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Ann Arbor, Michigan, August 5-8, 2007

A Comprehensive Set of Code Validation Data for Planing Boat Forces in Calm Water and Regular Waves

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ABSTRACT

A model of a monohull planing boat (Model 5658) was towed on Carriage 5 at the Naval Surface Warfare Center, Carderock Division (NSWCCD). The objective of the test was to generate a planing hull data set that could be used in the development of Computational Fluid Dynamics (CFD) based design tools for high-speed planing craft. To accomplish this objective, a detailed set of experimental data was obtained on the model in both the fixed trim and free-to-sink-and-trim conditions. The experimental data includes six-component force and moment data with the model fixed in pitch to the carriage over a matrix of different keel lengths, drafts, and pitch angles, through an equivalent full scale speed range of 25-50 knots. The model was run free-to-sink-and-trim to obtain force measurements over a test matrix of varying displacements and longitudinal centers of gravity (LCG). In this condition, the model was tested over a speed range corresponding to 5-50 knots full scale. The fixed and free data was obtained in calm water and regular head-sea waves. Extensive video documentation of the flow around the hull forms was obtained in conjunction with the measurements obtained on the model.

INTRODUCTION

Computational fluid dynamics codes have been used to predict flow primarily around displacement ships. In order to develop these codes to model the flow around high speed planing craft, a detailed set of data was needed for code validation. The CFD codes also need to handle the fully unsteady problem of an unconstrained high speed craft in waves. The data collected in this test provides a complete set in both calm water and regular head-sea waves for validation of CFD codes.

Typical CFD solutions are shown in Figures 1 and 2. These predications were made using CD-Adapco's Comet program. Figure 1 shows the hull bottom pressure of the monohull running at 40 knots in head seas. Increased pressures are observed over the first one-third of the wetted keel length of the model. Bottom pressures gradually reduce from bow to stern. Figure 2 shows the time history of drag and lift forces on the model running at 40 knots in head seas. Computations were made for one-half of the hull. The largest lift forces predicted for the full scale vessel are 850,000 N.

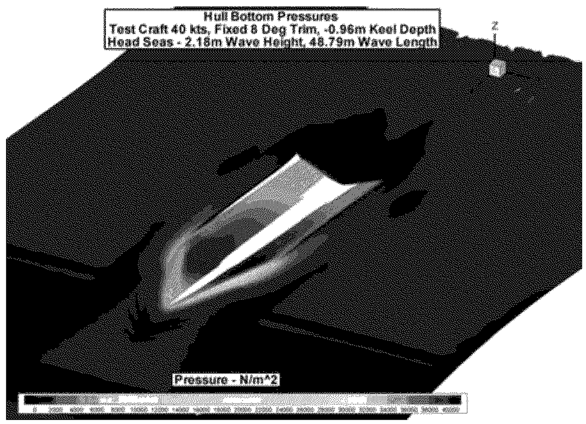

Figure 1: Hull bottom pressure predications for the monohull running at 40 knots in head sea waves.

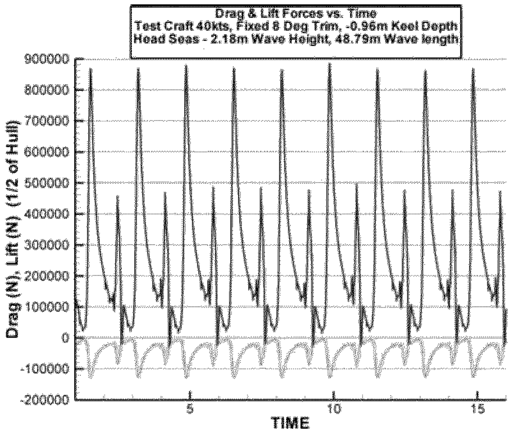

Figure 2: Drag and lift predictions for ½ of the hull at 40 knots in head sea waves.

MODEL DESCRIPTION

Model 5658 is a wooden model of a monohull planing boat built in 2006 by Computer Sciences Corporation in Laurel, Maryland. The hull form is representative of one used by the Combatant Craft Division. It was built to a linear scale ratio of 8.0. In order to use underwater photography to estimate chine length, keel length, and wetted surface area, the underside of the model was painted with a one inch grid in a checkerboard pattern.

MEASUREMENT METHODS

Measurements taken in the fixed condition included six-component force and moment, as well as wave height. Drag, pitch, acceleration, and wave height were measured in the free-to-sink-and-trim condition. All of the instruments were calibrated using NSWCCD standards. The calibration factors were entered into the data acquisition program which recorded them for each run in a pass file along with the raw data. The data acquisition program also recorded "spots" that contained data that had been converted to engineering units.

Forces/Moments on the Ship Hull

For the fixed trim cases, six-component force and moment measurements were made using two Kistler gages. The Kistler gages were mounted to the model interior, underneath each strut.

For the free-to-sink-and-trim cases, drag measurements were made using a standard block gage. The block gage that was used for the monohull was calibrated using NSWCCD standard calibration procedures over a range of 50 lbs.

Ship Motions

In the free-to-sink-and-trim condition, ship motions were measured using a combined GPS and inertial motion package. The combined motion package was installed at the LCG and measured roll, pitch, yaw, linear accelerations, and angular rate accelerations. The motion package consisted of a gyro enhanced orientation sensor (3DM-GX1), a SUPERSTAR II GPS, and a Persistor CF2 CPU. The 3DM-GX1 sensor consists of three angular rate gyros, three orthogonal DC accelerometers, three orthogonal magnetometers, and a multiplexer. The gyros track dynamic orientation while the accelerometers and the magnetometers track static orientation. The 3DM-GX1 combines the static and dynamic responses in real time and records 20 samples per second. The CF2 runs on battery power and combines and stores the data on a flash disk.

Two accelerometers were also used during the free-to-sink-and-trim runs. The accelerometers, mounted near the bow and the stern, measured accelerations in the z direction.

Wave Heights

Wave heights were measured using Senix TS-15S-IV ToughSonic distance sensors, often just referred to as "sonics." These sensors emit an ultrasonic pulse that bounces off of a target, and the return pulse is then read with a piezoelectric element. Using the speed of sound, the sensor is able calculate the distance to the object. The sonics can measure distances from 25 to 915 cm (10-360 in), with an accuracy of 0.015 cm (0.006 in). The sampling rate of the Senix sensors ranges from 1 to 100 Hz. For this test, the sonics were sampling at 10 Hz. A total of nine Senix sensors were used to measure wave height. Three of the sonics were calibrated over a range of 91 to 152 cm (36-60 in) in 10.2 cm (4 in) increments. These were placed forward of the bow at approximately 15.2 cm (6 in), 1.5 m (5 ft), and 3.0 m (10 ft) to measure the incoming waves.

The remaining six sonics were placed outboard of the model, three on the port side of the model and three on the starboard side. The port and starboard sonics were located distances of 15.2 cm (6 in), 30.5 cm (12 in), and 61.0 cm (24 in) from the edge of the hull. Since these sensors were placed closer together than the other set of sonics, there was a concern that they might interfere with each other as the ultrasonic pulse spreads out in a cone shape when it gets further from the sensor. As a result, these six sonics were positioned closer to the water surface and were calibrated from 28.0 to 63.5 cm (11-25 in) in 10.2 cm (4 in) increments.

Model Draft/Trim

Model draft and trim were measured using Senix TS-15S-IV ToughSonic distance sensors. The Sonics were mounted under the carriage and measured the distance to the hull below. They were calibrated over a range of 91 to 152 cm (36-60 in) in 10.2 cm (4 in) increments. One was mounted above the bow and the other above the stern.

During the free-to-sink-and-trim tests, two Acuity Research AccuRange 4000 laser range finders were used to measure trim. This allowed for greater accuracy than the sonic sensors were giving. They were calibrated over 61.0 cm (24 in) using the same method as the sonics. The analog outputs from the laser range finders were used to calculate trim. The locations of the laser range finders are shown in Figure 3 for the monohull.

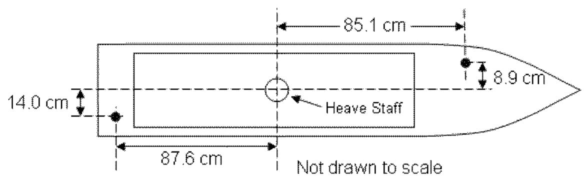

Figure 3: Location of the laser range finders used to measure pitch.

Motion Visualization

Four standard frame rate (30 fps) video cameras were used to visually document ship motions from multiple views – bow quartering, stern wake, stern quartering, and side.

An underwater camera was placed near the photo pit at the center of the basin to take underwater video of the model in the free-to-sink-and-trim condition. The camera was a Subsea Video Z-27. It was focused with the model directly over top. Underwater video was used to visualize chine length, keel length, and wetted surface using the grid that had been painted on the model.

TEST DESCRIPTION

Model 5658 was tested in the high speed basin on Carriage 5 at the Naval Surface Warfare Center, Carderock Division. Carriage 5 has a maximum speed of 25.7 m/s (84.5 ft/s, 50 knots). The high speed basin is approximately 4.9 m (16 ft) deep, 514 m (1687 ft) long, and 6.4 m (21 ft) wide. The basin has a pneumatic type wavemaker. The 6.4 m (21 ft) wavemaker dome is connected to a centrifugal type blower driven by a direct coupled variable speed DC electric motor rated at 75 kW (100 hp) and 1150 rpm. The wave absorber spans the full width of the basin at the shallow end opposite the wavemaker dome. The absorbers are a discontinuous 20 deg slope type made up of 7 permeable layers of rectangular precast concrete bar panels resting on an impermeable concrete slab that is supported by structural steel framework. Extending along the walls on each side of the basin are "U"-shaped steel wave absorber skimming troughs with their upper edges set about 6 mm (0.25 in) below the normal water level surface.

The model was tested fixed to the carriage over a test matrix that included three trims, three keel lengths, four speeds, and two wave conditions. For free-to-sink-and-trim condition, the model was attached to the carriage using a heave post. The test matrix included three displacements, three LCGs, ten speeds, and two wave conditions.

Fixed Trim

In the fixed towing configuration, the model was expected to experience high loads. To help strengthen the model, towing support plates were installed on top of the hull framing.

The monohull was attached to the tilt table by two struts. The Kistler gages were mounted on each tow plate and attached to the vertical struts. Figure 4 shows a schematic of how the model was attached to the carriage.

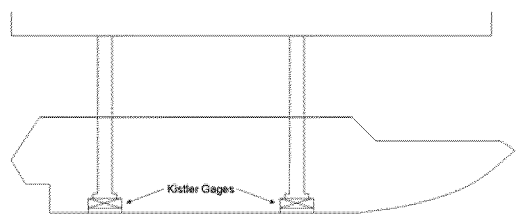

Figure 4: Towing schematic for the fixed condition.

In calm water, for the fixed condition, the monohull was tested over a speed range corresponding to 25-50 knots full scale and keel lengths corresponding to 10.7, 12.2, and 13.7 m (35, 40, and 45 ft) full scale. The speeds that were tested are shown in Table 1 and the keel lengths in Table 2. Three different pitch angles, shown in Table 3, were tested at each keel length and speed.

In waves, the model was tested over the speed range shown in Table 1. The keel lengths, which can be seen in Table 2, were scaled to represent 6.9 and 13.7 m (22.5 and 45 ft) full scale.

The test matrix included two fixed pitch angles of 2.5 and 4.3 degrees. The regular head seas waves were scaled to the significant wave amplitude and period that represent Sea State 3 and Sea State 4. Table 4 shows the height and frequencies of the two waves.

Table 1: Speed set for fixed trim in calm water and in waves.

Speed			
Full Scale		Model Scale	
(m/s)	(knots)	(m/s)	(knots)
12.9	25	4.5	8.8
18.0	35	6.4	12.4
20.6	40	7.3	14.1
25.7	50	9.1	17.7

Table 2: Keel lengths for fixed trim.

Keel Lengths					
Calm Water			Waves		
Full Scale		Model Scale	Full Scale		Model Scale
(ft)	(m)	(m)	(ft)	(m)	(m)
35	10.7	1.3	22.5	6.9	0.9
40	12.2	1.5	45	13.7	1.7
45	13.7	1.7			

Table 3: Pitch angles for fixed trim.

Pitch	
Calm Water	Waves
(degrees)	(degrees)
2.5	2.5
4	4.3
5.5	

Table 4: Wave conditions for fixed trim runs.

Wave Height			Wave Frequency
Full Scale		Model Scale	
(m)	(ft)	(m)	(Hz)
1.2	4	0.2	0.48
2.2	7.2	0.3	0.45

Dynamic Ballasting

Prior to testing, the monohull was swung using the “A-frame” inertial frame located in the NSWCCD, Maneuvering and Seakeeping (MASK) facility. This was done to determine the pitch gyradius and dynamic ballasting conditions, in order to accurately test the model in a free-to-sink-and-trim condition.

Free-to-Sink-and-Trim

A matrix database approach developed by Hoyt and Dipper (1989) was used to create a test matrix and obtain the data for both models in the free-to-sink-and-trim condition. By testing multiple LCG locations and displacements, a matrix was developed that allows for interpolation to specific full-scale operating conditions.

A fixed single point tow on a heave staff was used for the free-to-sink-and-trim runs. The tow point was located at the LCG location shown in Figure 5.

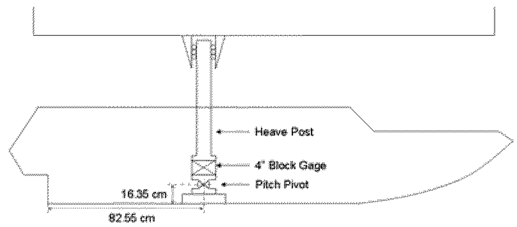

Figure 5: Towing schematic for the free-to-sink-and-trim condition.

In calm water, the monohull was tested over speeds ranging from 5-50 knots full scale. Table 5 shows the ten speeds that were tested. Three displacements and three LCGs were chosen to create a matrix that would allow for interpolation to the desired conditions. The displacements and LCGs are shown in Table 6 and Table 7, respectively.

Table 5: Speed set for the free-to-sink-and-trim runs in calm water and in waves.

Full Scale		Model Scale	
(m/s)	(knots)	(m/s)	(knots)
2.6	5	0.9	1.8
3.6	7	1.3	2.5
5.1	10	1.8	3.5
6.4	12.5	2.3	4.4
7.7	15	2.7	5.3
10.3	20	3.7	7.1
12.9	25	4.5	8.8
18.0	35	6.4	12.4
20.6	40	7.3	14.1
25.7	50	9.1	17.7

Table 6: Model displacements for the free-to-sink-and-trim runs.

Model Displacement	
(kg)	(lb)
48.5	107
53.1	117
57.6	127

Table 7: LCG locations for the free-to-sink-and-trim condition.

LCG	
Full Scale	Model Scale
(m)	(cm)
6.47	80.90
6.54	81.71
6.60	82.55

For the free-to-sink-and-trim condition in head sea waves, the monohull was tested at four speeds over a range of 5-40 knots full scale. Only one displacement, 53.1 kg (117 lb), and one LCG, 81.71 cm (32.5 in) were tested. The two wave conditions, shown in Table 8, corresponded to the significant wave amplitudes and periods of Sea State 3 and Sea State 4 regular head seas.

Table 8: Wave conditions for the free-to-sink-and-trim runs.

Wave Height			Wave Frequency
Full Scale		Model Scale	
(m)	(ft)	(m)	(Hz)
1.2	4	0.2	0.48
2.2	7.2	0.3	0.45

RESULTS & DISCUSSION

The coordinate system for the model scale forces is shown in Figure 6.

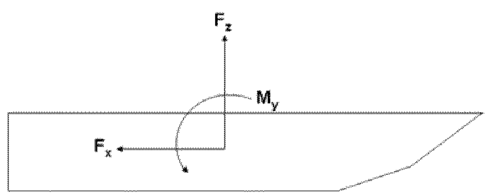

Figure 6: Side view of the monohull showing the force orientation.

Fixed in Calm Water

Average forces in the x and z direction were calculated for all of the runs. Figure 7 shows the average drag versus speed. As pitch and keel length increased, so did the drag. Drag forces were between 20 and 180 N. The trends for z force, shown in Figure 8, are similar in that the force increased with pitch and keel length. The maximum z force was approximately 900 N.

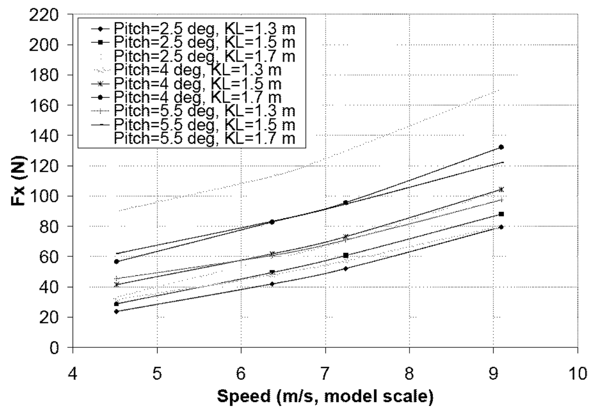

Figure 7: Drag versus speed for the fixed in calm water condition.

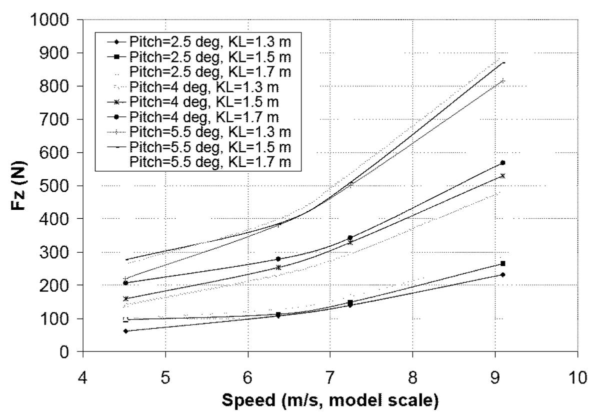

Figure 8: Z force verses speed for the fixed in calm water condition.

Fixed in Waves

For the fixed in waves analysis, each wave encounter was treated as a separate event. The peak x and z forces were calculated for each wave encounter and then averaged over the run. The peak drag forces are shown for the small waves in Figure 9 and the large waves in Figure 10. In both cases, drag increased as keel length and pitch increased. In the smaller wave condition, the monohull saw average peak drag forces ranging from 50 to 360 N and average peak z forces ranging from about 400 to 1950 N. Figure 11 shows the z forces for the small waves. In the larger waves, scaled to represent Sea State 4, the average peak drag was between 115 and 560 N. The force in the z direction ranged from 950 to 2880 N as shown in Figure 12.

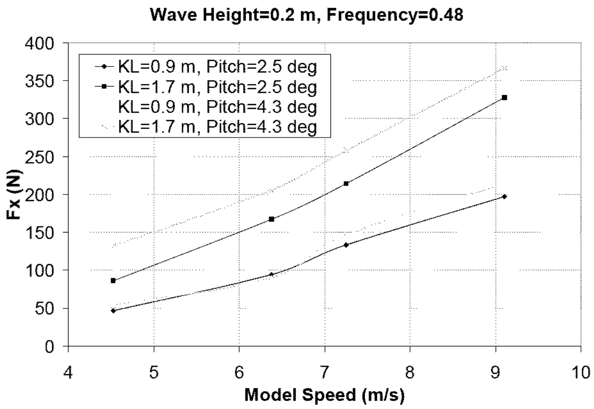

Figure 9: Average peak drag versus speed for fixed in the smaller wave condition.

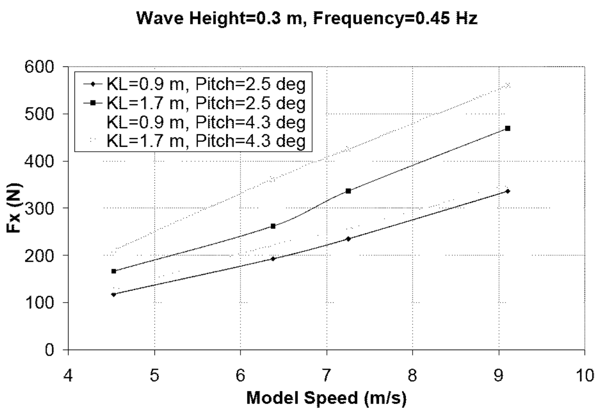

Figure 10: Average peak drag versus speed for fixed in the larger wave condition.

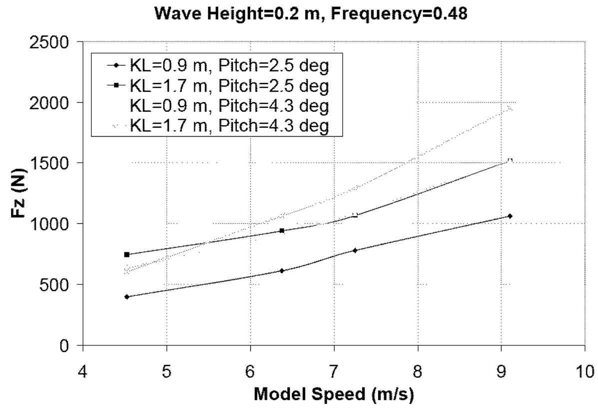

Figure 11: Average peak Z force versus speed for fixed in the smaller wave condition.

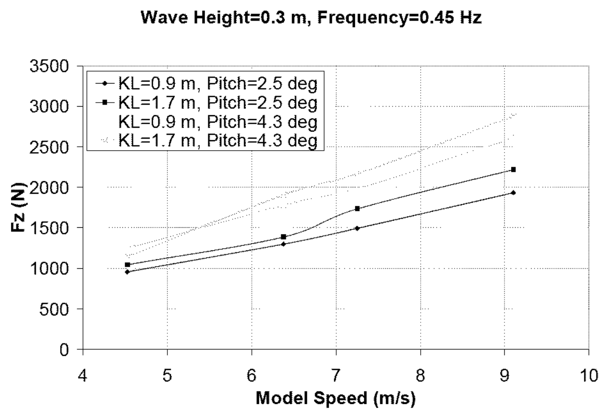

Figure 12: Average peak Z force versus speed for fixed in the larger wave condition.

Free-to-Sink-and-Trim in Calm Water

Drag and pitch were averaged for all of the runs. Figure 13 shows the drag force results for all of the displacements and LCGs. Displacement had a much larger effect on drag force than location of the LCG. The pitch results are shown in Figure 14. Pitch tended to decrease as the location of the LCG moved further forward. Drag forces ranged from 5 to 125 N. Pitch angle reached a maximum at 6.4 m/s (12.4 knots) model scale and ranged from 0.6 to 5.5 degrees.

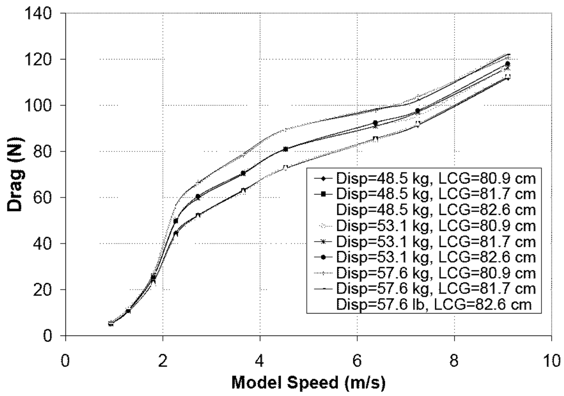

Figure 13: Drag versus speed for the free-to-sink-and-trim condition.

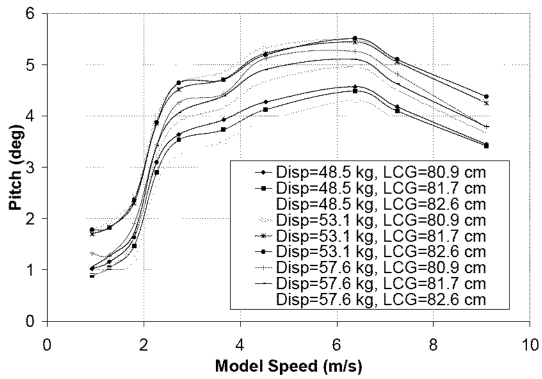

Figure 14: Pitch versus speed for the free-to-sink-and-trim condition.

Heave was calculated with the laser distance finders that were being used to calculate pitch. Since the distance finders were not located at the pivot point, the distance to the hull was adjusted to account for the vertical distance the model would move due to the pitch. The corrected distance was equivalent to the heave. The heave was averaged over each run and the results are shown in Figure 15. As seen in the graph, heave was between -1.4 and 7.1 cm.

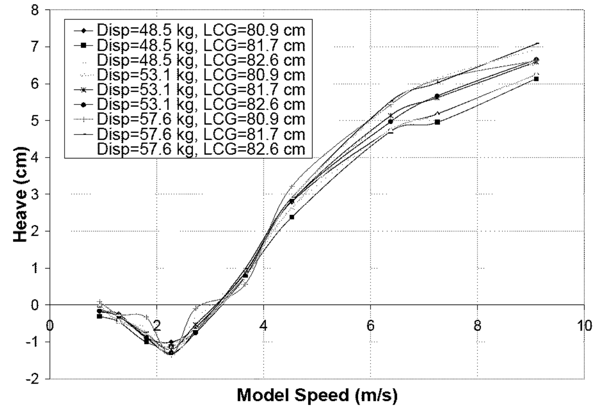

Figure 15: Heave versus speed for the free-to-sink-and-trim condition.

Still images from the underwater video clips were pieced together to provide a non-distorted image of the wetted surface for the monohull free-to-sink-and-trim in calm water. Keel length and chine length were measured off of the underwater photographs. The results were graphed in Figure 16 and Figure 17. Wetted surface was estimated from the pictures and the results are shown in Figure 18.

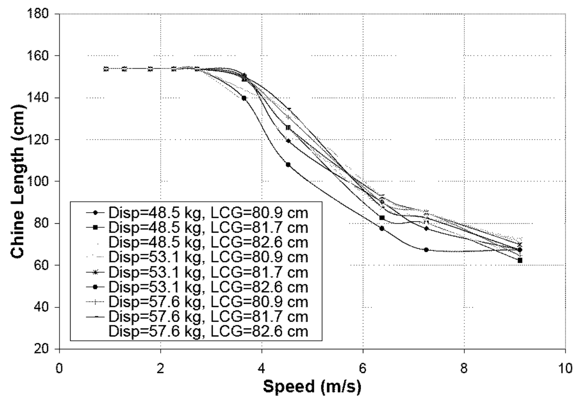

Figure 16: Chine length versus speed for the free-to-sink-and-trim condition.

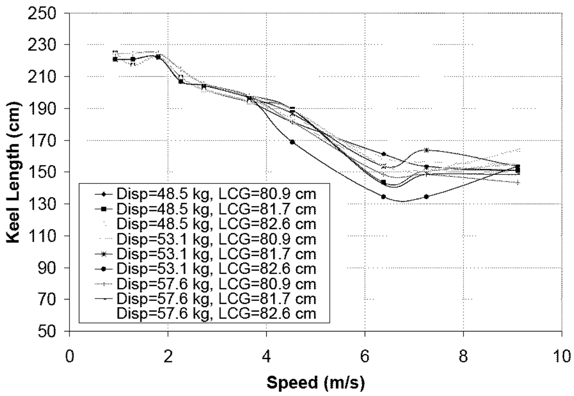

Figure 17: Keel length versus speed for the free-to-sink-and-trim condition.

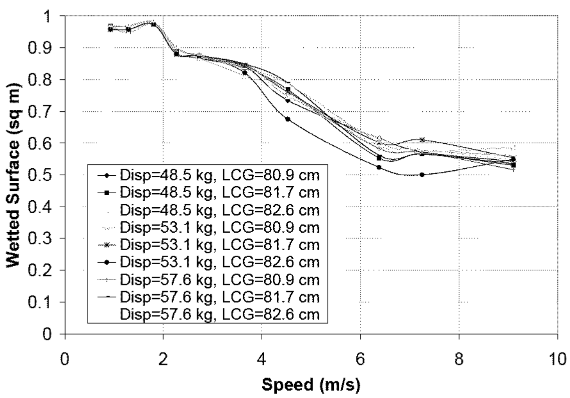

Figure 18: Wetted surface versus speed for the free-to-sink-and-trim condition.

Free-to-Sink-and-Trim in Waves

In waves, the free-to-sink-and-trim analysis was done similarly to the fixed condition. For each wave encounter, the peak pitch and peak drag forces were calculated. These forces were averaged over the entire run. Figure 19 is a series of graphs that was generated by the data analysis program for one run. The top graph shows the wave height. The program marked all the peaks with blue and troughs with red. It is easiest to see on the pitch graph that the program marked the peak pitch with blue. The same was done for drag force, but it is more difficult to see.

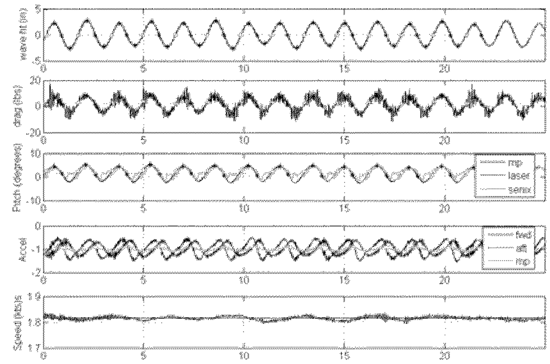

Figure 19: Series of graphs generated by the data analysis program for the free-to-sink-and-trim condition.

The average peak drag force for all of the speeds and the two wave conditions were graphed and the results can be seen in Figure 20. The same was done for average peak pitch as shown in Figure 21. The average peak drag was between 7.8 and 118 N, while the average peak pitch was between 4.5 and 12 degrees.

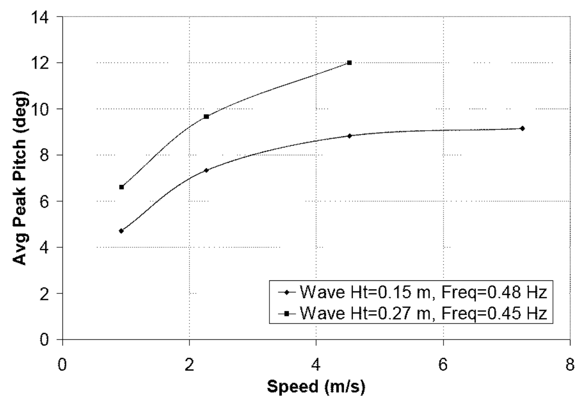

Figure 20: Average peak pitch for free-to-sink-and-trim in waves.

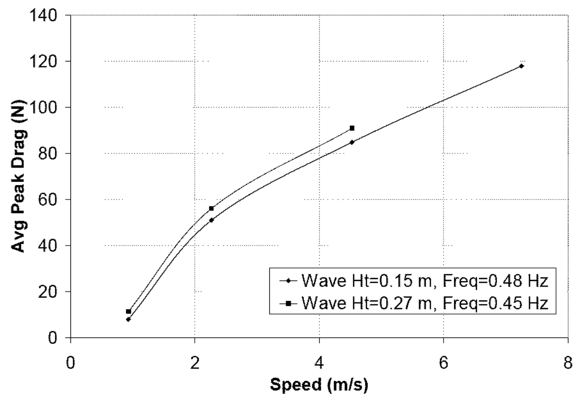

Figure 21: Average peak drag for free-to-sink-and-trim in waves.

USING THE ALMETER METHOD TO PRESENT PLANING BOAT DATA

Recent developments have been made in resistance prediction techniques for planing craft. One method, developed by Almeter (1999), predicts resistance based on similar boats but with different proportions or loadings. The Almeter method uses two non-dimensional variables known as the Almeter Number and the Clement Number. The Almeter Number is defined as:

$$A_n = \Delta/(1/2\ \rho\ LCG\ B_m\ V^2) \qquad (1)$$

Where:

B_m = Chine beam
LCG = Longitudinal Center of gravity
Δ = Displacement, weight
ρ = Mass density
V = Advance speed

Decreasing Almeter number corresponds to increasing speed. The Clement Number is defined as:

$$C_n = \nabla / (LCG^2\, B_m) \qquad (2)$$

Where:ben

B_m = Chine beam
LCG = longitudinal center of gravity
∇ = Volumetric displacement

Higher Clement Numbers correspond to higher loading. The planing boat data was graphed using Almeter's method. The logarithm of A_n was used to make the plot more readable. The negative values of the log of A_n correspond to higher planing speeds, while positive values indicate that the boat is in displacement mode. The hump regime is from log(A_n) of -1.0 to 0.0 and the planing regime is -1.0 and lower. Figure 22 shows non-dimensional resistance graphed using the Almeter method. Figure 23 shows trim graphed using the Almeter method. The data follows the trends that Almeter described.

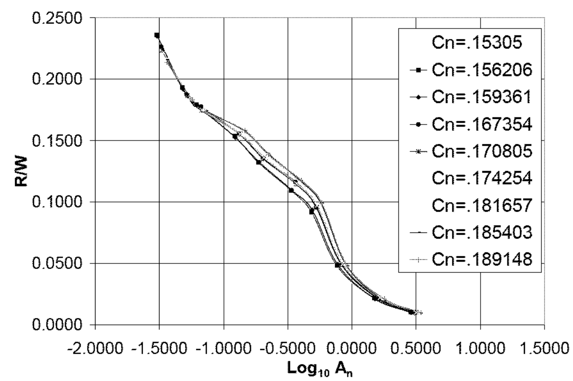

Figure 22: Model 5658 non-dimensional resistance versus the log of the Almeter Number.

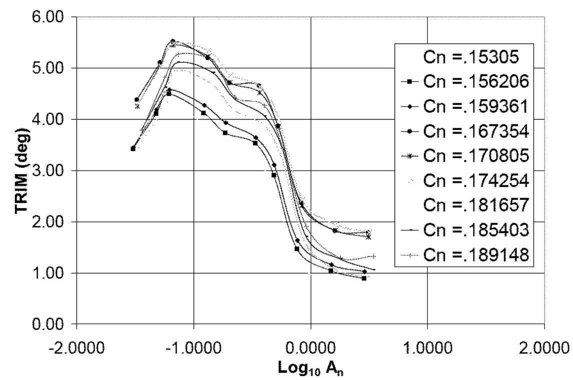

Figure 23: Trim versus the log of Almeter Number for Model 5658.

CONCLUSIONS

These tests produced a comprehensive data set for a monohull that can be used for CFD validation. The model was tested fixed to the carriage and free-to-sink-and-trim. In both cases, it was tested in calm water and in head-sea waves.

In the fixed condition, the model was tested by varying keel length and pitch over four speeds. For calm water, there were three keel lengths and three pitch angles tested. The drag force ranged from 23 to 170 N, while the force in the z direction ranged from 60 to 890 N. Two keel lengths and two pitch angles were tested in two wave conditions. In the smaller head-sea wave condition, the monohull saw average peak drag force ranging from 45 to 370 N and average peak z forces ranging from about 400 to 1950 lbs. In the larger head-sea wave conditions, the average peak drag was between 115 and 560 N. The force in the z direction ranged from 957 to 2875 N.

For the free-to-sink-and-trim cases, the monohull was tested by changing the displacement and the location of the LCG. Three displacements and three LCG locations were tested at 10 different speeds in calm water. Drag forces ranged from 4.5 to 123 N. Pitch angle reached a maximum at 6.4 m/s (12.4 knots) model scale. Pitch ranged from 0.6 to 5.5 degrees. Heave was between -1.4 and 7.1 cm. Only one displacement and LCG location was tested in waves. There were two wave conditions and the monohull was run at four speeds. The average peak drag was between 7 and 118 lbs, while the average peak pitch was between 4.5 and 12 degrees.

The use of the matrix method to obtain planing boat data gave many advantages. It allowed for interpolation to conditions that were not actually tested. This is especially useful since future full scale trials might not exactly match the load and LCG conditions that were tested in the tank. The matrix method also provided a self-consistent set of data which can be used to study the sensitivity of CFD codes for planing boat hulls. The data obtained using the matrix method is well suited to analysis using the Almeter method of planing boat resistance prediction.

REFERENCES

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DISCUSSION/REPLY