat section manufactured to incorporate real-world task elements; and the means to collect objective and subjective data from human participants. The VMS provided a viable testbed to assess certified U.S. Coast Guard crewmember's task performance while in motion.**


## I. Nomenclature

| | | |
|---|---|---|
| $\vec{a}_{BCG}$ | = | acceleration vector at Boat C.G. |
| $\vec{a}_{VMS}$ | = | acceleration vector at VMS Rotational Center |
| $\vec{a}_{BCM}$ | = | acceleration vector at Boat Crewmember position |
| $\vec{\omega}_{BCG}$ | = | angular velocity vector at Boat C.G. |
| $\vec{\dot{\omega}}_{BCG}$ | = | angular acceleration vector at Boat C.G. |
| $\vec{r}_{BCG\_VMS}$ | = | position vector of VMS rotational center w.r.t Boat C.G. |
| $\vec{r}_{BCG\_BCM}$ | = | position vector of Boat Crewmember w.r.t. Boat C.G. |
| $\vec{r}_{VMS\_BCM}$ | = | position vector of Boat Crewmember w.r.t. VMS rotational center |
| $KE$ | = | kinetic energy |
| $W$ | = | weight |
| $g$ | = | acceleration due to gravity |
| $V$ | = | velocity |
| $H(s)$ | = | transfer function |
| $\zeta_{\mathrm{vwo}}$ | = | damping factor |
| $\omega_{\mathrm{vwo}}$ | = | frequency factor |
| $K_{ro}$ | = | gain factor |
| $t_{success}$ | = | time captured to mark success |

## II. Introduction

The U.S. Coast Guard routinely uses a cutter deployed, rigid-hulled inflatable boat named Over-The-Horizon IV (OTH-IV), for rescue and law enforcement operations. "Cutter" is a term which refers to a Coast Guard vessel 65 feet in length or greater with accommodations for crew to live aboard, and the ability to deploy smaller boats including the OTH-IV [1]. A deployment method is a davit system capable of raising or lowering the smaller boat from the side of the cutter [2]. The davit suspends a specialized hook, designed to connect to a point, known as the lifting ring, on the OTH-IV. Recovering small boats at sea involves several crewmembers, both aboard the cutter and the smaller boat. Crewmembers on the cutter operate the davit to control hook height and guide the small boat with towlines. The coxswain steers the OTH-IV so the assigned crewmember can grab the suspended hook and attach it to the lifting ring [2]. The hookcan weigh 24-48 pounds and interacting with it can pose a risk to the crewmember depending on sea


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conditions, level of fatigue, and task expertise. All crewmembers train extensively at sea and on land, due to the inherent risk of boat recovery operations. Reliable tools are available to predict boat behavior during the recovery process, but methods for predicting corresponding human performance during the task have been limited.*

Between 2012 and 2017, a U.S. Coast Guard boat mishap reports stated of 1350 incidents, thirteen occurred during small boat recovery [3]. Mishaps can mean injury that results in a loss of a day's work, medical treatment beyond first aid, loss of consciousness, or material loss/damage valued above $5000. Eight incidents resulted in material damage, and four counted as injuries to crewmembers. Those injuries included falling overboard, pinched hand in hook, fall with knee injury, and a head impact with hook [3]. Determining a safe operating envelope for this recovery task has been a challenge for the U.S. Coast Guard, in part because sea-states are difficult to isolate and quantify in the real world.

In 2018, the U.S. Coast Guard collaborated with NASA to utilize the Vertical Motion Simulator (VMS), a large-displacement flight simulator, located at NASA Ames Research Center to investigate small boat recovery tasks. The goals were to 1) design an experiment and evaluate the VMS as a platform to test OTH-IV recovery operations for variable sea conditions, otherwise known as sea-states; and 2) collect data on the performance of the assigned crewmember responsible for connecting the suspended hook to the lifting ring.

This paper describes the design and setup of the first-of-its-kind small boat recovery simulation. By leveraging the VMS's large motion space and flexible architecture, the OTH-IV's response in varying sea-states can provide the Coast Guard with a simulation environment to collect data on the boat crewmember. Therefore, the results of this simulation may benefit the U.S. Coast Guard with future system design, operations and crew safety during severe recovery conditions.

## III. VMS Facility Description

The Vertical Motion Simulator has been in operation since 1980 and is a one-of-a-kind simulation research and development facility conducting studies involving human pilot cueing modalities and simulation fidelity, aircraft/spacecraft handling qualities and flight control design, and pilot-vehicle interface design [4]. During its operation, the VMS has contributed to aerospace programs and flight safety, particularly the design and development of flight control systems for modern aircraft like the Joint Strike Fighter and Space Shuttle Orbiter [4].

The VMS motion system, shown in Fig. 1, is an uncoupled, six-degree-of-freedom, combined electromechanical/electrohydraulic system [5]. It resides in a specially constructed 120-ft tower and uses nearly the entire interior volume of this tower. The motion system includes a vertical platform which spans with width of the tower. The carriage traverses the vertical platform and provides lateral and longitudinal motion. On top of the carriage is a gimbal system which provides roll, pitch, and yaw to the Interchangeable Cab (I-CAB). Table 1 shows the VMS motion system operational and system limits.

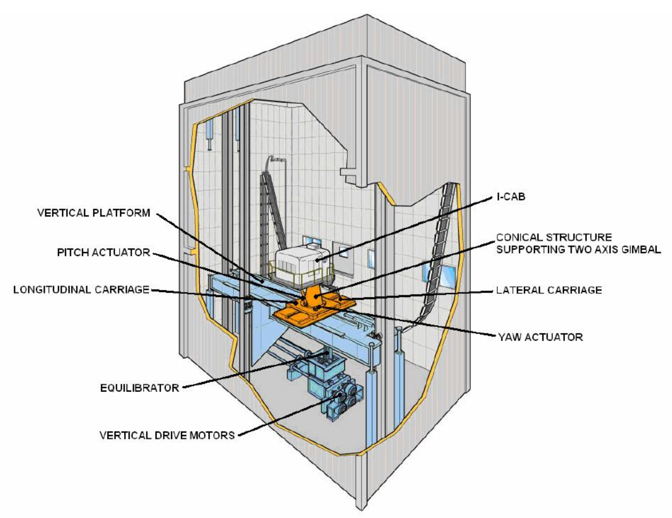


**Fig. 1 Vertical Motion Simulator diagram**

* Correspondence with U.S. Coast Guard subject matter experts (see acknowledgement) during the experiment design.

**Table 1 VMS motion system performance limits [5]**

| Degree of freedom | Displacement | | Velocity | | Acceleration | |
|---|---|---|---|---|---|---|
| | System limit | Operational limit | System limit | Operational limit | System limit | Operational limit |
| Longitudinal | ±4 ft | ±3 ft | ±5 ft/sec | ±4 ft/sec | ±16 ft/sec$^2$ | ±10 ft/sec$^2$ |
| Lateral | ±20 ft | ±15 ft | ±8 ft/sec | ±8 ft/sec | ±13 ft/sec$^2$ | ±13 ft/sec$^2$ |
| Vertical | ±30 ft | ±22 ft | ±16 ft/sec | ±15 ft/sec | ±22 ft/sec$^2$ | ±22 ft/sec$^2$ |
| Roll | ±0.31 rad | ±0.24 rad | ±0.9 rad/sec | ±0.7 rad/sec | ±4 rad/sec$^2$ | ±2 rad/sec$^2$ |
| Pitch | ±0.31 rad | ±0.24 rad | ±0.9 rad/sec | ±0.7 rad/sec | ±4 rad/sec$^2$ | ±2 rad/sec$^2$ |
| Yaw | ±0.42 rad | ±0.34 rad | ±0.9 rad/sec | ±0.8 rad/sec | ±4 rad/sec$^2$ | ±2 rad/sec$^2$ |

The I-CABS allow simulation of different vehicles by enabling a tailored cockpit. The design flexibility provides the visual environment, pilot inceptors, seats, displays and instrument panels to meet requirements provided by the researchers. Figure 2 shows an I-CAB suspended from an overhead crane in the tower while being installed atop the gimbal system. Constructed cabs meet rigid mechanical, hydraulic and electrical interface specifications to achieve the desired interchangeability. Each cab includes safety features for human occupancy such as five-point seat belts, smoke detection, emergency lighting and multiple exits.

**Fig. 2  Installation of I-CAB**

## IV. Experiment Setup

The USCG experiment focused on the crewmember responsible with connecting a hook to the lifting ring. The setup started by incorporating empirical boat position data into the VMS real-time environment to drive the motion system, followed by modifying a I-CAB to resemble the OTH-IV, and then developing a software operational model to monitor the simulation. All these factors ensured a repeatable and safe environment to test the crewmember's task performance as they maintained balance while in motion.

### A. Sea-state Profile

1) Large Amplitude Motion Program (LAMP): The program is a time-domain simulation model specifically developed for computing the motions and loads of a ship operating in extreme sea conditions [6]. Users can specify parameters such as wave height, speed of the boat, and other environmental factors. Table 2 shows the sea-state profiles provided by the Coast Guard researchers generated from LAMP. The result is a .csv

formatted, 400s long time history profile of the boat's position for all six-degrees (Surge, Sway, Heave, Roll, Pitch, and Yaw, sampled at 50Hz, evaluated at the OTH-IV Center of Gravity (C.G.).

**Table 2 Sea-state profile parameters**

| Sea-state | Significant Height (ft) | Modal Period (s) | Heading w.r.t wave (deg) | Speed (kts) |
|---|---|---|---|---|
| 3 | 2.9 | 7.5 | 0.0 | 6.0 |
| 4 | 6.2 | 8.8 | 0.0 | 6.0 |
| 5 | 10.7 | 13.0 | 0.0 | 6.0 |

2) Segmenting Profiles: The USCG researchers initially requested the experiment to represent a wide variety of sea-states with different wave height and period. However, fewer motion profiles simplified the validation of the VMS motion. Six 180s profiles were generated by copying segments of the 400s file, which were generated by using a MATLAB [7] script to split the full 400s profile into segmented profiles. This approach created segments that reduced the chances of the participants predicting the specific test profiles through repeated trials. Table 3 depicts how every 30s interval became a new start time for each profile. Motion ramped in over a period of 20s to full strength to avoid discontinuities in acceleration at the beginning of each trial.

**Table 3 Segmented sea-state profiles**

| time (s) | 30 | 60 | 90 | 120 | 150 | 180 | 210 | 240 | 270 | 300 | 330 | 360 | 400 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wave motion files | 180s profile_1 | | | | | | | | | | | | |
| | | 180s profile_2 | | | | | | | | | | | |
| | | | 180s profile_3 | | | | | | | | | | |
| | | | | 180s profile_4 | | | | | | | | | |
| | | | | | 180s profile_5 | | | | | | | | |
| | | | | | | 180s profile_6 | | | | | | | |
| | 400s profile (sea-state 3, 4, or 5) | | | | | | | | | | | | |

3) Rigid Body Motion: The VMS requires acceleration commands most commonly derived from equations of motion within a vehicle math model. Differentiated velocity and acceleration from the boat's center-of-gravity (BCG) positions replaced the equations of motion. The BCG accelerations are translated to the VMS rotational center to drive the motion system as shown in Eq. (1). The position vector between the BCG and the VMS rotational center, $r_{BCG\_VMS}$, is derived from the Boat Crewmember's position, $r_{BCG\_BCM}$, from the OTH-IV's technical drawing, and the crew member's position in the simulator relative to the VMS rotational center, $r_{VMS\_BCM}$, as shown in Figure 3.

$$\vec{a}_{VMS} = \vec{a}_{BCG} + (\vec{\dot{\omega}}_{BCG}\ x\ \vec{r}_{BCG\_VMS}) + \ (\vec{\omega}_{BCG}\ x\ \vec{\omega}_{BCG}\ x\ \vec{r}_{BCG\_VMS}) \tag{1}$$

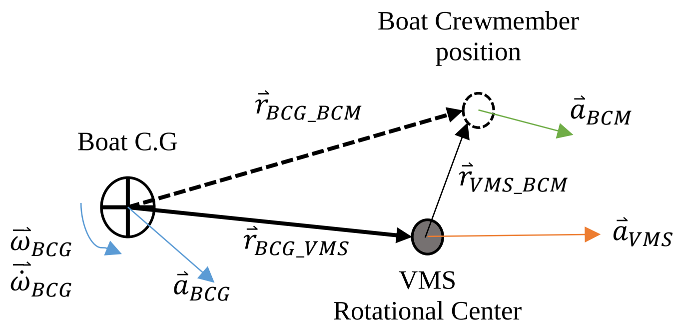


**Fig. 3 Rigid Body diagram**

**B. PSD validation**

The Power Spectral Density (PSD) of the VMS rotational center acceleration was analyzed to verify the energy distribution between the original 400s motion profile and the 180s segmented profiles. The full 400s sea-state motion profile represents a spectrum of signal frequencies distributed over the time series. If the 180s profiles did not contain similar frequency distributions as the 400s profile, then the segments would need to be longer. Figures 4a-f show the PSD analysis of acceleration command in all six-degrees-of-freedom for the segmented motion profile at sea-state three.

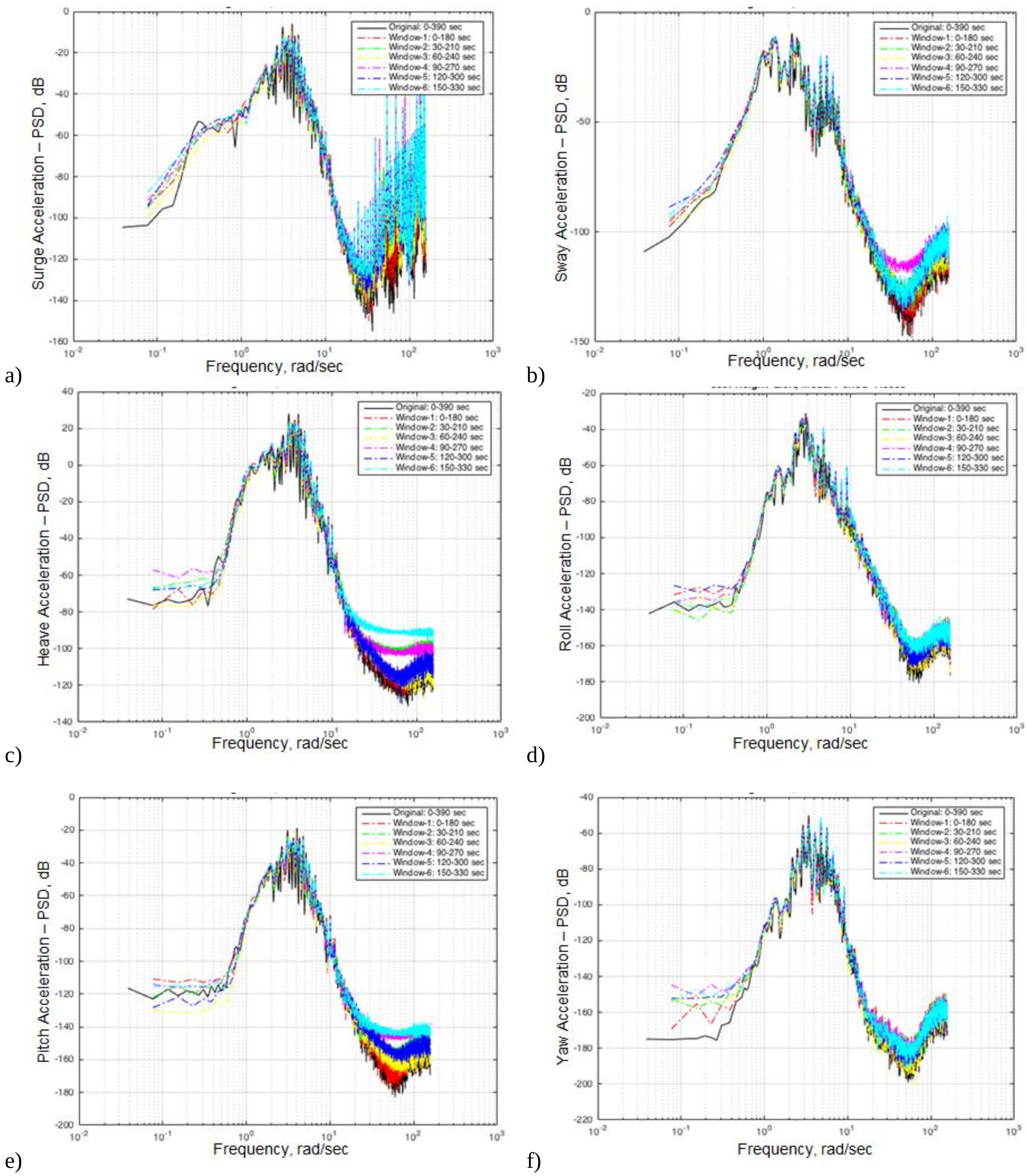


**Fig. 3 Sea-state 3 Acceleration PSD plots a) Surge axis, b) Sway axis, c) Heave axis, d) Roll axis, e) Pitch axis, f) Yaw axis**

The plots confirmed the segmented profiles showing similar power spectrum with respect to the original profile across the operational frequencies, but showed some discrepancy at frequencies below 0.4 rad/sec and above 20 rad/sec. The difference in the low frequency spectrum is due to the break frequency of the VMS' washout filter, which was set at 0.4 rad/sec. The selected break frequency reduced the position drift of the simulator caused from the acceleration commands. The difference in the high frequency is likely due to the sample size (400s vs. 180s), thus a lower resolution in a smaller sample. Figure 4c – Heave acceleration, shows the largest difference at high frequencies, which is possibly due to the inertia of the simulator.

### C. Cab and Hardware Modifications

The modifications to an I-CAB for this experiment were different from previous aerospace vehicle experiments conducted at the VMS. The recovery task required participants to stand as they would aboard the OTH-IV, gain control of a suspended hook and attach it to a lifting ring, and all while maintaining their balance through sea-state motion. The design called for a cab with no front canopy, visual system structure, instrument displays, or pilot inceptors. Figure 5 shows the resulting platform with an OTH-IV replica bow section surrounding the participant. The bow section is an aluminum structure capped with aluminum sheet metal and includes the lifting ring and a front bench. Padded foam was used to cover hard surfaces and sharp edges, as a hazard control.

The unrestrained nature of the task while in motion posed the great risk for participants. A harness system worn by the participant attached at four points prevented falls and allowed enough mobility to complete the task. Figure 5 shows three fixed length lanyards to prevent the participant from falling out of the bow section. A fourth self-retracting lanyard prevented the participant from falling down within the boat section. Additional polycarbonate sheeting was installed on the perimeter rail to prevent anything from falling off the cab's platform.

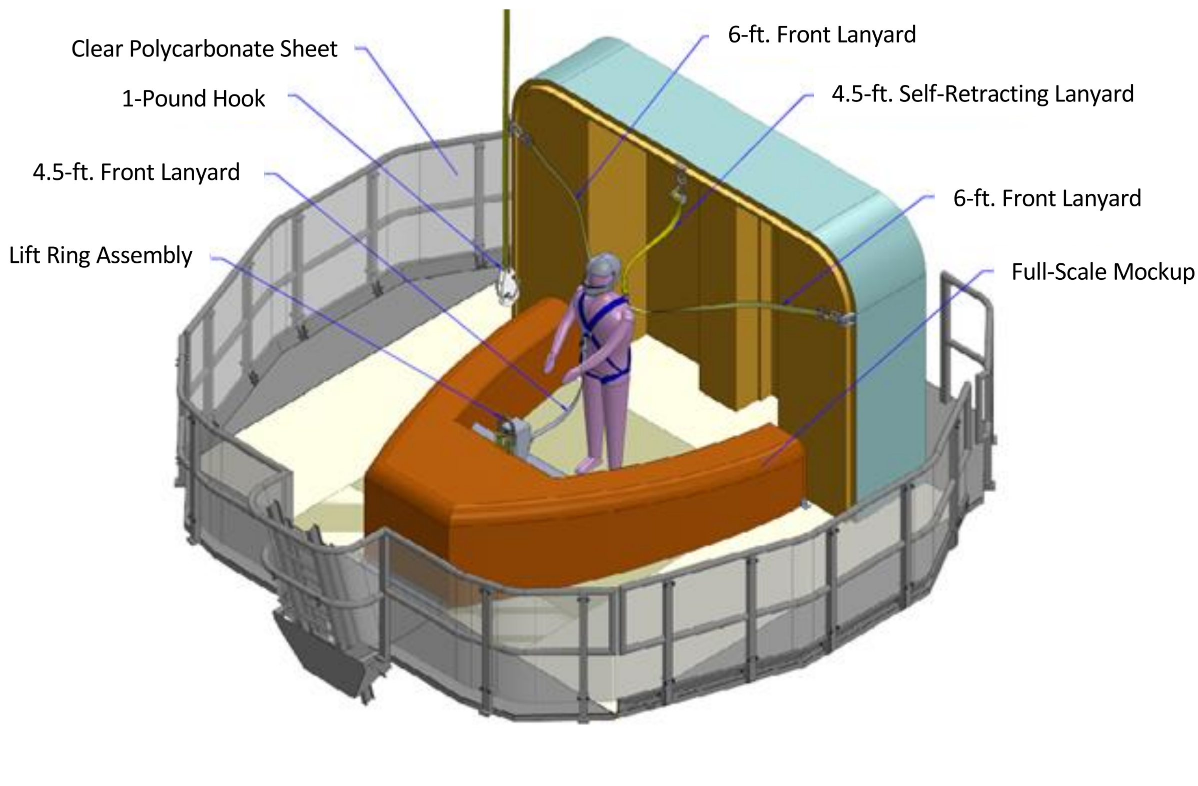


**Fig. 5 OTH-IV modified I-CAB**

The overhead crane, used to install the I-CAB, was fitted with a fixed length cable and suspended a hook similar to the arrangement in Fig. 5. The actual Coast Guard hook, weighing 24 pounds posed too large a risk for a VMS experiment. The suspended hook was therefore modified to address the risk of it striking the participant. Figure 6 shows a rendered model of the replica hook 3D-printed out of plastic with a full-functional hinge, latch mechanism, and aluminum handles. A magnetic breakaway disconnected the hook from the cable as a safety feature if the hook latched to anything while the cab was in motion. The magnet separated when a pulling-force greater than 16 pounds was applied. The resulting hook assembly used in the experiment weighed one pound.

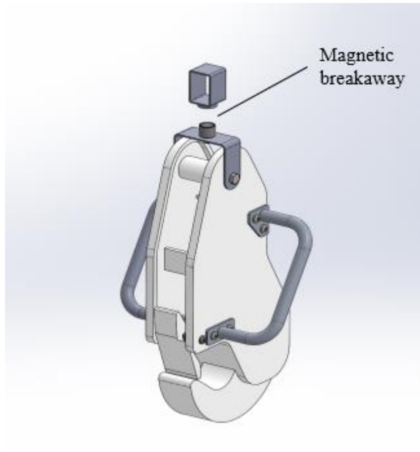


**Fig. 6 3D printed hook with magnetic breakaway**

The one-pound hook constraint came from a NASA standard regarding orbital debris since there was no other NASA standard found that addressed this type of hazard. The NASA standard states, *"Limit the risk of human casualty: The potential for human casualty is assumed for any object with an impacting kinetic energy in excess of 15 Joules…"*[8].

Figure 7 is a contour plot representing kinetic energy as seen in Eq. (2). The hook weight, *W*, varied between 0-25 pounds. The relative speed between hook and VMS, *V*, ranged from 0-30 ft/s. The green region depicts the acceptable design kinetic energy.

$$KE = 1/2 * (W/g) * V^2 \tag{2}$$

The red region represents weight/speed combinations greater than 15 Joules of impact energy. The maximum velocity from all six VMS axes combined plus the velocity of a swinging hook, with a speed of 5 ft/s would total 26.9 ft/s. This represents the worst-case scenario and was used as a conservative design point. According to VMS operational logs, no incident resulting in a maximum speed in all six axes has ever occurred.[†]

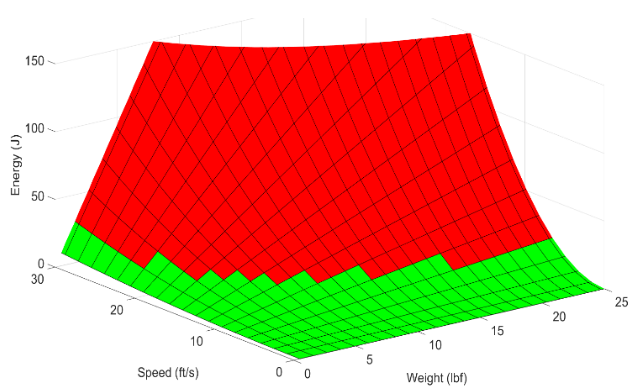


**Fig. 7 Kinetic energy contour plot**

[†] VMS operational logs are paper documents the motion operators maintain to track any errors, limits, or malfunctions the motion system may experience.

The hook weight reduction was an effort to limit the overall kinetic energy of an impact. Using the worst-case scenario as a speed constraint, a one-pound hook produces 15.3 Joules of energy. It is noted that the kinetic energy of the one-pound hook exceeds 15 Joules limit specified in the NASA standard for an unprotected human. In order to stay below the 15 Joule limit standard the participant was required wear a helmet as protective equipment. Table 4 shows kinetic energy for several objects including the 24 pound hook the U.S. Coast Guard actively uses.

**Table 4 Kinetic energy comparison**

| Object Description | Speed (ft/sec) | Energy (Joules) |
|---:|:---:|:---:|
| 9mm bullet | 1170 | 467 |
| 24-lb USCG lifting hook | 26.9 | 366 |
| 100mph baseball | 146 | 145 |
| 25mph softball | 36.7 | 24.8 |
| 1-lb 3D printed hook replica | 26.9 | 15.3 |

The last element to the recovery task required a modified lifting ring. Figure 5 shows the position of the lifting ring in the bow mockup. An installed sensor detected the hook and provided an analog signal to record the time of task completion. The MD-P18 sensor, as seen in Fig 8, is a photoelectric sensor from FSI Technologies. An adjustable threaded collar sets the height of the sensor to aide in calibrating the sensor. Calibrating the sensor to detect the hook at a distance less than three inches provided the most reliable response. The event was recorded at when the sensor detected the hook. Participants were instructed to verbally call out when the hook was connected in the event the sensor did not detect the hook. Post simulation analysis would confirm the time of task completion if called out verbally.

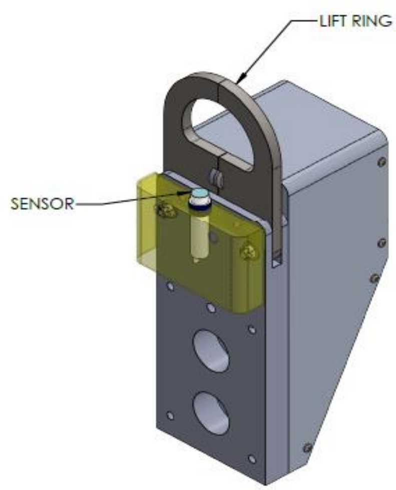


**Fig. 8 Lifting ring with sensor**

**D. The Recovery Operational Model**

The Recovery Operational Model provided additional control and monitoring to the sea-state profiles. Driving the VMS with the accelerations from the sea-states did not guarantee the participant could reach the suspended hook much less connect it to the lifting ring. The overhead crane used in the experiment could not simulate the davit's ability to control the hook height. To overcome the overhead crane limitation a controller referred to as the "Virtual Winch Operator" (VWO) was developed. The VWO generates external commands to the simulator motion system to position the cab at desired distance relative to the suspended hook. Instead of the hook being moved closer to the participant, as done by the davit operator, the motion platform was moved closer to the hook. Analysis done for each sea-state profile determined if the hook would hit anything on the cab. Areas on the cab identified as "Keep-Out Zones" provided a constraint to the external commands generated from the VWO. Another featured called "Park Mode" ramped out the motion once the participant successfully connected the hook to the lifting ring.

1) Keep-Out Zone: Despite the predictable wave patterns of the sea-state profiles, the model needed to monitor and verify the position of cab relative to the hook. Figure 9 shows a visualization of the Keep-Out Zones overlaying the modified cab.

- Zone 1 [green]: Surrounds the participant standing at the most forward position. The box dimensions are 4-ft wide by 2-ft deep and 1-ft above the participant.
- Zone 2 [blue]: Surrounds the bow mockup in front of the lifting-eye. The trapezoid dimensions are 5.72-ft wide by 3.17-ft deep and 2.13-ft to 2.61-ft high measured from the base of the lifting ring.

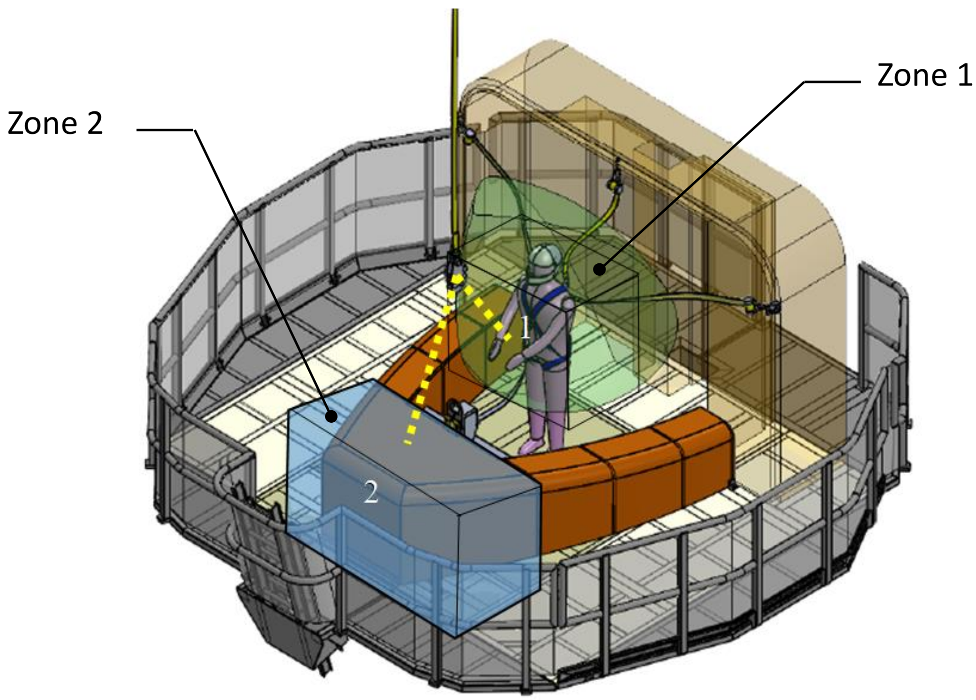


**Fig. 9 Visualization of Keep-Out Zones**

Each Keep-Out Zone was comprised of eight points. The surface made between four points was associated with a normal vector. A second vector was measured between each corner of the surface to the hook with a known height. The angle between the two vectors indicated if the hook would enter either of Keep-Out Zones. Tests showed that the algorithms correctly predicted any intrusion to the defined Keep-Out Zones.

2) Virtual Winch Operator (VWO): Control applied to the forward-aft, side-to-side, and up-down directions which positions the hook close enough to the lifting ring are referred to as an "Opportunity." The VWO generated motion commands to control the distance between hook and lifting ring for each sea-state profile. The VWO replaced the need for a crane operator or a coxswain to steer the OTH-IV for this experiment. The VWO command is a rate limited step input to a 2nd order low-pass filter. Equation (3) shows *H(s),* the 2nd order low-pass filter used in the VWO commands.

$$H(s) = \frac{{\omega_{vwo}}^2}{s^2 + 2\zeta_{vwo}\omega_{vwo}s + {\omega_{vwo}}^2} \qquad \zeta_{vwo} = 1.0 \qquad \omega_{vwo} = 1.0 rad/sec \tag{3}$$

The commands were applied in surge, sway, and heave axes to better position the lifting ring relative to the hook. A designed VWO profile unique to each sea-state profile was a reliable method to control the distance between cab and suspended hook. This approach provided the same opportunities to each participant.

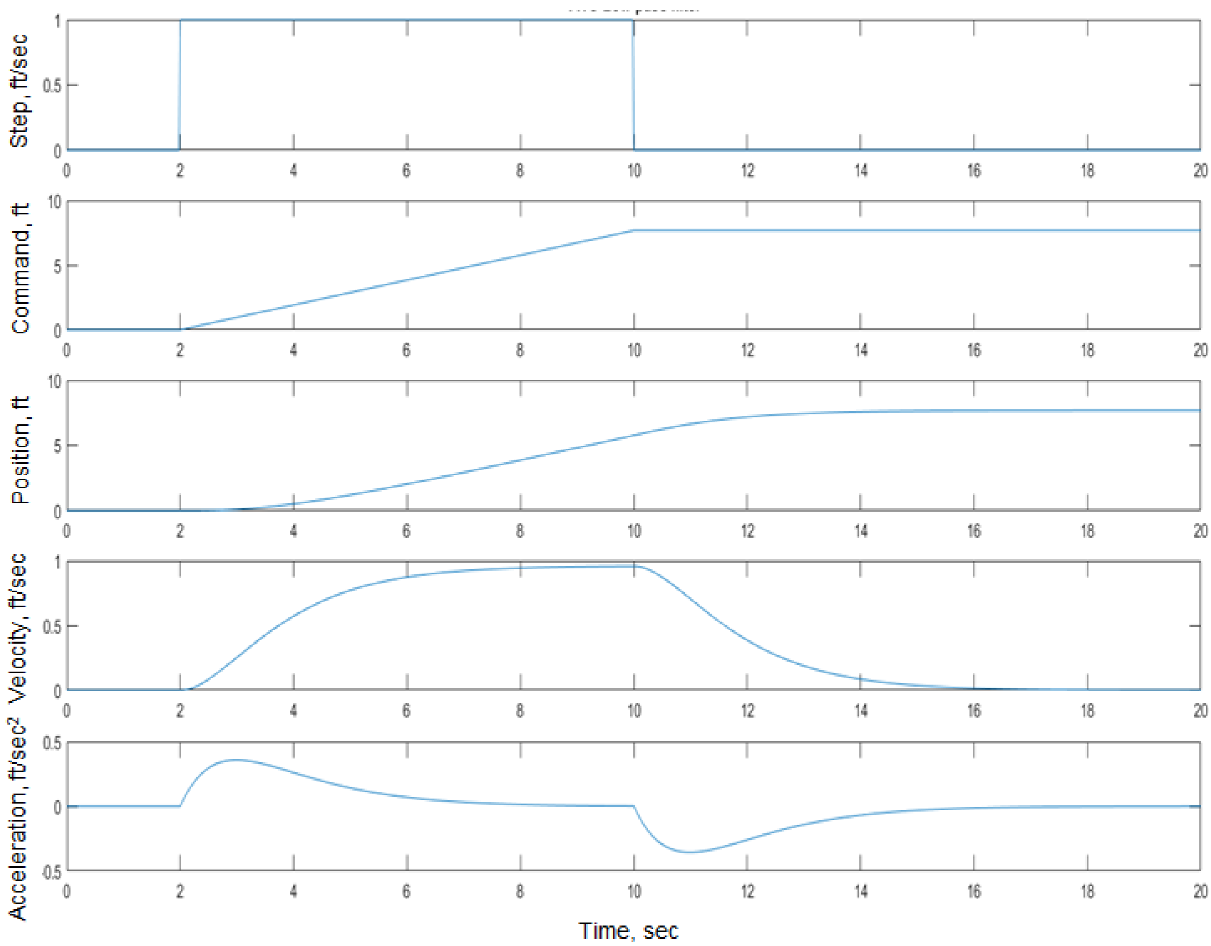


**Fig. 10 VWO transfer function response**

Figure 10 shows the results of the VWO step-input test in the heave axis, measured at the VMS rotational center. The step signal (top graph) represents the rate input which was integrated to generate commanded position. The position, velocity, and acceleration signals are the results of the 2nd order low-pass filter of the VWO and the VMS' washout filter. The plots have no discontinuities in velocity or acceleration, thus providing a smooth transition. The frequency in Eq. (3) was selected such that the maximum acceleration generated from the VWO would not exceed the human perceived acceleration threshold of 0.01g [9].

3) Park Mode: The last feature of the model determined how the motion would ramp out upon task completion. Attempting to stop the motion instantaneously could damage the simulator or injure participants. Therefore, a transition that does not exceed any simulator limits was necessary to end one trial and prepare for the next. The Park Mode design approach:

- Capture the simulator height when sensor detects hook
- Level the simulator and ramp out any sea-state commands
- Raise the simulator above the capture height to create slack in the cable

The transition from peak of wave to a level platform requires a smooth transition accomplished with a "ramp-out" gain factor, $K_{ro}$ as seen in Eq. (4). This approach zeroed out the acceleration commands over two seconds triggered by the sensor detecting the hook.

$$K_{ro} = 1.0 - 0.5 * (1.0 - \cos((time - t_{success}) * \pi/2) \quad (4)$$

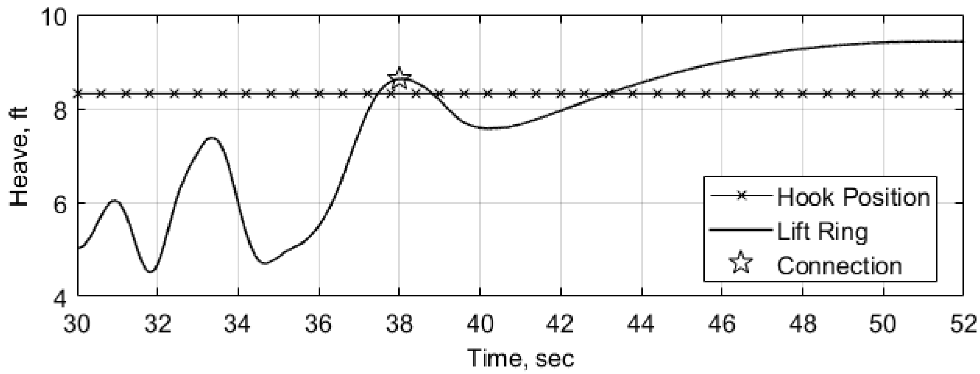


**Fig. 11 Heave position after Park Mode**

Figure 11 shows the vertical position of the lifting ring [solid] while in motion exceeded the height of the hook position [line,x] then the connection signal [star] triggered the Park Mode. The sensor activated at 38 seconds when the participant connected the hook then the motion stabilized in 10 seconds.

Once the motion ramped out, the participant was free to disconnect the hook from the lifting ring and prepare for the next trial. If the hook detached at the magnetic breakaway, the participant could easily reattach it. The simulation engineer reset the model and returned the cab to the starting position before the next sea-state. This approach achieved a great deal of repeatability and reduced the downtime between trials. At the end of most trials, the magnet detached, but the cab raised enough for the participants to reattach the hook for the next trial.

## V. Experiment Operations

The experiment was executed over the course of three weeks. During that time, 12 certified U.S. Coast Guard boat crewmembers acted as the experiment participants. Each participant was briefed on the experiment and tested under the same conditions. A series of familiarization tasks were created to introduce features of the experiment and allow the participants to experience the motion while practicing the recovery task. Data was collected on their performance in the form of video recording and .csv formatted files.

### A. Test matrix

Researchers generated a daily test matrix which randomized the eighteen sea-state profiles (six segments per sea-state three, four, and five). Checks were done to ensure participants experienced equal number of sea-states three, four, and five. The matrix was broken up into three blocks made up of 12 trials as seen in Table 5. After each block the participants were given a 10 minute break. Participants could repeat an attempt if an error occurred during the experiment.

**Table 5 Daily Test Matrix**

| | |
|---|---|
| Block 1 | 12 trials (sea-state 3,4,5)<br>10min break |
| Block 2 | 12 trials (sea-state 3,4,5)<br>10min break |
| Block 3 | 12 trials (sea-state 3,4,5)<br>10min break |

### B. Data Collection

Time history data such as simulator position, velocity, and acceleration were collected at 50Hz and saved as .csv formatted files. Several video cameras were installed on the I-CAB platform and positioned to observe the simulation in real-time. Video and audio recording aided the researchers in post simulation analysis. Figure 12 shows the camera feeds all around the participant, to monitor the experiment.

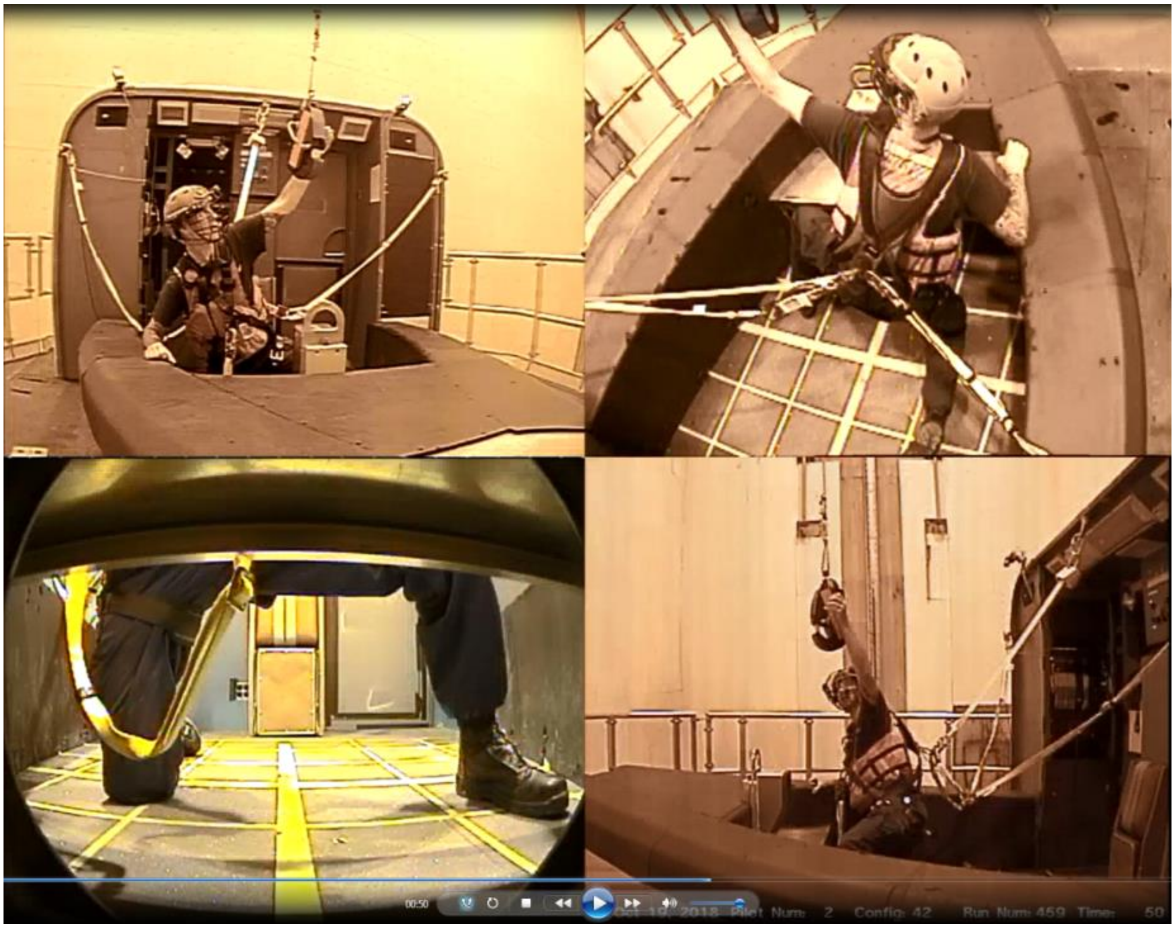

**Fig. 12 Video recording sample**

### C. Final motion profiles

Figure 13a-c represents the surge, sway, and heave position of the cab for one of the eighteen sea-state profiles used in the experiment. The signals shown are the hook position [line,x], the original sea-state profile [dashed], the associated VWO commands [dotted], and the sea-state profile + VWO [solid]. Figure 13d represents the distance between hook and the lifting ring for the original sea-state profile [dashed] and the sea-state profile + VWO [solid]. Figure 13d also marks an "Opportunity" [star] where the distance between the hook and lifting ring was less than six inches. The hook started at a known postion at the beginning of each trial and the VWO signal adjusted the height of the cab to assist the participant in connecting the hook.. The sum of the original sea-state profile and VWO commands comprised the final motion profiles [solid] used by the VMS.

The sea-state profile [dashed] in Fig. 13a shows the hook is too far to forward to connect. Figure 13c shows the sea-state [dashed] data exceeds the hook height at 50s, 58s, 72s, and 88s. Each graph shows that the original sea-state profile can result in few chances to connect the hook or collisions between the hook and cab. The VWO commands applied to all axes creates a better chance to connect the hook. Figure 13d shows the motion profile modified with the VWO created opportunities [star] to connect the hook at 38s, 72s, and 89s. Therefore, the external commands generated by the VWO created realiable and predictable opportunities for participants to complete the task.

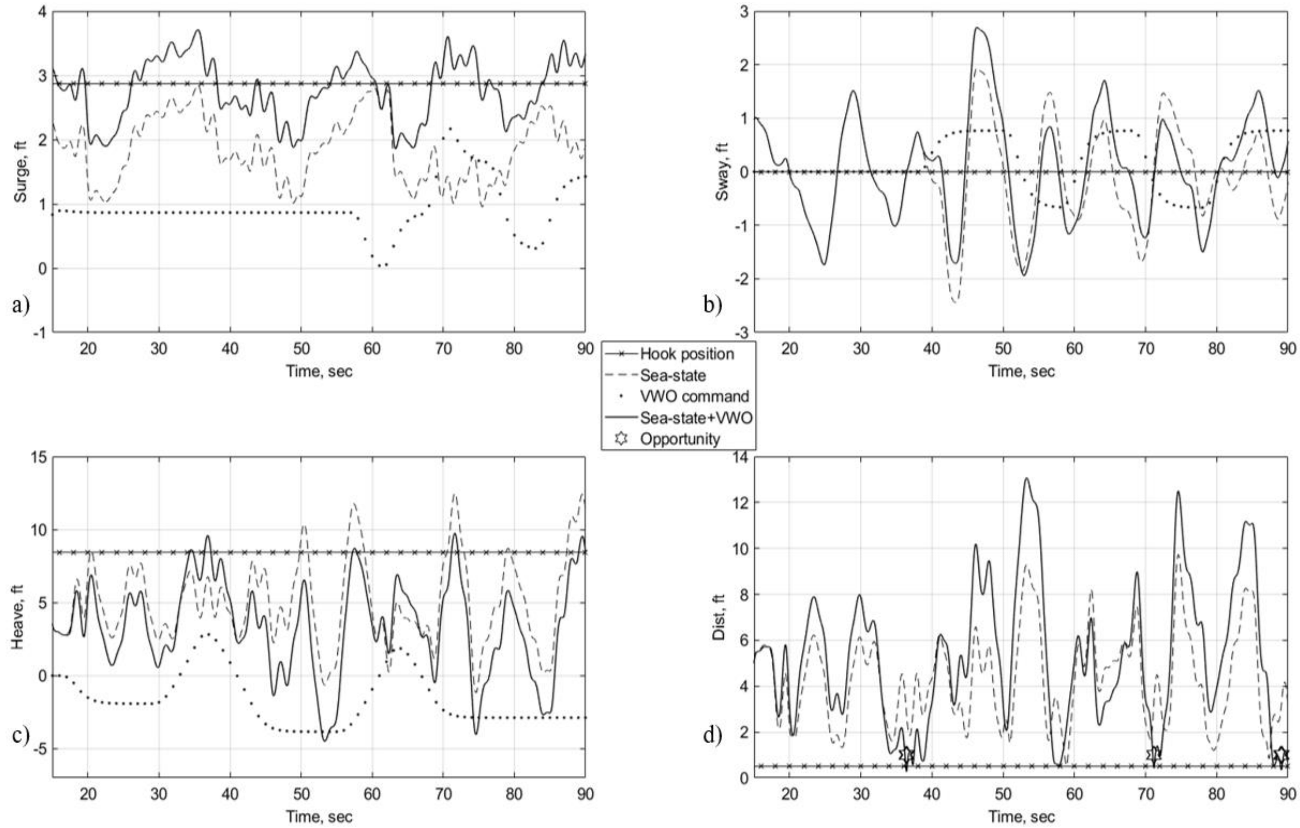


**Fig. 13 Final sea-state 5 profile with VWO a) Surge position, b) Sway position, c) Heave position, d) Distance to hook**

### D. Participant experience

Overall, the participants displayed little trouble accomplishing the boat recovery task. Participants reported that the wave motion was very accurate and saw the potential the VMS offered to studying OTH-IV boat operations. The subjective data and surveys included suggestions on how to improve the simulation in terms of realism and fatigue effects. One suggestion was to simulate when the OTH-IV slams against the cutter, which may interrupt participants from their task. Participants also highlighted the significance of fatigue, and that selecting participants immediately following a full day of work may yield different results.

The simulation introduced artificial elements to the task such as a fall-arrest harnesses and a plastic one-pound hook, but participants reported that the harness did not affect performance and they accepted the use of the lighter hook. Artifacts like the motion ramp-out after hook connection did not resemble real-world task elements. However, participants did not report that motion ramp-out produced a negative impact, due to the complexity of the test conditions.

## VI. Conclusion

The U.S. Coast Guard and NASA experiment goals were achieved by designing an experiment using the VMS to simulate varying sea-states and collecting human performance data on small boat recovery operations. Participants reported that the motion experienced at the VMS was realistic and the artificial features added to the experiment for safety and experiment management requirements were appropriate. As the first experiment to simulate a boat at the VMS, the USCG and NASA successfully demonstrated a reliable approach to modeling different sea-states for the OTH-IV, building a bow section of the OTH-IV and fitting it to an I-CAB, and developing hazard mitigations and safety features. Additionally, the approach described in this paper leveraged the VMS's flexible architecture to develop a system that can introduce more variety in sea-state profiles, collect more data, and improve the simulation to incorporate more real-world features.

## Appendix

Safety concerns surrounding the standing nature of the experiment called for an internal review by the NASA Ames Human Occupancy Review Board (HORB). The board examined the harness system, emergency procedures, impact mitigations and personal protective equipment (PPE). Applying the procedure: "identify, quantify and then mitigate" to each hazard addressed the safety requirements. The experiment collected the data while mitigating risk exposure to participants.

Per Ames Procedural Requirements [10], the risk matrix shown in Fig. 14, referred to as a 'Stop Light Chart' for all hazard risk management was used. The demarcations between the risk rating levels (*Low* [green], *Medium* [yellow], and *High* [red]) are shown as a function of Likelihood and Consequence. Subscripts in parenthesis are a mapping of Facility System Safety hazard risk assessments [11]. The Appendix contains material referring to hazard analysis, severity and likelihood relationship, risk management categories, and control requirements. The following list describes the identified hazards and controls.

### A. Consequence and Likelihood:

Identified hazards will be classified according to the Consequence and Likelihood, as seen in Table 6. The urgency for resolution of a hazard is dependent upon the combination of the consequence and likelihood of each hazard, or the HAZARD RISK ASSESSMENT (HRA).

**Table 6 Hazard Consequence and Likelihood**

| HAZARD CONSEQUENCE (SEVERITY) | |
|---|---|
| 5 | Catastrophic<br>**Injury:** Loss of life, or permanent disability.<br>**Property Damage**: Loss of facility, or direct cost of mission failure or property damage over $2M. |
| 4 | Critical<br>**Injury:** Severe injury, or permanent partial disability, or hospitalization.<br>**Property Damage**: Direct cost of mission failure and property damage between $500K and $2M. |
| 3 | Severe<br>**Injury:** Moderate injury, full lost workday(s), restricted workday(s).<br>**Property Damage**: Direct cost of mission failure and property damage between $50K and $500K. |
| 2 | Moderate<br>**Injury:** Minor injury, medication or medical treatment administered.<br>**Property Damage**: Direct cost of mission failure and property damage between $20K and $50K. |
| 1 | Minor<br>**Injury:** Only first aid was administered or no injury.<br>**Property Damage**: Direct cost damage less than $20K or occurrence or condition of employee concern where there is no property damage but possesses the potential to cause a mishap. |

| LIKELIHOOD (PROBABILITY) | |
|---|---|
| 5 | Very High;<br>Likely to occur greater than: $\mathbf{10^{-1}}$ |
| 4 | High;<br>Probably will occur between: $\mathbf{10^{-2} < P \leq 10^{-1}}$ |
| 3 | Moderate;<br>May occur between: $\mathbf{10^{-3} < P \leq 10^{-2}}$ |
| 2 | Low;<br>Unlikely to occur between: $\mathbf{10^{-6} < P \leq 10^{-3}}$ |
| 1 | Very Low;<br>Improbable less than: $P \leq \mathbf{10^{-6}}$ |

## B. Final Risk Acceptance / Risk Control Requirements

*Low - Low Residual Risk:* Low Residual Risk can be accepted by the Project after review, without Project Safety Review Board action.

*Moderate - Moderate Residual Risk*: Risk should be mitigated to an acceptable level. Moderate Residual Risk acceptance requires Project level acceptance with Project Safety Review Board concurrence.

*High - High Residual Risk:* Risk must be mitigated to an acceptable level. High Residual Risk acceptance requires a waiver. Risks rated as high require Project's PMC wavier approval.

| Likelihood | | | | | |
|---|---|---|---|---|---|
| 5 | L(3) | M(2) | H(1) | H(1) | H(1) |
| 4 | L(3) | M(2) | M(2) | H(1) | H(1) |
| 3 | L(4) | L(3) | M(3) | M(2) | H(1) |
| 2 | L(5) | L(4) | M(3) | M(3) | M(2) |
| 1 | L(5) | L(4) | L(4) | L(4) | M(3) |
| | 1 | 2 | 3 | 4 | 5 |

Consequence

**Fig 14 Risk Matrix (Stop Light chart)**

## C. List of experiment hazards

1) *HR-001 Instability caused by high acceleration:* The participant can fall due to sudden motion and by standing without restraints. Properly trained personnel, fall-arrest equipment & PPE, or sea-state validation reduces the risk of instability. Final: M(2)

2) *HR-002 Suspended hook contacts participant:* Impacts may occur if the participant is unable to avoid the hook due to high sea-state motion. The most unlikely scenario was analyzed and determined if the participant were hit in the head, they would be safe. Final: M(3)

3) *HR-003 Suspended hook contacts platform:* A similar situation to HR-002, but with property damage. Verifying that the hook does not hit the platform with the VWO ensures no manage damage will occur. Final: L(5)

4) *HR-004 Inadvertent hook motion:* A resultant of HR-002 or HR-003 would mean the hook was swinging with an un-deterministic trajectory to make problems worse. Final: M(3)

5) *HR-005 Suspended hook connect to participant:* Similar to HR-002 but less likely because it involves the hook making a connection to the participant. Final: M(3)

6) *HR-006 Suspended hook connect to platform:* Similar to HR-003 but less likely because it involves the hook making a connection to the platform. Final: L(4)

7) *HR-007 Sharp edges or points:* Falls due to instability are exacerbated by hard surfaces or sharp edges. Foam-covered surfaces and edges or the fall-arrest system restricted the mobility enough to protect participants. Final: M(3)

8) *HR-008 Participant falls due to syncope*: In the very un-likely event that the participant was to pass out the fall-arrest system and the padded surfaces will mitigate injury. Final: M(3)

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## References

1 Unknown author, "The Cutters, Boats, and Aircraft of the U.S. Coast Guard" 2015-2016. U.S. Coast Guard Headquarters, Washington D.C.

2 Unknown author, "Cutterboat – Over the Horizon (CB-OTH) MK III Operator's Handbook" January 2008. U.S. Coast Guard Headquarters, Washington D.C.

3 Unknown author, "U.S. Coast Guard Mishap Report". 2012-2017. U.S. Coast Guard Headquarters, Washington D.C.

4 Bimal L. Aponso, Steven D. Beard, Jeffery A. Schroeder, "The NASA Ames Vertical Motion Simulator – A Facility Engineered for Realism" Royal Aeronautics Society Paper AF2009-223, June 2009. NASA Ames Research Center, Moffett Field, CA.

5 George L. Danek, "Vertical Motion Simulator Familiarization Guide" NASA TM-103923 May 1993. NASA Ames Research Center, Moffett Field, CA.

6 Woei-Min Lin, Matthew Collette, David Lavis, Stuart Jessup, John Kuhn, "Recent Hydrodynamic Tool Development and Validation for Motions and Slam Loads on Ocnea-Going High-Speed Vessels", 2007 American Bureau of Shipping.

7 MATLAB & Simulink R2017b Software, Ver. 9.3, 9.0. Mathworks, Natick, MA 2017.

8 "Process for Limiting Orbital Debris", NASA STD-8719.14B April 2019.

9 Meiry, J.L.: "The Vestibular System and Human Dynamic Space Orientation, " NASA CR-628, 1966.

10 "Ames Procedural Requirement: Risk Management Process Requirements" APR-8000.4. NASA Ames Research Center, Moffett Field, CA.

11 "Facility System Safety Guidebook" NASA STD-8719.7. January 1998.