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R/V ATHENA MODEL (5365) RESPONSE IN WAVES

by

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NSWCCD



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14. ABSTRACT (continued)

A better physical understanding of the dynamic response of high speed craft in seas would allow for increased structural optimization. To support this understanding, a computational approach to predicting motions and loads was proposed. The publicly releasable hull form Naval Surface Warfare Center Carderock Division (NSWCCD) Model 5365 (*R/V Athena*) was chosen to facilitate public release of results to various computational teams. As part of this study, Model 5365 was tested in calm water, regular waves, and irregular waves in 2014 [1]. After reviewing data from that test, it was determined that the *R/V Athena* model (NSWCCD Model 5365) should be modified to enable towing from the longitudinal center of gravity. Model 5365 was then modified and re-tested in calm water, regular waves, and irregular waves. This report presents the results from testing in waves.

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ADMINISTRATIVE INFORMATION

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SUMMARY

Current structural design methods for high speed naval craft rely heavily on empiricism. Though these methods have been employed reliably for a number of years, it is likely that an unknown level of conservatism exists in the prediction of both global and local impact loads to ensure the vessel's structural design is robust. A better physical understanding of the dynamic response of high speed craft in seas would allow for increased structural optimization. To support this understanding, a computational approach to predicting motions and loads was proposed. The publicly releasable hull form Naval Surface Warfare Center Carderock Division (NSWCCD) Model 5365 (*R/V Athena*) was chosen to facilitate public release of results to various computational teams. As part of this study, Model 5365 was tested in calm water, regular waves, and irregular waves in 2014 [1]. After reviewing data from that test, it was determined that the *R/V Athena* model (NSWCCD Model 5365) should be modified to enable towing from the longitudinal center of gravity. Model 5365 was then modified and re-tested in calm water, regular waves, and irregular waves. This report presents the results from testing in waves.

INTRODUCTION

This model test was designed to provide a computational fluid dynamics (CFD) validation data set for semi-planing craft. The CFD predictions were evaluated in their ability to predict calm water performance, as well as motions and loads in regular and irregular waves. The measurements made during testing include:

1. Resistance, sinkage, and trim measurements for the model in calm water over a range of speeds
2. Six degree-of-freedom (DOF) forces and moments acting on the model over a range of speeds and wave conditions
3. Model motions and accelerations over a range of speeds and wave conditions
4. Impact pressures over a range of locations on the model the model at different speeds and wave conditions for model validation

This report will focus on the results from testing in waves; a previous report presents results from calm water model testing [2].

EXPERIMENTAL APPROACH

Facility Description

Measurements of the *Athena* model operating in calm water, regular, and irregular waves will be performed in the Deep Water Basin at NSWCCD using towing Carriage 2. The basin is approximately 1886 feet long, 51 feet wide, and 22 feet deep. Carriage 2 has a maximum towing speed of 20 knots (33.8 ft/s). A pneumatic wavemaker is located at the east end of the basin, with a wave absorbing beach at the west end. Additional details describing the facility can be found in [1].

Model Description

Model 5365 is an 8.25 scale model of the *R/V Athena*, shown in Figure 1. Figure 1, with a lines plan included in Figure 1. The *R/V Athena* is a converted PG-84 Asheville-class patrol gunboat which is operated out of Naval Surface Warfare Center - Panama City Division as a high speed research vessel. The model, built in 1979, was constructed out of wood and fiberglass. The model has been refurbished over its life time, and in 2002 it was measured using NSWCCD's laser tracker model measurement system. The detailed measurements of the model, shown in Figure 2 revealed an asymmetry in the hull in the region of the bow, on the starboard side of the model. Since the laser tracker may not resolve edge radii well, the transom edge radius was measured with machinist's gages and found to be 0.02 inches. This as-measured geometry is available from NSWCCD by request as an IGES geometry file.

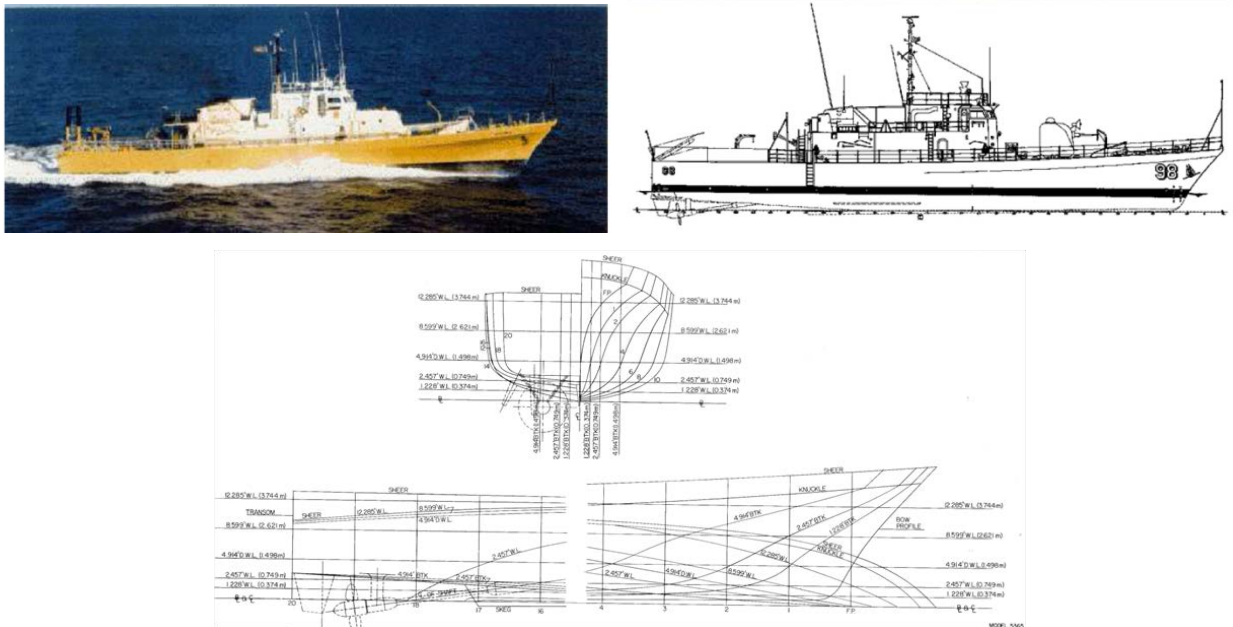


Figure 1. Full Scale *R/V Athena*.

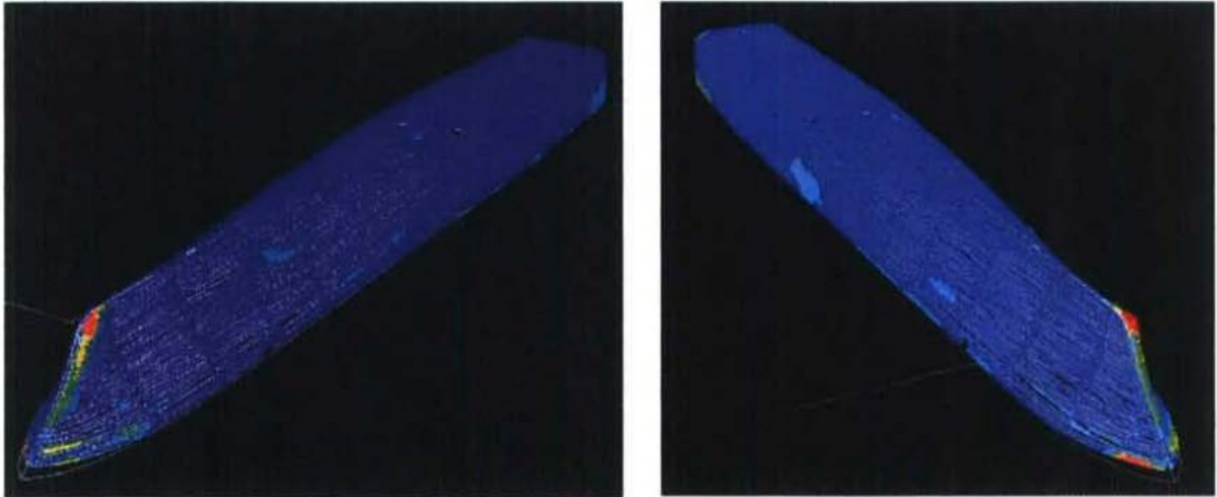


Figure 2. Laser Tracker Surface Measurements of model 5635 (largest deviation is 0.04 inches as shown in red).

The model was refurbished again in 2015 in preparation for this test. As a part of the refurbishment, the tow-point of the model was moved to align with the center of mass. This translation of the tow point allows for a more accurate representation of full scale motions, more comparable measurements to the CFD simulations, and increased model performance in large waves. A one inch square checkerboard grid (shown in Figure 3) was added to enable better images of the wetted surface area during testing. Turbulence stimulators were placed on the model along a line 2 inches aft of and parallel to the leading edge of the bow. The turbulence stimulators are acrylic cylinders, 1/8 inch high, with a diameter of 1/8 inch. Table 1 shows the as-tested model scale particulars. The model was ballasted to the same waterline used during the 2014 test [1]. Table 2 shows the data from the hydrostatic analysis at the ballasted condition.

A discrepancy between the marked waterline and the IGES geometry file was discovered when verifying hydrostatic equilibrium with the observed sinkage and trim. After leveling the model on a calibration bench and re-scanning the hull, the marked waterline had a trim (pitch) angle discrepancy of 0.16 degrees of trimmed down by the bow. The sinkage and trim values in this report are relative this initial hydrostatic trim condition. The initial hydrostatic condition was determined using the as-tested measurements of model weight and center of gravity. The geometry file used for CFD comparisons and hydrostatic equilibrium are oriented parallel to the baseline defined in the lines plan, shown in Figure 1.



Figure 3. Image of Model 5365 showing the yellow and black paint scheme, waterlines, and station lines.

Table 1. As-Tested Model Characteristics.

Parameter	As-Tested Value (D) $\pm$ Uncertainty (U)
Scale Ratio	8.25
Degrees of Freedom	Heave, Trim
Displacement, Δ	858.00 ± 0.30 (lbf)
As-Tested Basin Water Density at $74.01 \pm 0.30^\circ\text{F}$, ρ	1.93415 ± 0.0011 (slugs/ft ³)
Displaced Volume, $\nabla = \Delta / \rho * g$	13.7887 ± 0.0092 (ft ³)
Static Trim Angle from Baseline*, (θ (+bow up))	$0.119 \pm 0.020^\circ$
Longitudinal Center of Gravity, LCG (+FAP)	96.024 ± 0.082 (inch)
Vertical Center of Gravity, VCG (+ABL)	9.74 ± 0.38 (inch)
Longitudinal Center of Tow Point, LTP (+FAP)	97.381 ± 0.063 (inch)
Vertical Center of Tow Point, VTP (+ABL)	10.040 ± 0.063 (inch)
Pitch Mass Moment of Inertia, $I_{y,CG}$ (about CG)	$18,536 \pm 339$ (lbf-ft ²)
Pitch Radius of Gyration, $k_{y,CG}$ (about CG)	55.78 ± 0.51 (inch)
Length Between Perpendiculars, LBP	224.000 ± 0.036 (inch)
Length of the Waterline*, LWL	224.227 ± 0.040 (inch)
Length Overall, LOA	238.308 ± 0.036 (inch)
Beam Overall, BOA	35.044 ± 0.036 (inch)
Depth Overall, D	25.353 ± 0.036 (inch)
Maximum Waterline Beam*, BWL (near STA 14)	33.218 ± 0.040 (inch)
* Indicates that value was determined from hydrostatic analysis and not measured directly +FAP = positive values forward of the aft perpendicular +ABL = positive values above the baseline	

Table 2. As-Tested Model Hull Form Data from Hydrostatic Analysis.

Parameter	As-Tested Value
Longitudinal Center of Buoyancy, LCB (+FAP)	95.917 (inch)
Area of the Waterplane, A_{WP}	37.79 (ft ²)
Immersed Area of Midship Section, A_M	157.8 (inch ²)
Midship Waterline Beam, B_M	30.12 (inch)
Baseline Draft at Midship, T_M	7.321 (inch)
Hull Draft at Midship, T_M'	7.233 (inch)
Immersed Area of Maximum Section, A_x (at STA 12)	169.2 (inch ²)
Waterline Beam at Maximum Section, B_x (at STA 12)	31.12 (inch)
Hull Draft at Maximum Section, T_x	7.160 (inch)
Waterline Beam at Transom, B_T	27.21 (inch)
Hull Draft at Transom Section, T_T	3.302 (inch)
LCB/LWL (+FAP)	0.428
LCG/LWL (+FAP)	0.428
LWL/LBP	1.001
LWL/BWL	6.750
LWL/ B_x	7.206
LWL/ T_M	30.63
B_x/T_x	4.346
Slenderness Ratio, LWL^3/∇	7.792
Block Coefficient, $C_B=(\nabla/LWL*B_x*T_x)$	0.477
Prismatic Coefficient, $C_P=\nabla/A_x*LWL$	0.628
Midship Sectional Area Coefficient, $C_M=A_M/B_M*T_M$	0.716
Maximum Sectional Area Coefficient, $C_X=A_x/B_x*T_x$	0.759
Vertical Prismatic Coefficient, $C_{VP}=\nabla/T_x*A_{WP}$	0.612
Static Wetted Surface Area, S_o	46.14 (ft ²)
Wetted Surface Coefficient, $C_S=S_o/LWL*(2*T_x+B_x)$	0.6521
Slenderness Ratio, LWL^3/∇	7.792
+FAP = positive values forward of the aft perpendicular	
+ABL = positive values above the baseline	

Test Conditions

The *Athena* model was tested in calm water, regular waves, and irregular waves at a variety of speeds. The target test conditions are listed in Table 3. Ambient conditions during the test were nominally a 74°F basin water temperature, 80°F air temperature, and an 80% relative humidity. The calm water speeds were chosen to match resistance, sinkage, and trim curves from the previous model test in 2014 [1]. Additional calm-water speeds were added to increase the resolution of the predicted resistance, sinkage, and trim curves, along with a planing speed at the upper end of the range. The regular and irregular wave conditions were chosen to span a range of wave heights, periods, and steepness using inputs from the CFD community comparing to this experimental data.

Table 3. Athena Model Test Conditions.

Speed (kts)	Fn	Wave Type	Wave Height, H _s (inch)	Wave Period, T _p
2.0	0.14	Calm		
3.1	0.22	Calm		
3.7	0.25	Calm		
4.2	0.29	Calm		
6.3	0.43	Calm		
7.7	0.53	Calm		
9.0	0.62	Calm		
12.2	0.84	Calm		
14.5	1.00	Calm		
3.7 6.3 9.0	0.25 0.43 0.62	Regular	2.97	2.30
3.7 6.3 9.0	0.25 0.43 0.62	Regular	6.36	2.30
3.7 6.3 9.0	0.25 0.43 0.62	Regular	6.36	2.70
3.7 6.3 9.0	0.25 0.43 0.62	Regular	6.36	1.91
3.7 6.3 9.0	0.25 0.43 0.62	Irregular	4.2	2.61
3.7 6.3 9.0	0.25 0.43 0.62	Irregular	9.0	3.06

MEASUREMENT METHODS

Visualization

Standard frame rate (30 fps) digital video cameras were used to record the motion of the free surface and flow separations from multiple views. The standard views included a starboard profile view, a starboard stern quartering view, and a bow view. Video was digitized and archived during testing. Underwater video was collected during calm water test runs to characterize the wetted surface area. The underwater camera location had a limited perspective of the bow spray sheet and the waterline elevation along the mid body. This limited perspective did not permit a quantitative estimate of the wetted surface along the painted checkerboard grid. The above water profile view does show the wetted waterline along the painted checkerboard grid, but the spray sheet obscures a portion of the wetted waterline and prevents a quantitative evaluation of the wetted surface area.

Forces and Moments

The 6-DOF force and moment measurements were acquired through two separate dynamometers mounted on the model. The main dynamometer was attached to the model above the tow point and measured the forces and moments in an Earth fixed orientation during testing. There was an additional dynamometer mounted at the model's stern and connected to a grasshopper fixture. The grasshopper fixture is a balanced flexible arm which is designed to apply minimal vertical forces and is used to restrict yaw motions of the model. Because this additional fixture can absorb some of the drag forces, the dynamometer measures forces exerted on the fixture to determine the total drag on the model. Since the dynamometer is installed below the grasshopper fixture, the forces exerted on the fixture are measured in the body fixed orientation. These body fixed forces are transformed to an Earth fixed orientation before being used to calculate the total drag on the model. The dynamometers were manufactured at NSWCCD using four 3-axis Kistler force sensors (Type 9602A3211). Four sensors are used in each 6-DOF system to increase accuracy, effective range, and durability during testing. These sensors have an effective range of approximately ± 500 pounds in the x and y direction, and ± 900 pounds in z at 100% full scale, but can be switched to operate at 10% of full scale (± 50 pounds in the x and y, and ± 90 pounds in z). At full scale, the resolution is 0.45 pounds for x and y, and 0.41 pounds in z. The standard error for both scales is $\pm 5\%$. Conversion between voltage and force measurements was performed via a matrix calibration to remove crosstalk between the sensors. The calibration was conducted using a custom 6 DOF calibration rig fabricated at NSWCCD. A more detailed description of the dynamometers and calibration is included in Appendix A.

Motions

A Kearfott KN-5050 inertial measurement unit (IMU) was used to measure the 3-DOF angular positions and angular rates. This IMU consists of a ring laser gyro and employs GPS position aiding when GPS signals were available. The position aiding feature was not used for

this test effort since GPS position signals were not available indoors. This IMU provided a kinematic state estimate using an onboard Kalman filter algorithm that outputs digital sentences at a data rate of 50 Sps.

The IMU was rigidly mounted to a platform (Figure 4) and provided measurements of the model's pitch, pitch rate, heave, heave rate and longitudinal and vertical acceleration. Angular offsets between the as-installed IMU and the model baseline were measured using a handheld inclinometer (Pro360) and compared with the trim and heel angle results at hydrostatic equilibrium. The as-installed trim offset measured using handheld inclinometer was 0.3 degrees down by the bow. The IMU average trim angle for all the static floating runs 0.389 degrees down by the bow. These two offset measurements were consistent with the offset trend when comparing to the trim angle calculated from the string potentiometers.

The Kearfott inertial measurement unit provided kinematic data as a RS-422 serial stream. The RS-422 protocol was converted to a RS-232 protocol and then passed through a Lantronix UDS 2100 serial to Ethernet converter. The Lantronix UDS 2100 converter was connected to the network switch and collected directly by the data acquisition computer. The IMU bias uncertainty for heading was $\pm 0.84^\circ$ and the roll/pitch accuracy bias uncertainty was $\pm 0.056^\circ$ at a 95% confidence level. The IMU outputs data at 50 Sps.



Figure 4. As-installed IMU.

Sinkage and Trim

Two string potentiometers (string pots) were used to measure vertical displacement of the model at the bow and the stern. The string potentiometers used were UniMeasure model PA-50-004, which had a 50-inch range and a maximum error of ± 0.125 -inch. These potentiometer measurements provided tow post sinkage (heave) and running trim (pitch) angle via trigonometry calculations using the known locations of string connections relative to the tow post gimbal. This calculated tow post sinkage and running trim are reported as the changes from the floating static condition, which does not include the initial tow post position below the waterline nor the hydrostatic trim angle. The string potentiometers were attached using eye screws that were mounted as far apart as possible to increase the accuracy of the trigonometry calculations for tow post sinkage and trim. The aft string potentiometer was mounted on the transom, or 0.0 inches forward of the aft perpendicular. The forward string potentiometer was mounted 237.46 inches forward of the aft perpendicular. The calculated running trim angle from the string potentiometer was found to have a lower total uncertainty than the IMU pitch measurements, and was considered the best value for reporting running trim angle in calm water.

The output voltage from the string potentiometers were converted to inches of displacement with positive values for retracting string displacement (upward heave). The potentiometer analog voltage signals were zeroed prior to each test run while the model was floating statically to control for the uncertainty typically present in this type of sensor (signal drift). Zeroing the analog voltage provided hull vertical displacement measurements relative to the static waterline. These measurements were collected as analog signals at a sampling rate of 25,000 Sps with a 20 Hz oscillation limit for the mechanical tensioner.

Impact Pressure

Eighteen pressure sensors were mounted on the bottom of the model hull during testing, including fifteen Nova Sensor NPI-19 series low pressure sensors (m/n NPI-19A-015AV) and three Entran EPX series miniature pressure transducers (m/n EPX-V02-50P-Z2). The NPI-19 series pressure sensors had a reference pressure area with a 0.680 inch diameter. The EPX series pressure sensors had a reference pressure area with a 0.150 inch diameter. Pressure data was collected at 6,250 Sps for calm water runs and 25,000 Sps during each wave run. These sensors were used to measure single point slamming pressures during the in-wave model tests. The pressure sensor locations and sensor number are shown in Figure 5. Table 4 lists the pressure sensor x, y, and z locations. A three by three array of NPI-19 sensors with one inch spacing were mounted just aft of the highest pressure location determined from previous CFD simulations. Three sets of three pressure sensors, oriented in a vertical line, (two NPI-19 and one EPX) were mounted fore and aft of the nine sensor array to both increase the area of recorded pressure data and to serve as a benchmarking test to determine the most effective pressure sensor type and sealant for this testing.

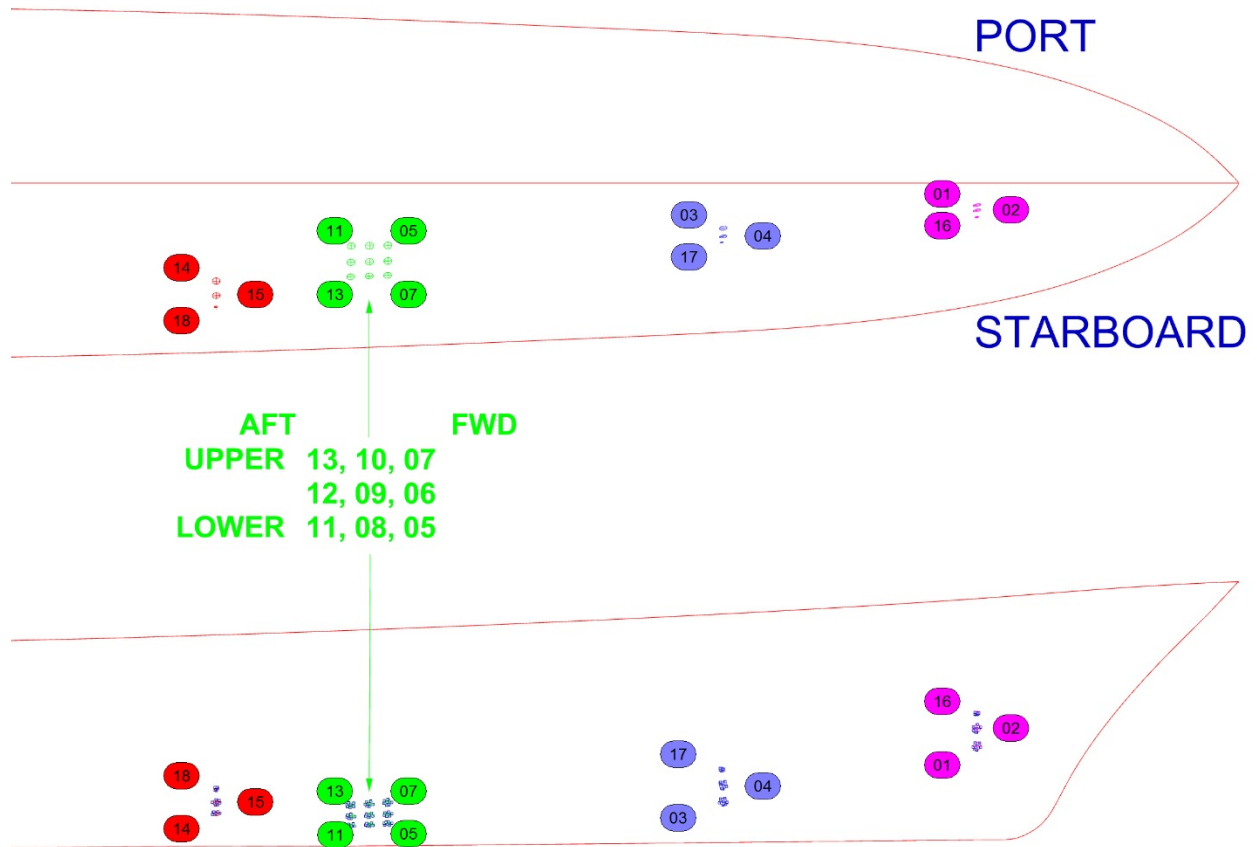


Figure 5. Pressure gauge locations and sensor number on *Athena* model 5365.

Table 4. Pressure gage locations.

No.	Pressure Sensor Make and Model	S/N	Sensor Diameter (inch)	Pressure Sensor Center Coordinates As-Scanned		
				x (inch +FAP)	y (inch +PCL)	z (inch +ABL)
1	Nova Sensor NPI-19A-015AV	S/N 75	0.150	215.269	-2.060	9.822
2	Nova Sensor NPI-19A-015AV	S/N 86	0.680	215.256	-2.581	11.490
3	Nova Sensor NPI-19A-015AV	S/N 76	0.680	191.255	-4.299	4.551
4	Nova Sensor NPI-19A-015AV	S/N 79	0.150	191.251	-5.056	6.133
5	Nova Sensor NPI-19A-015AV	S/N 71	0.680	159.517	-5.915	2.438
6	Nova Sensor NPI-19A-015AV	S/N 90	0.680	159.523	-7.395	3.342
7	Nova Sensor NPI-19A-015AV	S/N 78	0.680	159.502	-8.775	4.442
8	Nova Sensor NPI-19A-015AV	S/N 88	0.680	157.783	-5.949	2.361
9	Nova Sensor NPI-19A-015AV	S/N 74	0.680	157.777	-7.459	3.243
10	Nova Sensor NPI-19A-015AV	S/N 81	0.680	157.756	-8.812	4.347
11	Nova Sensor NPI-19A-015AV	S/N 72	0.680	156.049	-5.971	2.286
12	Nova Sensor NPI-19A-015AV	S/N 85	0.680	156.019	-7.520	3.151
13	Nova Sensor NPI-19A-015AV	S/N 80	0.680	156.000	-8.895	4.217
14	Nova Sensor NPI-19A-015AV	Inactive	0.680	143.264	-9.263	3.415
15	Nova Sensor NPI-19A-015AV	S/N 84	0.680	143.267	-10.629	4.499
16	Entran EPX-V02-50P-Z2	Inactive	0.150	215.252	-3.189	12.965
17	Entran EPX-V02-50P-Z2	Inactive	0.680	191.130	-5.565	7.654
18	Entran EPX-V02-50P-Z2	Inactive	0.680	143.241	-11.678	5.790

Accelerometers

Three accelerometers were utilized during the *Athena* model testing, one vertical accelerometer was located near the bow, one tri-axial accelerometer at the tow post (near the LCG), and one vertical accelerometer further aft; specific locations are listed in Table 5. The accelerations used were Silicon Designs model 2260-025g MEMS type accelerometers. These accelerometers have a nominal frequency response of DC to 1,000 Hz and a nominal sensitivity of 160 mV/g. The accelerometers were mounted to give positive values upward in the body fixed orientation. The Earth fixed gravity vector was removed by subtracting the mean value from the raw accelerometer signals.

Table 5. Accelerometer locations.

Location	Sensor Coordinates			Installed Trim Angle (degrees +leading edge up)
	x (inch +FAP)	y (inch +PCL)	z (inch +ABL)	
Forward	203.98	0.00	1.72	0.1
LCG	97.38	-8.00	7.01	0.4
Aft	11.20	0.00	4.56	0.5

Wave Elevations

Senix ToughSonic 30 ultrasonic wave elevation sensors (model TSPC-15S-232) were used to measure the as-encountered wave surface characteristics from carriage mounted sensors, and the stationary wave characteristics from a basin mounted wave boom. The stationary wave boom (truss section) was cantilevered from the basin wall over the water and provided the stationary structure for mounting a wave elevation sensor. The wave boom extended 22.4 ft from the basin wall and contained three ultrasonic sensors. Three additional ultrasonic sensors were mounted on the carriage forward (on centerline), port, and starboard of the model centerline; locations are shown in Table 6. These sensors carriage mounted wave elevation sensor provided near field wave data as encountered. The wave elevation sensor output data at 10 Sps.

Table 6. Carriage mounted locations for wave elevation probes.

Location	Wave Probe Coordinates	
	x (inch +FAP)	y (inch +PCL)
Center	258.0	0.0
Starboard	279.6	9.0
Port	279.6	-9.0

Carriage Speed

Carriage 2 is equipped with a wheel encoder that has been calibrated to output carriage speed. This carriage speed signal was collected by the data acquisition system and time synced with the other data channels. Carriage speed uncertainty estimates were taken from the calibration documentation available onboard the carriage.

Data Collection

The data acquisition system (DAS) consisted of two National Instruments (NI) 9188 cDAQ chassis configured to collect analog and digital signals. The two NI 9188 cDAQ chassis were hardware synced using NI 9469 modules. The data from the sensors were collected and stored on a standalone computer connected to the cDAQ chassis via an 8 port 1 Gigabyte network switch. Most DAS channels for this test were collected as analog signals that were conditioned and sampled via NI modules (model No. 9239) that simultaneously sample four-channels at 24-bit delta-sigma analog-to-digital conversion (ADC) resolution. These NI 9239 modules employ a combination of analog and digital filtering to reject out-of-band signals and provide for anti-aliasing. NI 9239 modules prevent signal aliasing with a hardware low-pass pre-filter along with an on-module digital filter that was automatically configured based on the digital sampling rate. Analog signals were collected at a sampling rate (f_s) of 6,250 samples per second (Sps) giving an effective acquired signal bandwidth of approximately 0 to 3,125 Hz. This

signal bandwidth may be further reduced depending on the response characteristics of a particular sensor.

A data acquisition program (titled DAQ 5.0) developed at NSWCCD using LabVIEW 2014 was used to control the data acquisition chassis, modules, signal zeroing, signal conversion to engineering values, and the data collection. An example display of this program interface is shown in Figure 6. All the analog and digital channels were hardware synced in time using the master time base clock on the cDAQ chassis. The data acquisition program collected two sets of data. A raw voltage data set was collected during the entire run (PASS file). Simultaneously, an engineering value data set (with zeroing and calibration factors applied) was collected during steady state sections of the run which were selected by the operator (SPOT file).

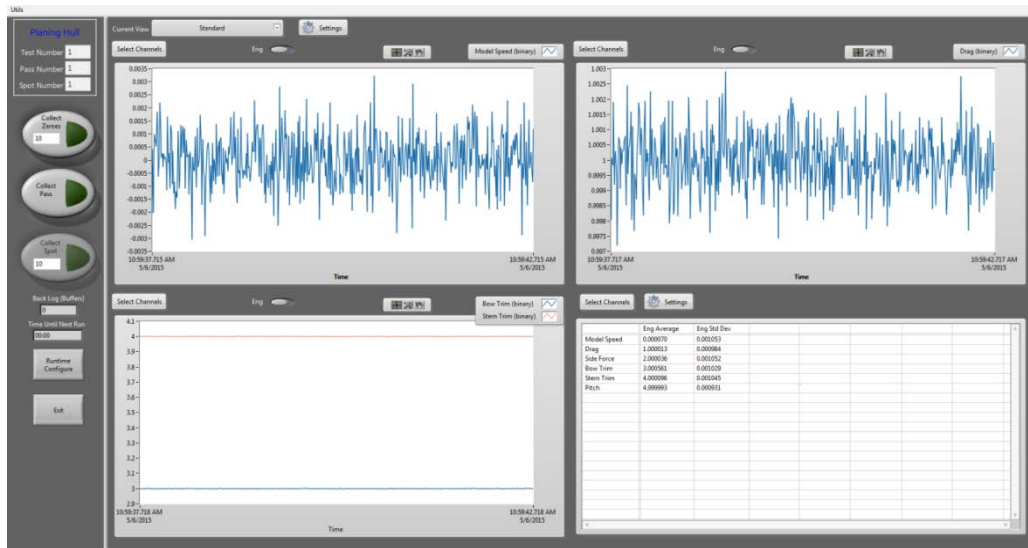


Figure 6. A screenshot of the LabVIEW data acquisition program

Test Procedures

The wave runs began with the model in a floating, zero speed condition. A ZERO data file was collected in this floating static condition before imitating a set of wave conditions from the wave maker. After the waves reached the model and stabilized at the target wave conditions, the test engineer would then start a PASS file data collection. This was then followed by the carriage operator manually accelerated the carriage to the target steady speed. The carriage operator signaled the test engineer when the target steady speed was achieved. The test engineer then initiated a SPOT file data collection. As the carriage approached the basin safety stops, the operator signaled to the test engineer before manually decelerating the carriage to a stop at the end of the basin. The basin waves had an approximate settling time of 60 minutes between runs with the longitudinal wave dampers secured out of the water.

ANALYSIS

The data collected during the *Athena* model testing in regular and irregular waves went through various initial processing steps before identifying peak values (explained in more detail in the following descriptions). The data sets included water level measurements, heave, pitch, pressure, and acceleration. Figure 7 is a profile view of the *Athena* model during a calm water run. Figure 8 shows two profile views of the *Athena* model during a run in regular waves, before and during an impact.

Figure 9 shows an example time series of the water level measurement from the center Senix ultrasonic sensor, with the blue line showing the original signal and the red line showing the filtered signal. Due to some issues with the sensor and data acquisition system, the data contains spikes at a rate close to the instrument sample rate. The data was first filtered to remove the spikes (using a median filter) and then resampled at 10 Hz, which was the sample rate of the instrument. After filtering, peaks and troughs were identified using a relative extrema algorithm. Figure 9 shows an example filtered time series from Spot #173 (wave amplitude ($H/2$) of 3.3 in, wave period (T) = 2.3s, model speed (U) = 9 knots) with the wave peaks (red stars) and wave troughs (blue stars) identified.

An initial analysis was performed to find the pressure gages of interest using Spot #176 ($H/2=3.3$ in, $T=2.3$ s, $U=9$ knots), as it was a spot within the condition with the largest observed motions. Figure 10 shows the results of this initial analysis, where the blue line shows the average and standard deviations of all pressure gages, while the black dashed lines show the maximum and minimum values. This plot shows that the largest pressures were recorded on gage 5, which is located 80 inches aft of the bow. Gage 2 was chosen to include a sensor close to the bow, where slams are typically expected. The pressure time series (at 25000 Hz) were not filtered before determining peaks.

Acceleration peaks were determined for the accelerometer near the bow and the accelerometer near the LCG, because it was expected that these locations would experience the largest accelerations. Accelerations were filtered using a low pass Butterworth 6th order filter, with a cutoff of 100 Hz and were not corrected for ship pitch or installed trim angle (accelerometers were installed as close as parallel to baseline as possible). Drag, heave and pitch were decimated to 1000 Hz (from a recorded frequency of 25000 Hz) before the peaks were identified. Pressure peaks from gage 2 and gage 5 were also identified. Example time series of all variables are shown in Figure 11.

All regular wave runs were analyzed in this manner; these results are presented and discussed in the following section. The larger irregular wave condition (target significant wave height of 9 inches, peak period of 3 s) at all three speeds, along with the smaller irregular wave condition (target significant wave height of 4.2 inches, peak period of 2.6 s) at the lowest speed were also analyzed in this manner; again, these results are presented and discussed in the following section.

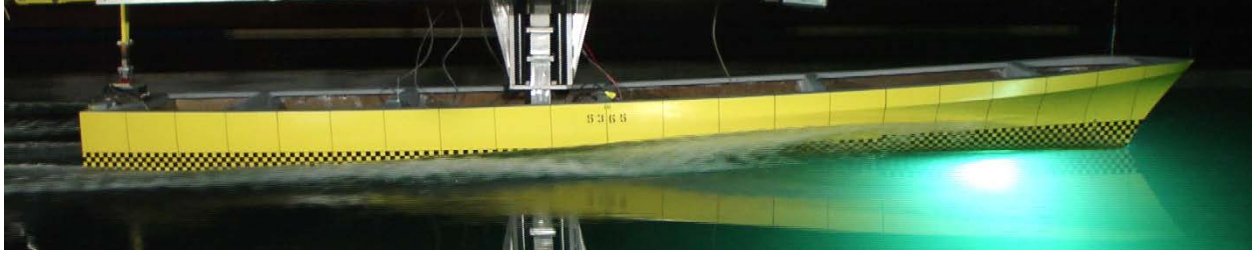


Figure 7. *Athena* in Calm-Water at 14.5 knots.

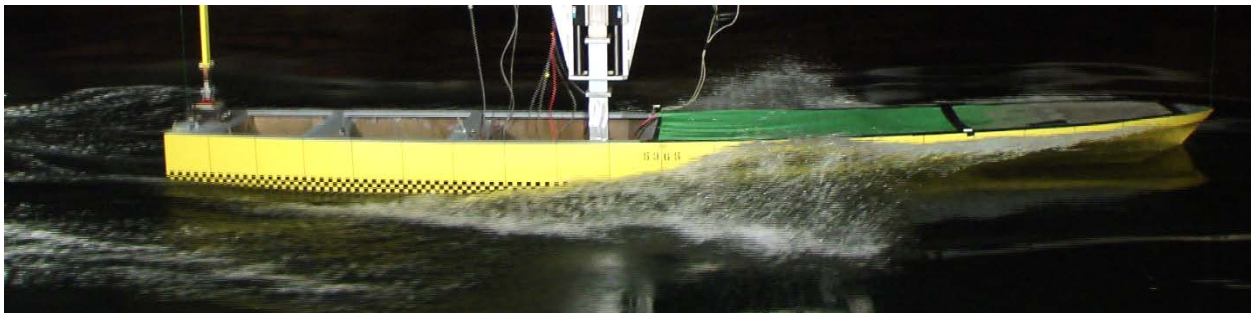


Figure 8. Example image of *Athena* in waves ($H/2=3$ in, $T=2.3s$) at 9 knots.

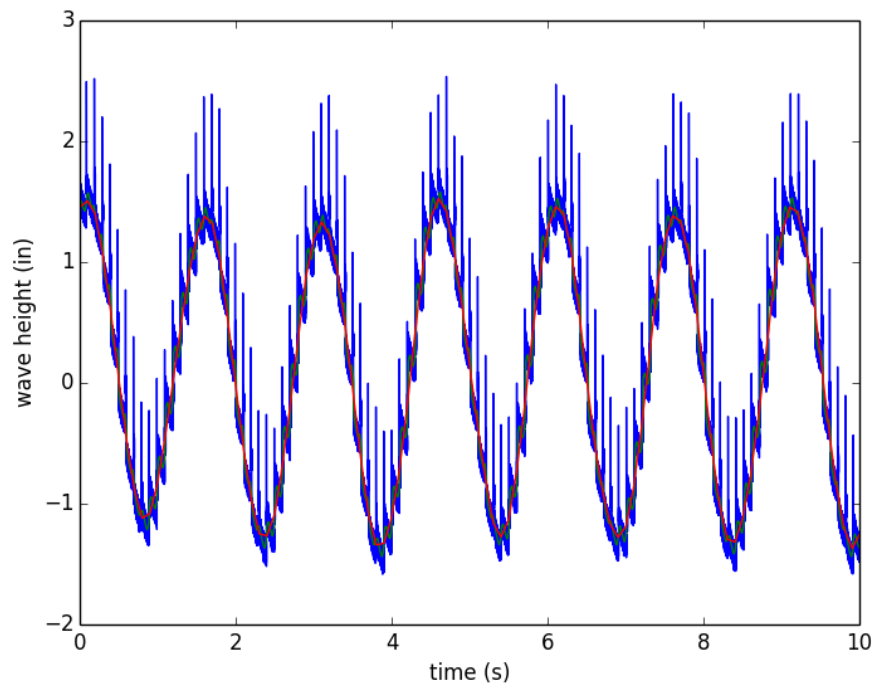


Figure 9. Regular wave filtering example. Raw data is in blue, filtered data is in red.

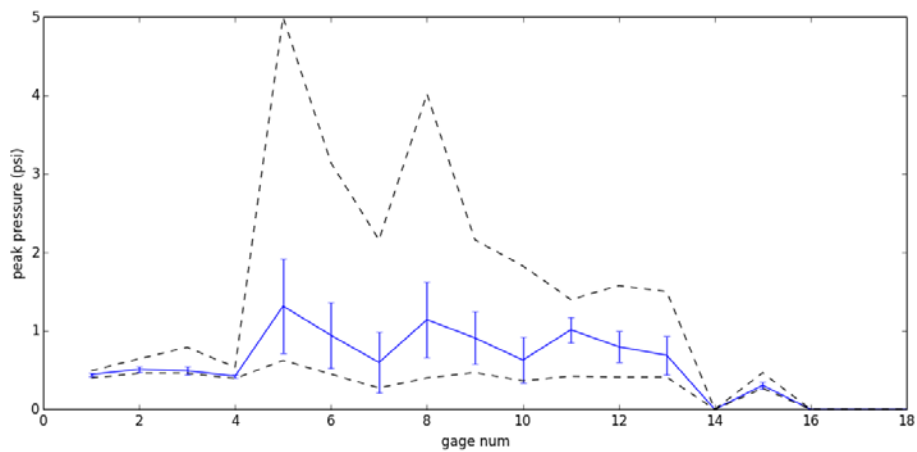


Figure 10. Average and standard deviation of peaks from Spot 176 ($H/2=3.3\text{in}$, $T=2.3\text{s}$) for all pressure gages (in blue). Dashed lines are maximum and minimum.

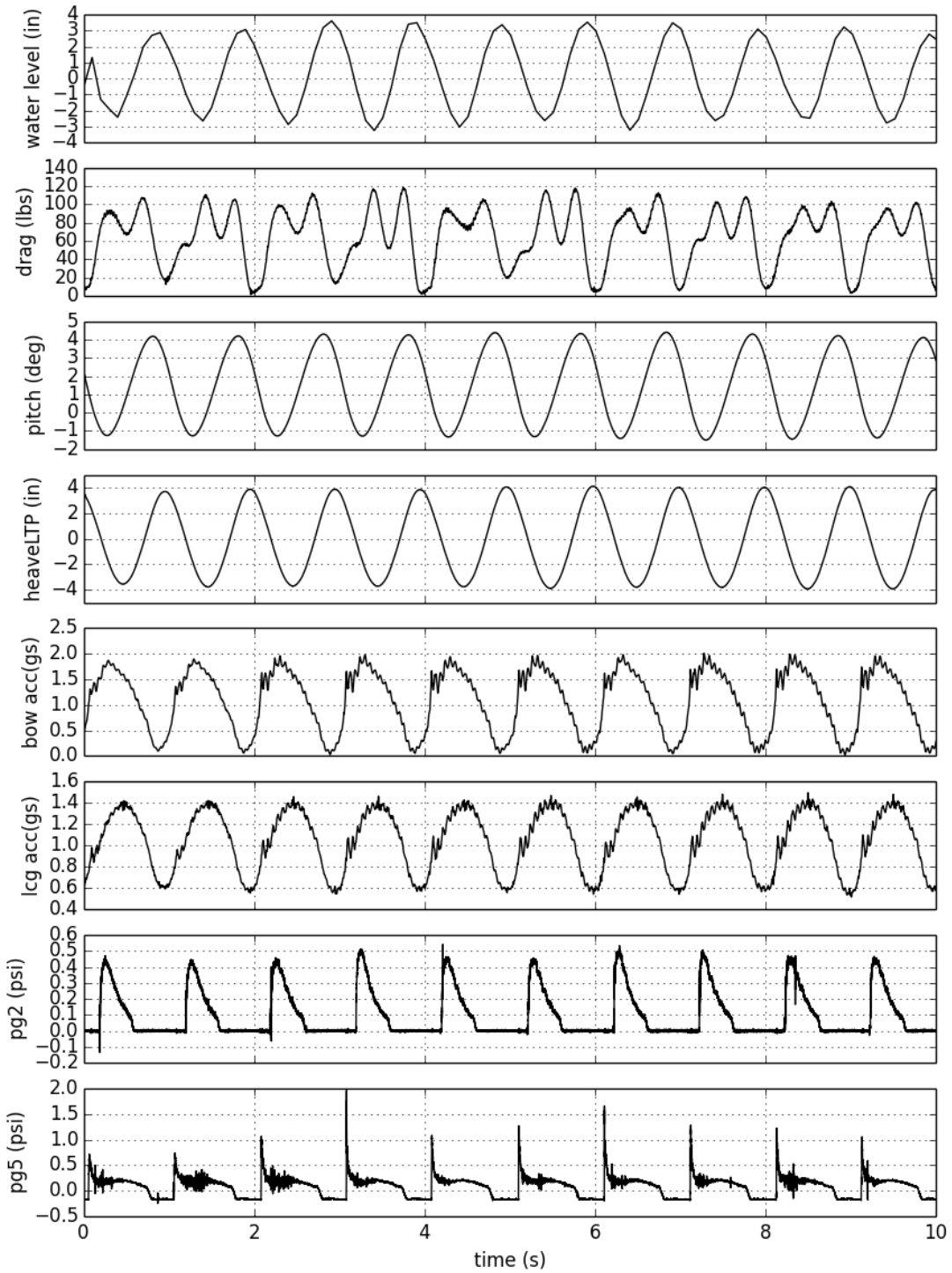


Figure 11. Example time series of wave height, drag, pitch, heave, vertical acceleration (at bow and LCG), and pressure (at gage 2 and gage 5) from Spot 179 ($H/2=3$ in, $T=2.3$ s, $U=9$ knots).

RESULTS AND DISCUSSION

Uncertainty Analysis Estimates

The experimental values (D) were averaged across the test runs for each test condition. Total uncertainty (U) values were derived from the experimental precision uncertainty (P) and the estimated bias uncertainty (B) following the Coleman and Steele approach with the degrees of freedom (DoF) (ν) as described in reference [3]. The degrees of freedom used in this approach is taken as one less than the number of independent test runs (i.e. $\nu = N_{runs} - 1$).

The uncertainties were estimated at a 95% confidence level, giving a 95% probability that the true mean value lies within the reported confidence interval (i.e. $\mu_{true} = (D - U, D + U)$).

The precision (or random) uncertainty quantifies the repeatability of the measurement. Precision uncertainties were calculated using the end-to-end method described [3]. The bias uncertainty is the fixed component of the total uncertainty and is also referred to as systematic uncertainty. The total uncertainty was the root sum square of the bias and precision uncertainties. Ideally, both the bias and precision uncertainty should contribute equally to the total uncertainty and the total uncertainty value should be small compared to the measured value.

Mass Properties

The model mass properties were measured using the process described in Appendix B. Table 7 shows the values and uncertainties for model mass properties relevant to performance in calm water and waves. Uncertainties were calculated via the methods prescribed in Coleman and Steele [3]; a detailed description of the uncertainty calculations is available in the calm water test report [2].

Table 7. Uncertainty in as-tested mass properties.

Description	As-Tested Value, D	Total Uncertainty, U	U as % D
Displacement, Δ (lbf)	858.00	0.30	0.035%
LCG (inch +FAP)	96.024	0.082	0.085%
VCG (inch +ABL)	9.74	0.38	3.9%
Pitch Mass Moment of Inertia, $I_{y,CG}$ (lbf-ft ² about CG)	18,536	339	1.8%
Pitch Radius of Gyration, $k_{y,CG}$ (inch about CG)	55.78	0.51	0.91%

Regular waves

Table 8 shows the results from the wave analysis for the regular wave conditions, including the mean and standard deviations (σ) of the peaks and troughs, the period (T), the encounter period (T_E), and the number of peaks. The standard deviations are shown both as a value and a percentage of the mean. Figure 12 shows a plot of the means and standard deviations of the wave peaks. For most of the conditions, the standard deviations are less than about 10%.

However, for the group of waves with $T=1.9s$, the standard deviations are much larger. There is a significant amount of variation in these wave time series (an example is shown in Figure 13), likely due to an issue with the wavemaker. Figure 14 shows a histogram of the wave peaks, which further illustrates the variation in waves. The measured wave height for the $T=2.8s$ regular wave was lower than the desired wave height. This is most likely due to the variability of the wavemaker blower power and degradation of the wave within the basin.

Figure 15 through Figure 21 show the average and standard deviation of the peaks identified for the various data sets described in the previous section, plotted against the encounter frequency in Hz. The legend shows the average wave conditions for each condition.

Figure 15 shows the heave peak trends. In general, the largest heave values are for the 3.3 inch, $T=2.3s$ wave amplitude (shown in red), with the largest heave at an encounter frequency of about 1 Hz. This frequency is close to the natural pitch frequency of the model (1 Hz). Figure 16 shows the trends for pitch peaks. Pitch appears to increase until it reaches an encounter frequency between 0.8 and 1.0, after which it starts decreasing.

Figure 17 shows the trends for resistance. In general, the largest resistance value was for the 3.8 inch, $T=2.8s$ wave amplitude at the highest encounter period. Overall, the resistance increased with encounter frequency.

Figure 18 and Figure 19 show the trends for the pressure peaks from gage 2 and gage 5. In general, the pressures from gage 5 are larger than for gage 2, as expected and explained in the previous section. Also, the pressures are largest for the same group of waves as cause the largest heave values (3.3 inch, $T=2.3s$ wave amplitude, shown in red), and the largest overall pressures occur at an encounter frequency of 1 Hz, close to the natural pitch frequency of 1 Hz.

Figure 20 and Figure 21 show the trends for acceleration peaks at the bow and LCG. In general, the accelerations are larger at the bow than at LCG. Also, the 3.3 inch, $T=2.3s$ wave amplitude tend to cause the largest accelerations in general. As with the other variables, the largest acceleration values overall are at an encounter frequency of 1 Hz, close to the pitch natural frequency of the model (1 Hz).

Figure 22, Figure 23, and Figure 24 show the average drag, heave and pitch compared with the same measurements in calm water. In general, the wave measurements are larger than the calm water measurements, and demonstrate the same trends.

Irregular waves

A single “spot” (one run down the basin) of each irregular wave condition was analyzed in a similar manner to the regular wave runs. Table 9 shows the acceleration and pressure statistics resulting from this analysis, where “1/10” represents the average of the 1/10 highest values. The values include U (model speed), H_s (significant wave height, average of the 1/3 highest waves), T_{pe} (peak period of encounter spectrum), T_p (peak period of spectrum), T_{ze} (average period of encounter spectrum), T_z (average period of spectrum), BVA (bow vertical acceleration), LCGVA (vertical acceleration at LCG), PG2 (pressure gage 2), PG5 (pressure gage 5), and num PG2 peaks (number of peaks in spot for pressure gage 2). The acceleration and pressure locations selected for analysis were the locations which had the largest peak values. This table shows that in general, the acceleration and pressure peaks increase with speed and wave height/period. The accelerations at the bow tend to be larger than the accelerations measured at LCG, similar to the trends observed with regular waves. The pressures measured at

gage 5 tend to be larger than the pressures at gage 2, also similar to the trends observed with the regular waves.

Figure 25 shows a cumulative distribution of the acceleration peaks for the irregular wave conditions (same conditions as Table 9.) This plot also shows accelerations are larger at the bow than they are at the LCG. In addition, the accelerations are larger for higher speeds and larger waves. Figure 26 shows a cumulative distribution of the pressure peaks for the irregular wave conditions (again, same conditions as Table 9.) As shown in the table, the pressures are higher for gage 5 than for gage 2 especially at higher speeds. As with the accelerations, the pressures are larger for higher speeds and larger waves in general.

Table 8. Wave statistics.

U	mean peaks	σ peaks		mean troughs	σ troughs		T _E	T	# peaks
(kts)	(in)	(in)	%	(in)	(in)	%	(s)	(s)	
3.7	1.7	0.11	6%	-1.4	0.12	9%	1.5	2.3	273
6.2	1.7	0.11	7%	-1.3	0.12	9%	1.2	2.3	211
9.0	1.8	0.17	9%	-1.3	0.19	14%	1.0	2.3	322
3.8	4.1	0.55	13%	-3.0	0.65	22%	1.2	1.9	393
6.2	3.9	0.51	13%	-2.8	0.61	21%	0.9	1.9	388
9.0	3.9	0.49	12%	-2.9	0.57	20%	0.7	1.9	445
3.7	3.7	0.23	6%	-3.2	0.26	8%	1.5	2.3	294
6.2	3.7	0.23	6%	-3.2	0.28	9%	1.2	2.3	145
9.0	3.9	0.27	7%	-3.2	0.29	9%	1.0	2.3	319
3.7	3.4	0.23	7%	-3.1	0.21	7%	1.9	2.7	66
9.0	3.3	0.08	3%	-3.1	0.13	4%	1.3	2.7	43

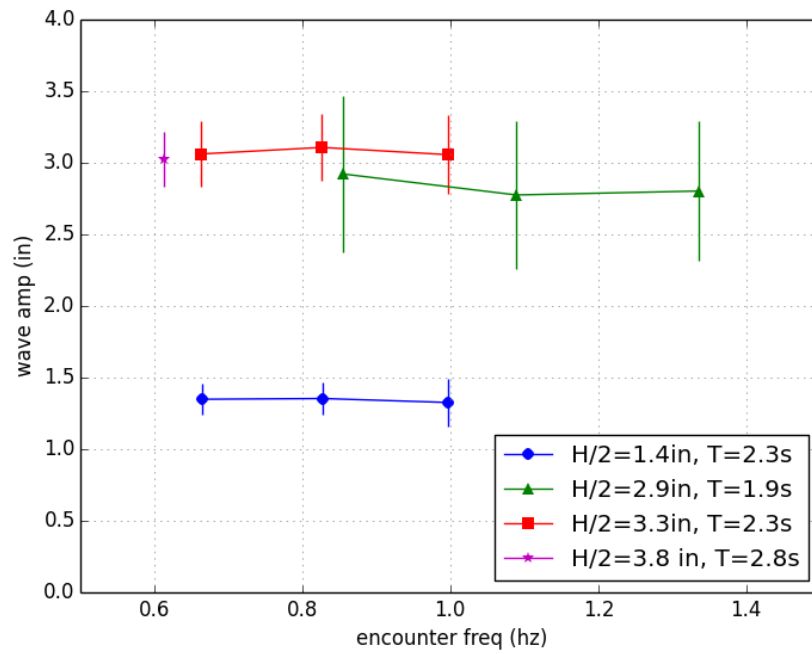


Figure 12. Average and standard deviation of wave peaks.

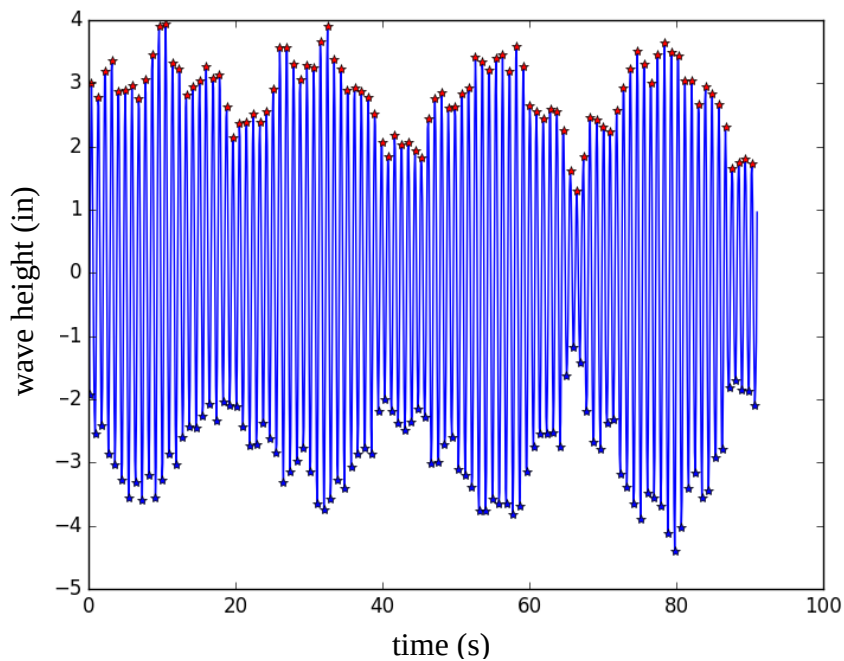


Figure 13. Wave time series from 1.9s wave.

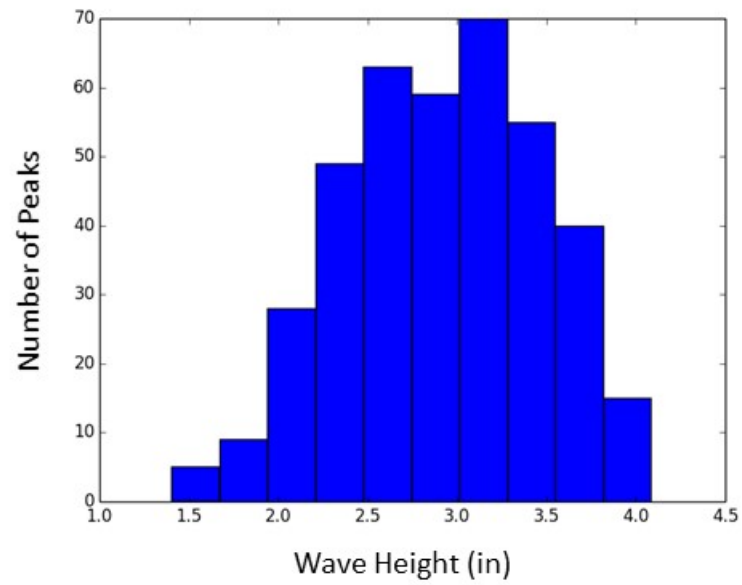


Figure 14. Wave height histogram from 1.9s wave.

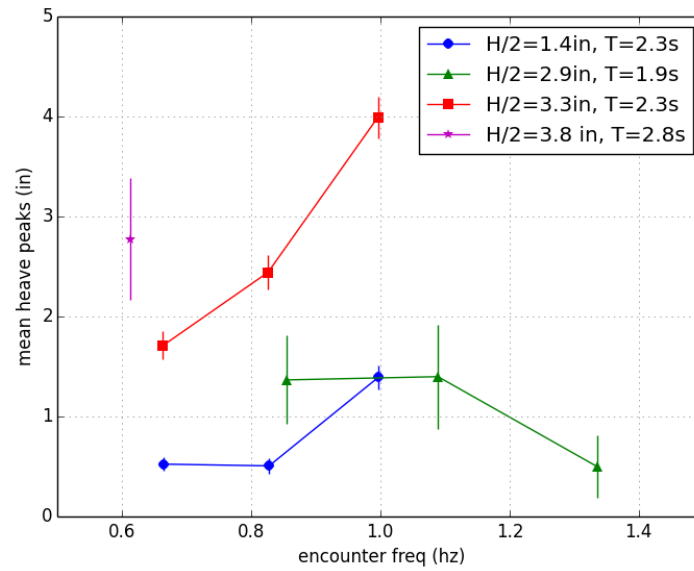


Figure 15. Average and standard deviation of peaks from heave time series.

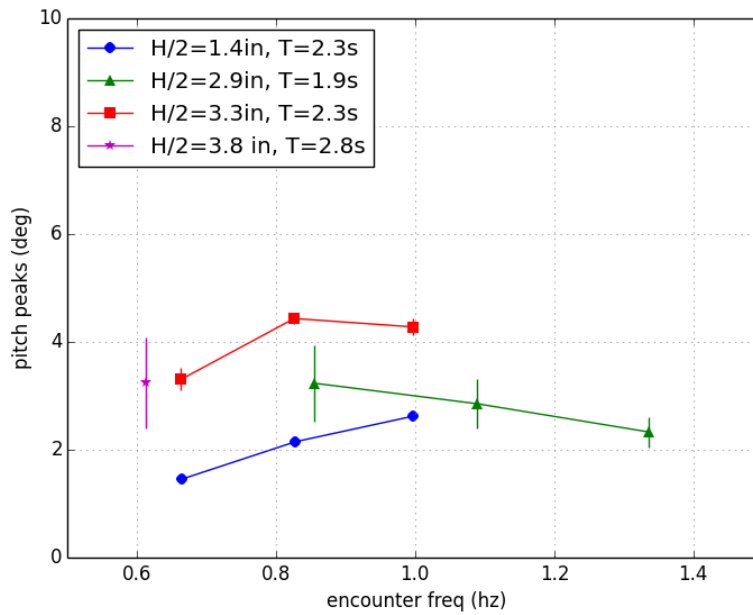


Figure 16. Average and standard deviation of peaks from pitch time series.

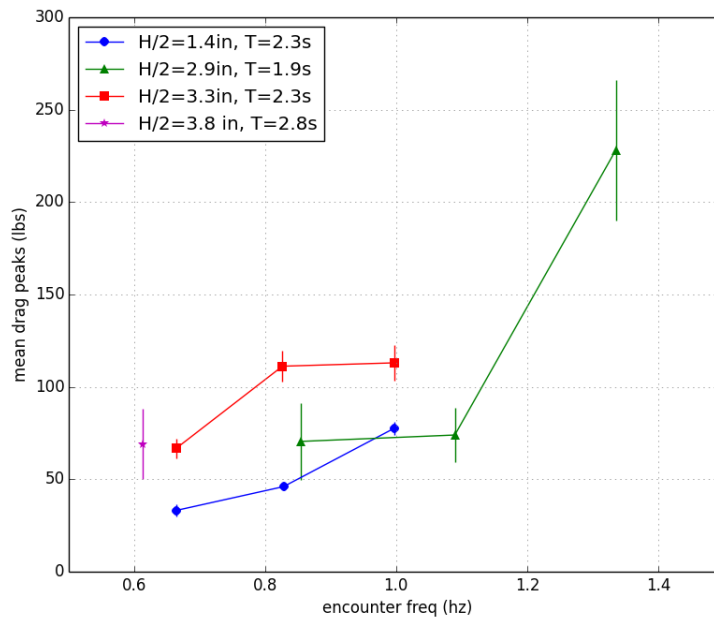


Figure 17. Average and standard deviation of peaks from drag time series.

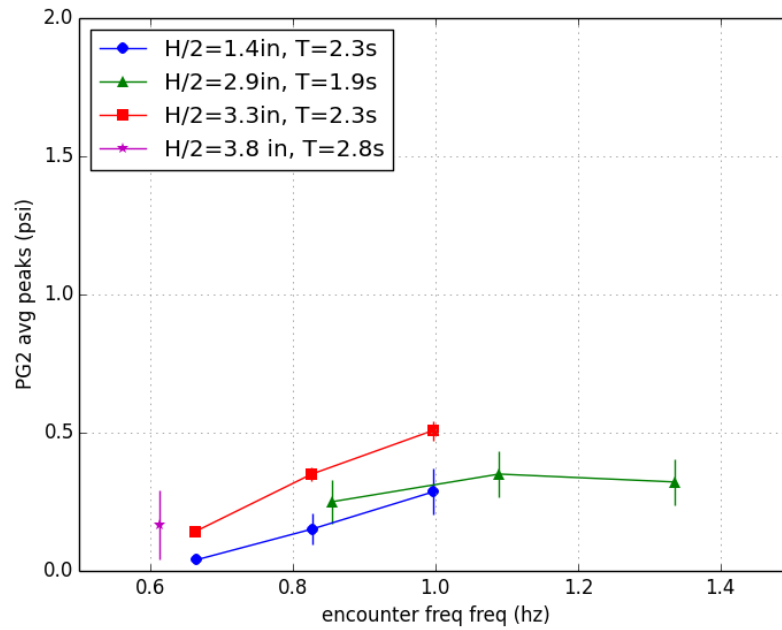


Figure 18. Average and standard deviation of peaks from pressure gage 2.

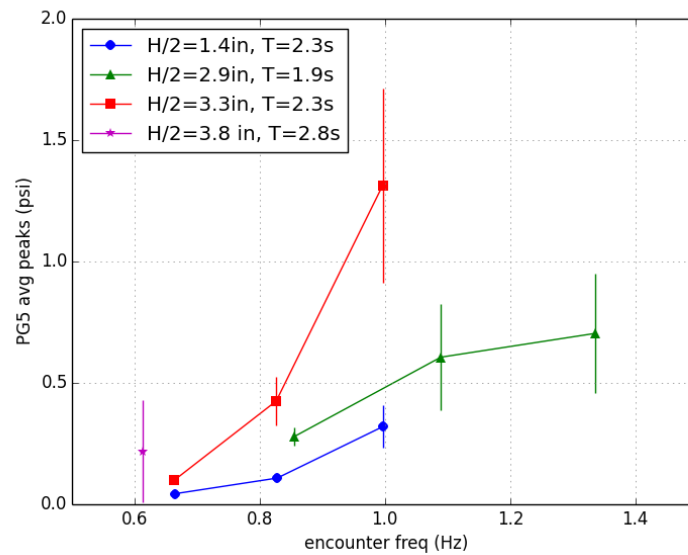


Figure 19. Average and standard deviation of peaks from pressure gage 5.

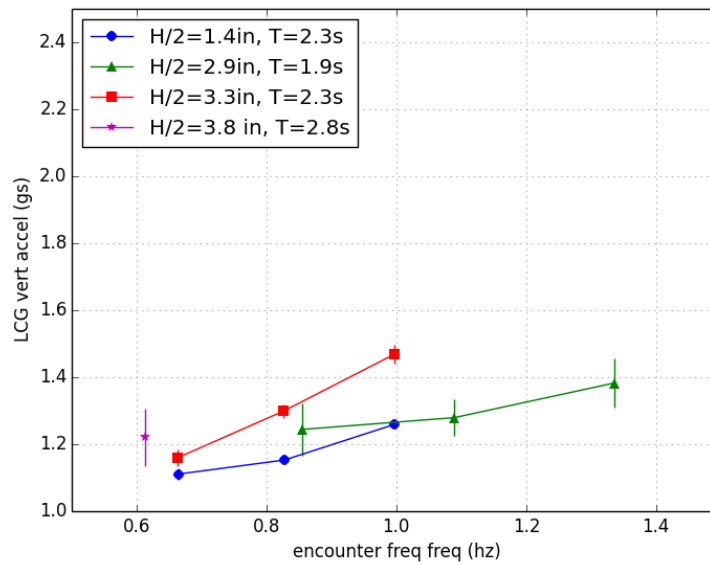


Figure 20. Average and standard deviation of peaks from accelerometer located at LCG.

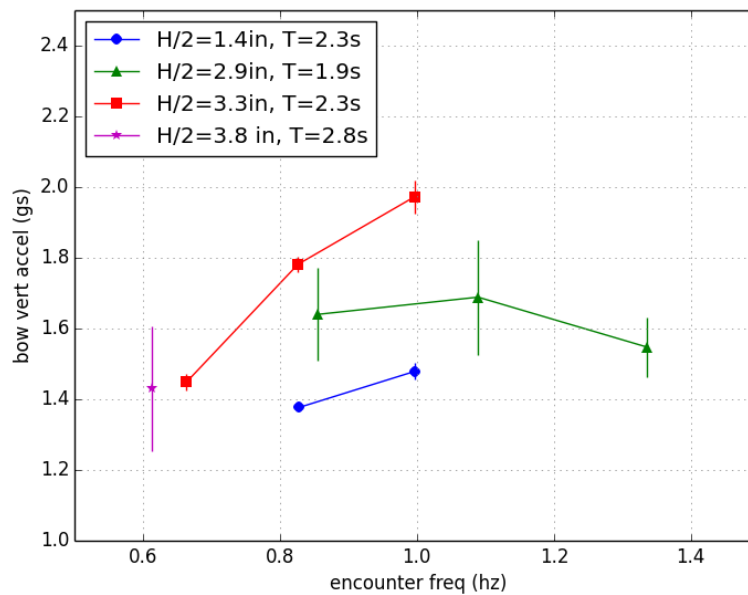


Figure 21. Average and standard deviation of peaks from accelerometer located at the bow.

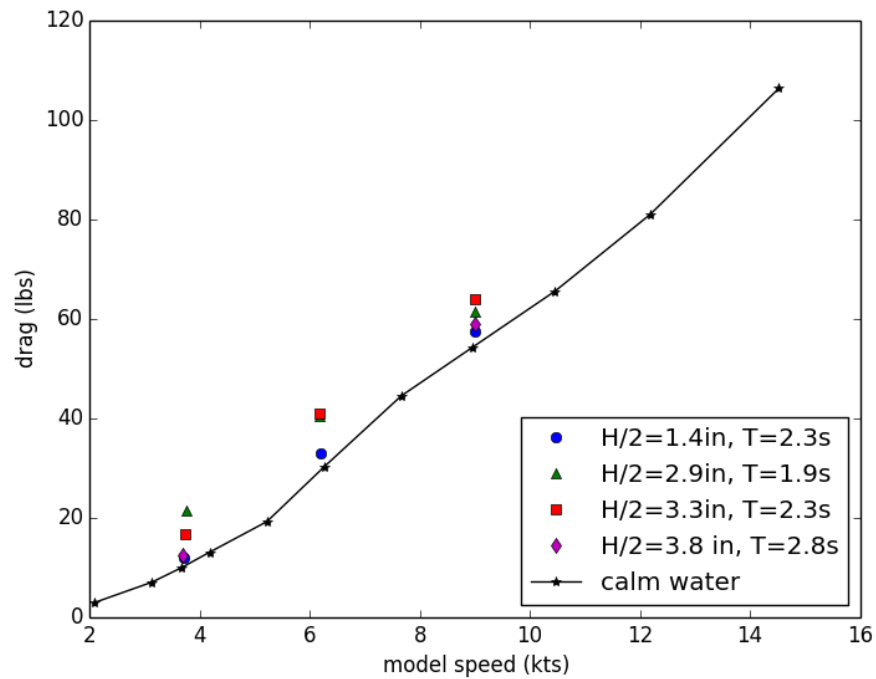


Figure 22. Average drag for waves (symbols) vs. calm water (line).

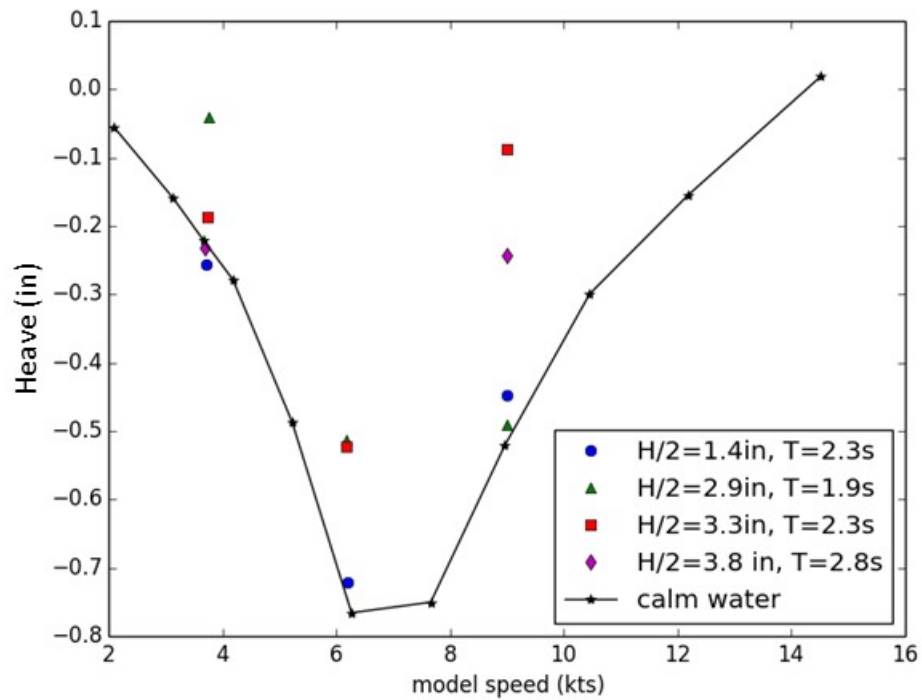


Figure 23. Average heave for waves (symbols) vs. calm water (line).

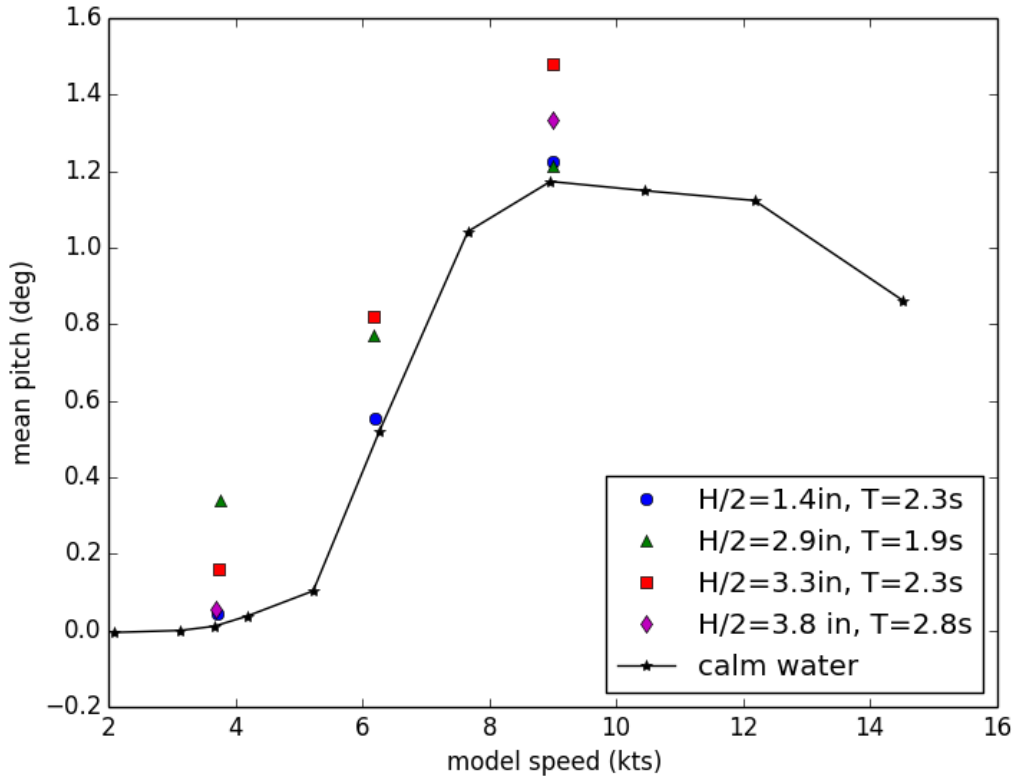


Figure 24. Average pitch for waves (symbols) vs. calm water (line).

Table 9. Results of irregular wave analysis.

spot	U (kts)	Hs (in)	Tpe (s)	Tp (s)	Tze (s)	Tz (s)	1/10 BVA (gs)	1/10 LCGVA (gs)	1/10 PG2 (psi)	1/10 PG5 (psi)	num PG2 peaks
241	9.00	2.9	1.2	2.5	0.7	1.9	1.5	1.3	0.4	0.4	59
260	3.76	7.4	2.1	3.0	1.3	2.1	1.6	1.2	0.2	0.3	149
263	6.19	6.3	2.1	3.4	1.0	2.0	1.8	1.4	0.4	0.6	77
289	9.00	8.6	2.0	3.6	0.6	1.7	1.9	1.5	0.5	1.2	51

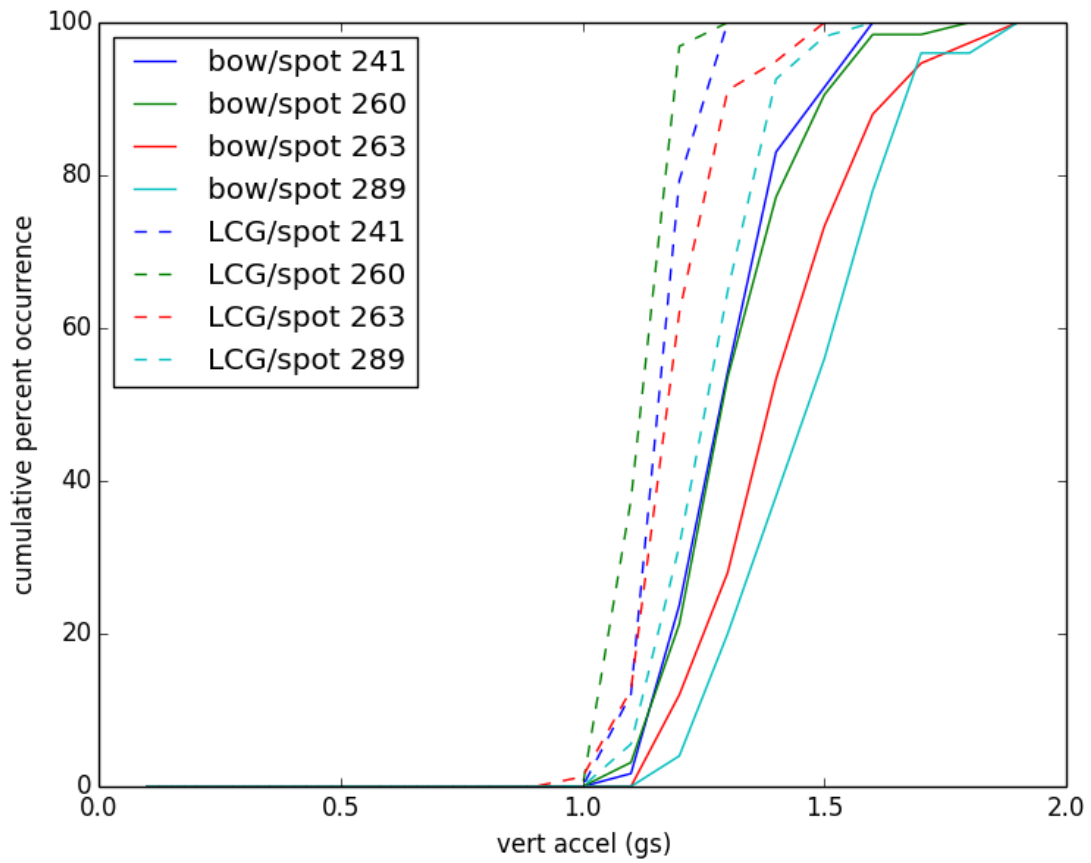


Figure 25. Cumulative distribution of vertical acceleration peaks.

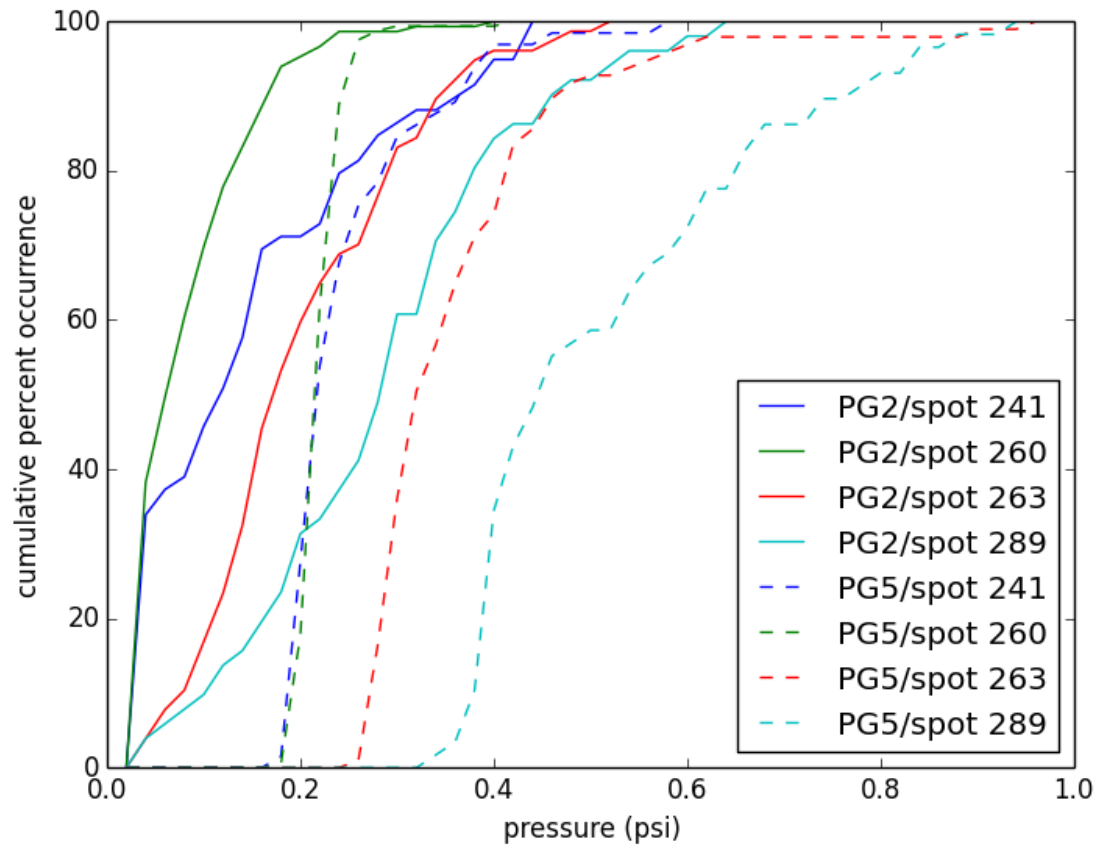


Figure 26. Cumulative distribution of pressure peaks.

CONCLUSIONS

During the 2015 *Athena* model test, data was collected with the model running in calm water, regular waves and irregular waves. The calm water was analyzed and compared with numerical predictions [2]. The data collected while testing regular and irregular waves have been decimated and filtered as necessary, with the peaks determined for individual wave encounters. In general for regular waves, the peak values were highest for the waves with amplitude of 3.3 inches, and a period of 2.3s. Of these larger values, the peak values tended to be highest for the wave-model speed combinations that resulted in an encounter frequency near the natural pitch frequency. For the irregular seas, pressures and accelerations tended to increase with increased wave height and speed. Future work will include comparisons of this data with computational predictions, as well as a more in-depth study of the trends and uncertainty estimates.

RECOMMENDATIONS

The methods for determining the location of the running waterline and determination of the dynamic wetted surface area could be improved if frictional and residuary components of resistance at full scale are an important test objective. Underwater photographs that are extracted from video need a significant amount of lighting (intensity and number of lights). There is a tradeoff between the ease of staging underwater fixtures directly on the basin bottom and the reduced lighting needs when staging is constructed at a lower depth. During this test, numerous lights were necessary to illuminate the underwater hull thru 20 feet of water. This only provided minimally acceptable hull illumination; limited the video and photograph resolution; and significantly loaded the electrical breaker panels supplying power to the underwater lights. This issue could be mitigated if available time and resources were available to better optimize the underwater staging; and using lower power, high intensity, LED lights suitable for underwater operation.

Additional above water cameras could be strategically placed on the carriage to observe the separation of the bow spray sheet from the hull surface. Several trial runs would be needed to identify the hull location to focus a camera and where a camera could be secured to the underside of the carriage.

SYMBOLS, ABBREVIATIONS, AND ACRONYMS

3-DOF	Three degrees-of-freedom
6-DOF	Six degrees-of-freedom
+ABL	Positive values above the baseline
B.....	Beam or Bias uncertainty
BVA	Bow Vertical Acceleration
BWL.....	Beam along the waterline
C _B	Block coefficient
CFD	Computational Fluid Dynamics
CL	Centerline
D.....	Depth or Reported Mean Value
DAS.....	Data Acquisition System
E	Error
+FAP	Positive values forward of the aft perpendicular
F_n	Length Froude Number, $F_n = \frac{U}{\sqrt{gLWL}}$
fps.....	Feet per Second
f _s	Data sampling rate
ft	foot/feet
fwd	Forward
F _x	Longitudinal resistance from a dynamometer
F _z	Vertical resistance from a dynamometer
g.....	Gravitational acceleration, g=32.174 ft/s ²
GPS	Global Positioning System
H _s , H _{1/3}	Significant wave height
Hz.....	Hertz or cycle per second
in	inch(es)
IMU	Inertial Measurement Unit
I _y	Pitch moment of inertia
k _y	Pitch gyradius
lbf	pound(s) force

LCB.....	Longitudinal Center of Buoyancy
LCG	Longitudinal Center of Gravity
LCGVA.....	Longitudinal Center of Gravity Vertical Acceleration
LTP	Longitudinal center of Tow Point
LBP or L_{PP}	Length between perpendicular
LWL.....	Length of the waterline
NI	National Instruments Corporation
NSWCCD	Naval Surface Warfare Center Carderock Division
ONR.....	Office of Naval Research
P	Precision uncertainty
+PCL.....	Positive values port from the centerline
RMS	Root-Mean-Square
R_t	Total resistance
s.....	Sample standard deviation
S_o	Static wetted surface area
Sps.....	Samples per second
T	Draft, target value, or wave period
T_{CG}	Draft at center of gravity
T_e	Encounter wave period
$T_m, T_p,$	Modal, or peak, wave period
$T_{me}, T_{pe},$	Modal, or peak, encounter wave period
T_z	Average wave period
T_{ze}	Average encounter wave period
U.....	Total uncertainty or model speed
V	Volume or model speed
VCG	Vertical Center of Gravity
VTP	Vertical center of Tow Point
Δ	Displaced weight
θ	Static trim angle or sensitivity coefficient
σ	Heave or sinkage, or population standard deviation
τ	Running trim angle
ν	Degrees of freedom

∇.....Displaced volume

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APPENDIX A: DYNAMOMETER CALIBRATIONS

The dynamometer was constructed using four Kistler force sensors capable of measuring force in 3 axes. The sensors were sandwiched between two plates of 1-inch thick heat-treated 17-4 stainless steel and preloaded to the manufacturer's specification. The voltages were recorded using a computer based data acquisition system. The gage assembly is shown in Figure A-1.

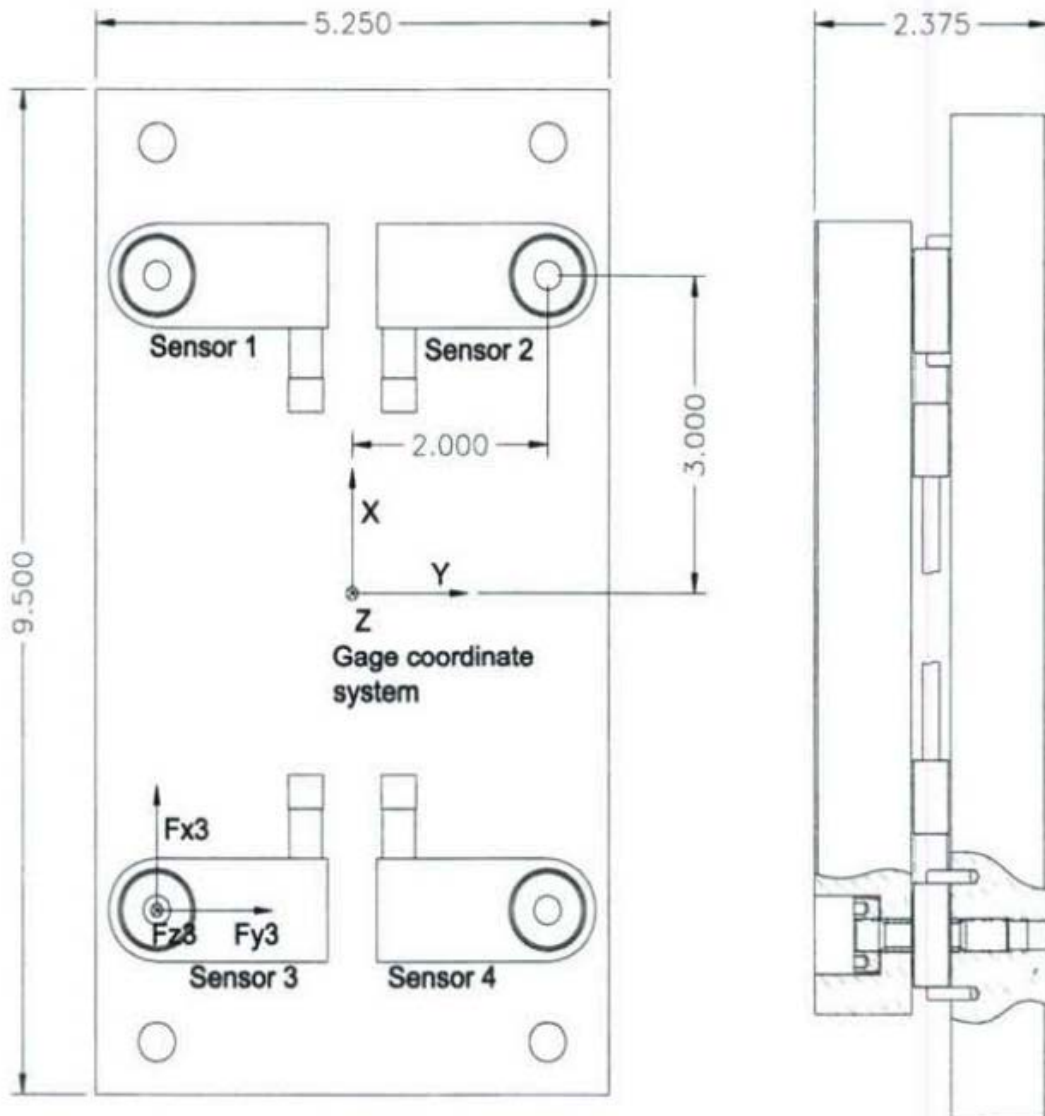


Figure A-1. Dynamometer Assembly.

To calibrate the dynamometer, NIST traceable calibration weights were hung from dynamometer using a calibration fixture with known, fixed moment arms. The input load and the output voltages were recorded for each calibration point. Each axis was loaded in force and

moment independently for a total of approximately 140 calibration points. The measurements were averaged for 3 seconds at 100 Sps. The voltages were converted to engineering units using the single axis calibrations performed prior to assembly of the dynamometer. Since the individual sensor coordinate systems did not align with the dynamometer coordinate system the forces from the sensors were rotated into the dynamometer coordinate system. The forces and moments on the dynamometer assembly were calculated using equations A-1 through A-6:

$$F_{x_{sum}} = F_{x1} + F_{x2} + F_{x3} + F_{x4} \quad (A-1)$$

$$F_{y_{sum}} = F_{y1} + F_{y2} + F_{y3} + F_{y4} \quad (A-2)$$

$$F_{z_{sum}} = F_{z1} + F_{z2} + F_{z3} + F_{z4} \quad (A-3)$$

$$M_{x_{sum}} = R_y * (-F_{z1} + F_{z2} - F_{z3} + F_{z4}) \quad (A-4)$$

$$M_{y_{sum}} = R_x * (-F_{z1} - F_{z2} + F_{z3} + F_{z4}) \quad (A-5)$$

$$M_{z_{sum}} = R_y * (F_{x1} - F_{x2} + F_{x3} - F_{x4}) + R_x * (F_{y1} + F_{y2} - F_{y3} - F_{y4}) \quad (A-6)$$

where F_{xN} is the input load in X gage direction from gage N,

F_{yN} is the input load in Y gage direction from gage N,

F_{zN} is the input load in Z gage direction from gage N,

R_x and R_y are the moment arms between the gages and dynamometer coordinate systems,

$F_{x_{sum}}$ is the sum of forces in X dynamometer direction,

$F_{y_{sum}}$ is the sum of forces in Y dynamometer direction,

$F_{z_{sum}}$ is the sum of forces in Z dynamometer direction,

$M_{x_{sum}}$ is the sum of moments about the X dynamometer axis,

$M_{y_{sum}}$ is the sum of moments about the Y dynamometer axis, and

$M_{z_{sum}}$ is the sum of moments about the Z dynamometer axis.

The input loads and the above calculated forces and moments were used to generate an interaction matrix (A^{-1}) that minimizes the regression errors, using pseudo inverse technique as shown below.

$$F_{sum} = F * A \quad (A-7)$$

$$A^{-1} = ((F^T * F)^{-1} * F^T * F_{sum})^{-1} \quad (A-8)$$

where F_{sum} is the (6 x N) matrix containing the force and moment outputs as dynamometer voltage signals, and

F is the (6 x N) matrix containing the applied, or calibration, loads (forces and moments).

Equation A-9 is then used to derive an applied loads from the dynamometer voltage signals.

$$F = F_{sum} * A^{-1} \quad (A-9)$$

The calibration errors can then be estimated using equation A-10.

$$Error = F - F_{sum} \quad (A-10)$$

The dynamometers were calibrated before and after the test. Table A-1 and Table A-2 below summarize the post-test calibration results of each dynamometer. The bias uncertainties at a 95% confidence level in surge and sway were estimated using the calibration error standard deviation given in the table. The surge and sway bias uncertainties for the forward tow post dynamometer were $B_{Fx\text{fwd}}=0.26$ lbf and $B_{Fy\text{fwd}}=0.16$ lbf respectively. The surge and sway bias uncertainties for the aft grasshopper dynamometer were $B_{Fx\text{aft}}=0.22$ lbf and $B_{Fy\text{aft}}=0.28$ lbf respectively. These bias uncertainties in the component directions for each dynamometer were used to estimate the total resistance uncertainty.

Table A-1. Tow Post Dynamometer (S/N 2003-3) Calibration Results.

	Fx (lbf)	Fy (lbf)	Fz (lbf)	Mx (ft-lbf)	My (ft-lbf)	Mz (ft-lbf)
Range	100	100	650	122.9167	122.9167	50.78125
Max Error (%Range)	0.14 (0.14%)	0.11 (0.11%)	0.62 (0.10%)	0.18 (0.14%)	0.19 (0.15%)	0.15 (0.30%)
Min Error (%Range)	-0.32 (-0.32%)	-0.42 (-0.42%)	-1.11 (-0.17%)	-0.10 (-0.08%)	-0.17 (-0.14%)	-0.59 (-1.16%)
Standard Deviation, s	0.07	0.08	0.26	0.03	0.05	0.15

Table A-2. Aft Grasshopper Dynamometer (S/N 2003-4) Calibration Results.

	Fx (lbf)	Fy (lbf)	Fz (lbf)	Mx (ft-lbf)	My (ft-lbf)	Mz (ft-lbf)
Range	100	100	650	122.9167	122.9167	50.78125
Max Error (%Range)	0.20 (0.20%)	0.17 (0.17%)	0.80 (0.12%)	0.14 (0.11%)	0.17 (0.14%)	0.09 (0.18%)
Min Error (%Range)	0.31 (0.31%)	0.50 (0.50%)	0.89 (0.14%)	0.18 (0.14%)	0.24 (0.20%)	0.06 (0.12%)
Standard Deviation, s	0.12	0.15	0.32	0.05	0.08	0.03

APPENDIX B: SWINGING PROCEDURE AND MODEL LOADING

An inertial frame was used to swing the model for determination of the model mass properties. This inertial frame consists of an steel A-frame with approximate dimensions of 12 feet high, 8.4 feet long, and 8 feet wide. A pivot post suspended from the steel structure was used to support the model as a rigidly connected pendulum. The pivot post was configured with a roller bearing joint and beam fixture that was used to rigidly fasten the model to the A-frame. This A-frame and associated pivot hardware have an approximate capacity for models up to 1,200 pounds, 22 feet long, and 6 feet wide. The A-frame can be readily reconfigured to swing a model about both the roll and pitch axes. The roll and yaw moments of inertia were not measured since the model was only tested in the heave and pitch degrees of freedom. Figure B-1 shows the model as-configured on the inertial A-frame apparatus. The swinging procedures used to measure the model's mass properties follow standard NSWCCD guidance.



Figure B-1. Model as-swung on the inertial A-frame.

The model's mass properties were configured prior to testing to the same values used in the 2014 test. The as-tested mass properties were determined after the test was completed to capture minor model configuration changes that occurred during testing. These configuration changes resulted from rigging constraints on the tow post, instrumentation changes, and refinements in ballast weights to achieve zero hydrostatic heel and trim angles. The tow post gimbal and A-frame pivot were both attached to the onboard mounting plate that was fixed at 97.381 inches forward of the aft perpendicular (FAP). This mounting plate location was not adjustable. The model's ballast weight was shifted to achieve a zero hydrostatic trim angle as indicated by the marked waterline before proceeding with testing. This ballast weight shift moved the as-tested longitudinal center of gravity (LCG=96.024 inches +FAP) aft of the

mounting plate center (i.e. longitudinal tow post location, LTP=97.381 inches +FAP). All mass moment of inertia measurements were reported about the as-tested center of gravity.

The as-swung mass properties did not include the as-tested weight components for the carriage tow post and rigging. These component weights were included analytically when deriving the as-tested mass properties. The tow post weight acted as a point load at the gimbal axis of rotation and was assumed to have no moment of inertia contribution to the as-tested moment of inertia.

The model's vertical center of gravity (VCG) was determined via static inclining moments while mounted to the A-frame pivot. This inclining was performed by moving an inclining weight longitudinally and measuring the change in trim angle due to the corresponding moment of the inclining weight. From these values, the model VCG was determined relative to the A-frame pivot and then reported relative to the model baseline. This inclining procedure was performed over a range of angles to establish a suitable linear trend for deriving the as-swung VCG.

The pitch moment of inertia was determined by swinging the model about the A-frame pivot. The swing oscillations were limited to four degrees or less for consistency with the small angle approximation used to solve the differential equation relating mass moment of inertia to the oscillation natural period. The parallel axis theorem was then used determine and report mass moment of inertia about the as-tested center of gravity.

Table B-1. Athena model loading during testing and post-test swinging.

Model Loading Component	Value (D)	Total Uncertainty (U)
As-Swung Model Weight (lb)	840.09	0.14
As-Swung Model LCG (inch +FAP)	97.381	0.067
As-Swung Model VCG (inch +ABL)	9.65	0.39
As-Swung Model Pitch Gyradius (inch about CG)	57.22	0.47
As-Tested Tow Post and Rigging Weight (lbf)	35.00	0.10
As-Tested Tow Post and Rigging LCG (inch +FAP)	97.381	0.063
As-Tested Tow Post and Rigging VCG (inch +ABL)	10.040	0.063
Removed Trimming Ballast Weight (lbf)	17.09	0.10
Removed Trimming Ballast LCG (inch +FAP)	165.506	0.063
Removed Trimming Ballast VCG (inch +ABL)	5.790	0.063
As-Tested Model Weight (lbf)	858.00	0.22
As-Tested Model LCG (inch +FAP)	96.024	0.076
As-Tested Model VCG (inch +ABL)	9.74	0.38
As-Tested Model Pitch Gyradius (inch about CG)	55.78	0.51

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