Naval Surface Warfare Center
Carderock Division
West Bethesda, MD 20817-5700

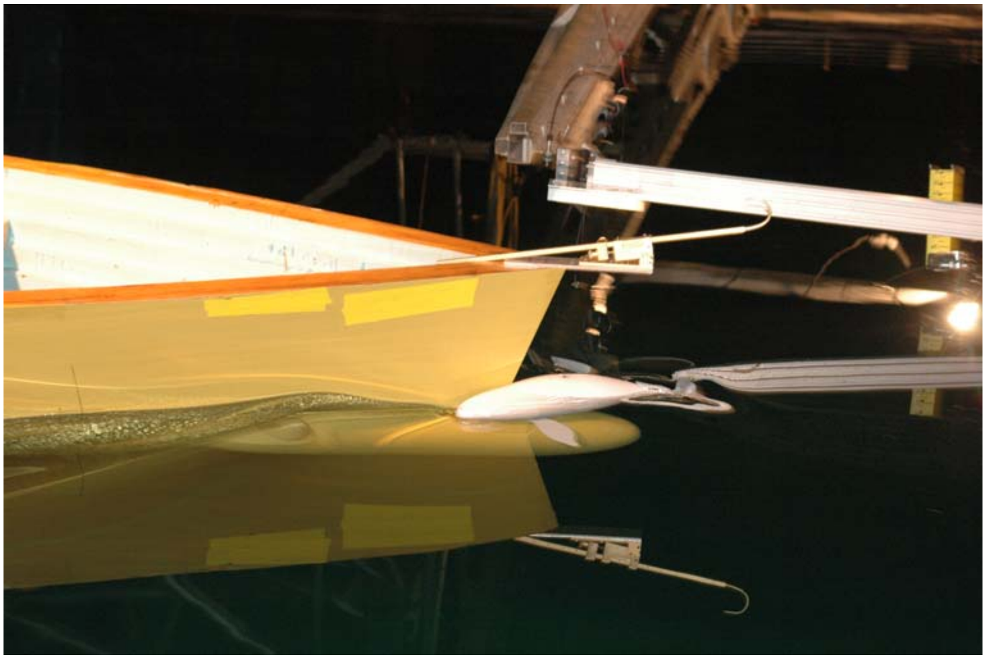
NSWCCD-50-TR–2007/053 June 2007

Hydromechanics Department Report

Model Scale Simulation of a Ship-Whale Encounter

by

Jonathan Slutsky



Distribution authorized to U.S. Government agencies and their contractors only, administrative/operational use; June, 2007. Other requests for this document shall be referred to the Naval Surface Warfare Center, Carderock Division, Code 50.

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

1. REPORT DATE *(DD-MM-YYYY)* 1-Jun-2007	**2. REPORT TYPE** Final	**3. DATES COVERED** *(From - To)* 3/12/2007 –3/24/2007

4. TITLE AND SUBTITLE Model Scale Simulation of a Ship-Whale Encounter	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Jonathan Slutsky	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES) Naval Surface Warfare Center Carderock Division 9500 Macarthur Boulevard West Bethesda, MD 20817-5700	**8. PERFORMING ORGANIZATION REPORT NUMBER** NSWCCD-50-TR-2007/053
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Gregory K. Silber National Marine Fisheries Service 1315 East West Highway Silver Spring, MD 20910	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution authorized to U.S. Government agencies and their contractors only, administrative/operational use; June, 2007. Other requests for this document shall be referred to the Naval Surface Warfare Center, Carderock Division, Code 50.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

An experimental model test program investigated the close range interactions between a surface ship, including appendages and an operating propeller, and a whale at or near the water surface. A hull similar to a commercial container ship was tested in encounters with an instrumented whale model at a range of ship speeds, whale positions, and whale angles. Accelerations experienced by the whale model were recorded and analyzed to measure the severity of collisions.

15. SUBJECT TERMS
Shipstrike, North Atlantic Right Whale, Container Ship, Collision, Endangered Species

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Jonathan Slutsky
a. REPORT UNCLASSIFIED	**b. ABSTRACT** UNCLASSIFIED	**c. THIS PAGE** UNCLASSIFIED	SAR	0	**19b. TELEPHONE NUMBER** *(include area code)* 301-227-7010

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Contents

Tables

Figures

US CUSTOMARY AND METRIC EQUIVALENTS

1 foot per second (ft/s)	0.3048 meter per second (m/s)
1 knot	0.5144 meter per second (m/s)
1 pound force (lbf)	4.4480 newtons (N)
1 degree angle	0.01745 radians
1 horsepower (hp)	0.7457 kilowatts (kW)
1 long ton (LT)	1.016 metric ton, tonne (MT, t) 1016.0 kilograms (kg)
1 inch water @60 degrees Farenheit	248 pascals (Pa)

Abstract

An experimental model test program investigated the close range interactions between a surface ship, including appendages and an operating propeller, and a whale at or near the water surface. A hull similar to a commercial container ship was tested in encounters with an instrumented whale model at a range of ship speeds, whale positions, and whale angles. Accelerations experienced by the whale model were recorded and analyzed to measure the severity of collisions. The danger zone ahead of the ship (within which a whale would be run down) was identified.

Administrative Information

This test was performed at the David Taylor Model Basin in March 2007 under an with the National Marine Fisheries Service. The test was funded under Job Order Numbers 07-1-5200-209-10, 07-1-5200-210-10, and 07-1-5200-211-10.

Introduction

In the North Atlantic right whale (*Eubalenus glacialis*) population, ship-whale collisions (shipstrikes) are believed to be the major cause of human-related mortality.(Reference 1) The Large Whale Ship Strike Database reports 53 right whale shipstrikes, with 41 resulting in the confirmed death of the whale. The feeding and swimming habits of the right whale make it particularly vulnerable to shipstrike: it is a slow swimmer and diver that spends much of its time at or near the surface. The North Atlantic population is uniquely susceptible to shipstrike because the whales' feeding and calving grounds lie on or near major shipping lanes. (Reference 2) Shipstrike is also known to be a danger to other large whale species.

Numerical models based on spatial statistics (Reference 3) can predict when a collision is likely to occur, that is, when a notional ship form intersects with the coordinates of a simulated whale. The results from these studies are useful in examining the effects of high-level parameters such as the spatial distribution and movements of whales, but do nothing to address what happens when a ship and a whale are themselves in close enough proximity that a collision is likely to occur. Analytical potential flow studies (References 4 and 5), which do address the hydrodynamic forces when a ship and whale are in close proximity, have concentrated on the cases where the whale has been outside the width of the ship track, and predict that the ship's bow wave will deflect the animal away from the ship, and propeller suction will not be sufficient to draw it in.

The injuries reported in whales struck by ships seem to indicate that there are two potentially lethal injury mechanisms in a shipstrike event. The first is impact, where the force of the collision is sufficient to cause major blunt trauma to the whale's body. This type of injury kills by breaking bones and/or causing internal bleeding. The second mechanism is contact with the ship's propulsors, most commonly unshrouded propellers.

This usually results in large, deep cuts to the whale, up to and including the amputation of fins and flukes. Mortality here is due to blood loss.

This experiment was designed to test the close range interactions between a surface ship, including appendages and an operating propeller, and a whale at or near the water surface. The whale's position and orientation were varied with respect to the ship track, and a range of ship speeds covering the operating range of commercial vessels were tested.

Model and Instrumentation Description

The ship model was selected from among existing models for its size and similarity to current commercial Panamax container ship designs. Model 5665, with a scale ratio of $\lambda=24.67$ was selected because it possessed the desired design characteristics to represent a commercial container ship: an elliptical bow bulb with a fine entrance and large flare, a full midships section area, and a dry transom stern with a single skeg supported propeller. (Figure 1)

The model was instrumented with block gauges for drag and side force, a Taylor Model Basin (TMB) reluctance dynamometer and RPM pickup to measure propulsor performance, and trim pots fore and aft. A fixed platform towpost was used in the test. Thus the model was fixed in sinkage and rise, but permitted to trim. The model was ballasted to a full scale condition of 32,600 tonnes at a draft of 7.56 meters, approximately half of the design displacement for the specific vessel represented by the model, but representative of a broad range of commercial vessels.

Instrumentation selected for the whale model was a SnapShock triaxial accelerometer. This is a small (1.5"x3.2"x1.5", 7oz) accelerometer with built in timekeeping and data storage capabilities. When user selected thresholds for acceleration and/or velocity are exceeded, the instrument records acceleration and velocity data for a user defined time window or until another activation event occurs. A watertight enclosure was constructed for the instrument that controlled the alignment of the instrument's axes.

The overall dimensions of the whale were selected to match the scale of available ship models and to accommodate the instrument housing. Linear measurements were derived from the statistical review of available right whale morphology and body lines given in (Reference 6) so as to fall within the range of known full grown adults. (Figure 2) The shape of the jaw and appendages (fluke and fins) were simplified for strength and ease of construction. The center of mass was chosen to be at or near the volume centroid of the model & instrument assembly. No data was available on mass distribution in a living animal. The instrumented whale model possessed approximately 10% reserve buoyancy.

The whale was constructed from a thermoplastic resin according to 3D computer definitions using in-house rapid prototyping capabilities. Alignment tabs for the instrument casing were built into the whale model such that the coordinate system of the accelerometer was aligned with the major axes of the whale model's body. (Figure 3, Table 1)

The experimental conditions required the ability to control the lateral position and orientation of the whale in the test basin, but for the whale to be free floating at the time of the encounter with the ship. For this purpose, a retractable arm was constructed to mount to the existing wave probe support boom. (Figure 4) This arm consisted of two aluminum extrusions connected by a commercial spring hinge. A simple latching mechanism and retractable pin to hang the whale model were controlled by cable latches activated by a solenoid. The solenoid was activated by radio control from the towing carriage such that the whale model was held in place until a few seconds before the encounter with the ship model, then released. This system worked very efficiently throughout the test, allowing excellent control of the whale's position and initial angular orientation with very little drift between release and encounter.

A sketch of the overall testing arrangements are shown in Figure 5.

Experiments

Leaving aside whale depth and behavior, the controlling variables for a shipstrike event were believed to be (a) ship speed, (b) offset (whale distance from the ship centerline), and (c) orientation (whale angle relative to the ship course). (Figure 6, Table 2)

Ship speeds were set at 5 knot increments ranging from 5 knots to 25 knots. This range captures the operating speeds of all but the fastest commercial vessels from bare steerage way up through transit speeds.

Whale offset was measured from the point of release of the whale model, just aft of the point of maximum girth, and was tested at conditions representing full scale offset distances of 0 ft, 20 ft, 40 ft, and 60 ft, which corresponds to offset over half-beam ($O/B_{1/2}$) values of, 0, 0.38, 0.76 and 1.14. Panamax beam is 105 ft, thus the test conditions ranged from the centerline of the ship track to just outside the ship's beam.

Angle was measured between the ship's course and a line running along the whale's centerline from tail to head, such that a head-on (head to stem) collision is defined as 180 degrees, and an overtaking (tail to stem) collision is 0 degrees. Angles from 0 through 315 degrees were tested in 45 degree increments. In the range of angles where the initial impact was to the tail section of the whale model (roughly 315-0 degrees and 0-45 degrees), the whale model tended to respond in a manner that emphasized the fact that, unlike a living whale, the model was a rigid body, e.g. catching the tail on the stem of the ship and being pushed along. Because this response was obviously unrealistic, not to say hard on the model, fewer test runs were conducted at these angles, especially at higher ship speeds. Generally, three test runs were performed at each condition.

Representative photos of the test rig in operation are shown in Figure 7.

Results

The first result was to identify which combinations of offset, angle and ship speed led to a collision and which did not. For cases when a collision occurred, impact severity A_I was measured by identifying the maximum acceleration recorded in any of the whale fixed x y and z (longitudinal, transverse, or vertical) directions and taking the magnitude of the overall acceleration at that instant.

$$A_I = \sqrt{AX_{TPeak}{}^2 + AY_{TPeak}{}^2 + AZ_{TPeak}{}^2} \qquad (1)$$

Encounters that did not cause the accelerometer to activate (no acceleration component greater than 0.1 g and no velocity component greater than 1.0 ft/s) are assigned an arbitrary A_I of zero. This is not a perfect measure of collision severity, because it does not take into account successive peaks or the length of the encounter event, but it gives a reasonable figure of merit for comparing impact severity. Future experiments might consider measuring the whale's movements in an earth-fixed reference frame in order to correlate with the whale-fixed accelerations recorded by the instrument.

The primary factor in determining the likelihood of collision was whale offset distance. This makes perfect sense, since the fluid disturbance about of a moving ship is confined to the area immediately around the hull, so as the whale was positioned outside of that zone, the encounter quickly dropped off in severity. At the forty and sixty foot offset distances, only a small fraction of the encounters registered on the accelerometer. Impacts on the stem were also more severe than glancing blows along the ship's entrance for obvious reasons. (Figures 8 and 9)

Overall, the highest accelerations encountered were large enough to exceed the capacity of the accelerometer, registering approximately 17g in all three axes (a total magnitude of 30g) in high speed centerline collisions. As one would expect, severity of collision correlated closely with speed.

Orientation was not strongly related to impact severity, except in odd cases, such as a fin or fluke hanging into the path of the ship's stem. These cases should more properly considered as a subset of the offset problem, and have been removed from the dataset as outlying points. The effect of orientation at two ship speeds for the centerline offset are shown in Figure 10.

Tabular acceleration data are given in Appendix A.

Qualitatively, the results have a number of interesting features. For centerline conditions below 15 knots ship speed, the whale when struck rolled up and over the bow bulb, with the most severe impact appearing to come when the stem above the bulb hits the animal. At speeds of 15 knots and above, there was a marked increase in the violence of the collisions and a change in the response of the whale model. Hydrodynamic forces were sufficient to pin the whale to the bow bulb, and in some cases suck the whale under the bottom of the hull. In some cases it was seen to quickly surface a small distance aft and bounce down the side of the ship with a primarily vertical motion. In other cases, the whale passed completely under the ship and reappeared quite far aft.

This type of condition (the whale forced under the bow) produced the only propeller strike observed during testing. At a 25 knot ship speed, with the whale oriented broadside to the ship track on the centerline, it was sucked under the hull and was hit by the propeller. The initial prop impact occurred on the left side of the whale model, ahead of and above the pectoral fin. Subsequent prop scars are visible on the ventral surface of the whale, nearly on the centerline at about two thirds of the body length from the nose. (Figure 11) The oblique angle of the propeller impact marks relative to the whale model's centerline is consistent with observed results from real-world injuries. The spacing between the three sets of scars is not consistent with the continuous series of wounds observed, but the pairs of marks from successive blades are at comparable distances. (Figure 12) The propeller strike was clearly visible on the shaft line instrumentation, causing a distinct spike in thrust, torque, and RPM. (Figure 13)

Injuries to whales from real-world shipstrikes imply that propeller strikes are more common than the results of this experiment seem to show. It is not possible to draw any firm conclusions on the reasons for the discrepancy, but several possible explanations suggest themselves. First, the whale model was floating at the water surface for all the tests performed. This meant that the whole bulk of the ship was between the whale and the propeller at the beginning of an encounter. In order to contact the propeller, the whale had to be either drawn under the hull or sucked a significant distance under the transom. If the whale were at a depth comparable with the ship's draft during the encounter, the chances of a propeller strike might significantly increase.

Another possible explanation for the lack of propeller strikes is related to one of the fundamental compromises of the experimental design: the whale model is not only a rigid body, but is guaranteed to remain perfectly still during the encounter with the ship. For many testing conditions, the whale model passed very closely down the side of the ship. This frequently resulted in the whale model passing within two diameters of the propeller, and sometimes more closely than that. If the whale was not inert, but capable of a startle or escape response (e.g an attempt to dive), it is possible that the animal's action could bring it into contact with the propeller.

At the twenty and forty foot offset distances, light impacts occurred some distance down the ship's entrance from the stem, as one would expect. From the point of contact, the whale model slid down the ship's side, either in contact with the skin of the ship or very close to it. The whale model did not come in contact with the propeller as the stern passed, but it was observed to turn such that the nose faced the propeller inflow. This behavior appeared to be somewhat speed dependent, with a tighter turn observed at higher ship speeds. Increasing propeller RPM beyond the self-propulsion point also increased the observed response.

At the sixty foot offset distance, the whale model showed little or no response to the ship either quantitatively or qualitatively.

Response of the whale model to the ship's bow wave was less than expected. The results of the Knowlton et al. potential flow simulation (Reference 4 and 5) predicted significant sway response from the bow wave, sufficient to move the whale out of the way of the ship when it was positioned just inside the maximum ship beam. At the 20 and 25 knot speeds the ship generates a significant bow wave, but the whale model was observed to respond with one cycle of primarily vertical disturbance, with little or no noticeable horizontal movement.

The results of this experiment also have implications for the study of physiological injury mechanisms in real world shipstrikes. Ship speed does have a substantial influence on impact severity, but it is beyond the scope of this project to consider precisely how the measured accelerations might relate to the lethality of a collision. The behavior of the whale model in low speed centerline collisions appears to correlate well to certain types of reported injuries: blunt trauma to the whale's head or abdomen, and the occasional cases where an animal is carried into port wrapped around a ship's stem, but this is a speculative judgment and only deals with a single type of collision. The results of this experiment might be of interest to biologist or physiologist considering the probable effects of the impact on a living whale.

Conclusions

This experiment demonstrated the basic hydrodynamics of an encounter between a ship and a floating body, and also provided some insight into the dynamics of the specific ship-whale case.

Major conclusions are:

- The greatest accelerations experienced by the whale model occurred at the centerline (0 ft) offset condition.

- Measured accelerations experienced by the whale model appear to fall off exponentially with offset distance.

- At the centerline and 20ft offset conditions ($0<O/B_{1/2}<0.38$), mean measured acceleration is highly dependent on ship speed.

- At the 40ft and 60ft offset conditions ($0.76<O/B_{1/2}<1.14$), measured accelerations were less than one g (32.2 ft/s^2), and most encounters were not sufficient to trigger the accelerometer at all.

- The ship's bow wave did not impart significant sway force to the whale model. No deflection away from the ship track was observed.

- This suggests that in terms of measured accelerations, the danger zone is narrower than the overall beam. Using an arbitrary cutoff of 2g (64.4 ft/s^2) gives a danger zone approximately 35 feet wide, or 1/3 the overall ship beam.

- Peak measured accelerations vary significantly from event to event, especially within the centerline offset condition. This may indicate that some aspect of the collision dynamics is not being captured by the current experimental configuration.

- The likelihood of collision is controlled entirely by whale offset from the centerline of the ship track. The flow about the ship was not observed to significantly deflect the whale model in the lateral direction under any test conditions.

- The orientation of the whale relative to the ship track does not appear to significantly effect collision severity, though this may in part be a result of the use of a rigid body whale model.

- Propeller suction was sufficient to change the orientation of the whale model, but not to draw it into the blades.

- Contact with the propeller was observed only in a case when the whale was first sucked under the hull by the bow.

Acknowledgments

Mr. Hung Vo of Code 53 designed the whale instrumentation system and remote control release mechanism and provided invaluable assistance during the test. Mr. Ryan Hanyok of Code 34 provided excellent video support throughout the test despite acting at short notice.

THIS PAGE INTENTIONALLY LEFT BLANK

Tables

Table 1 – Whale Model Particulars

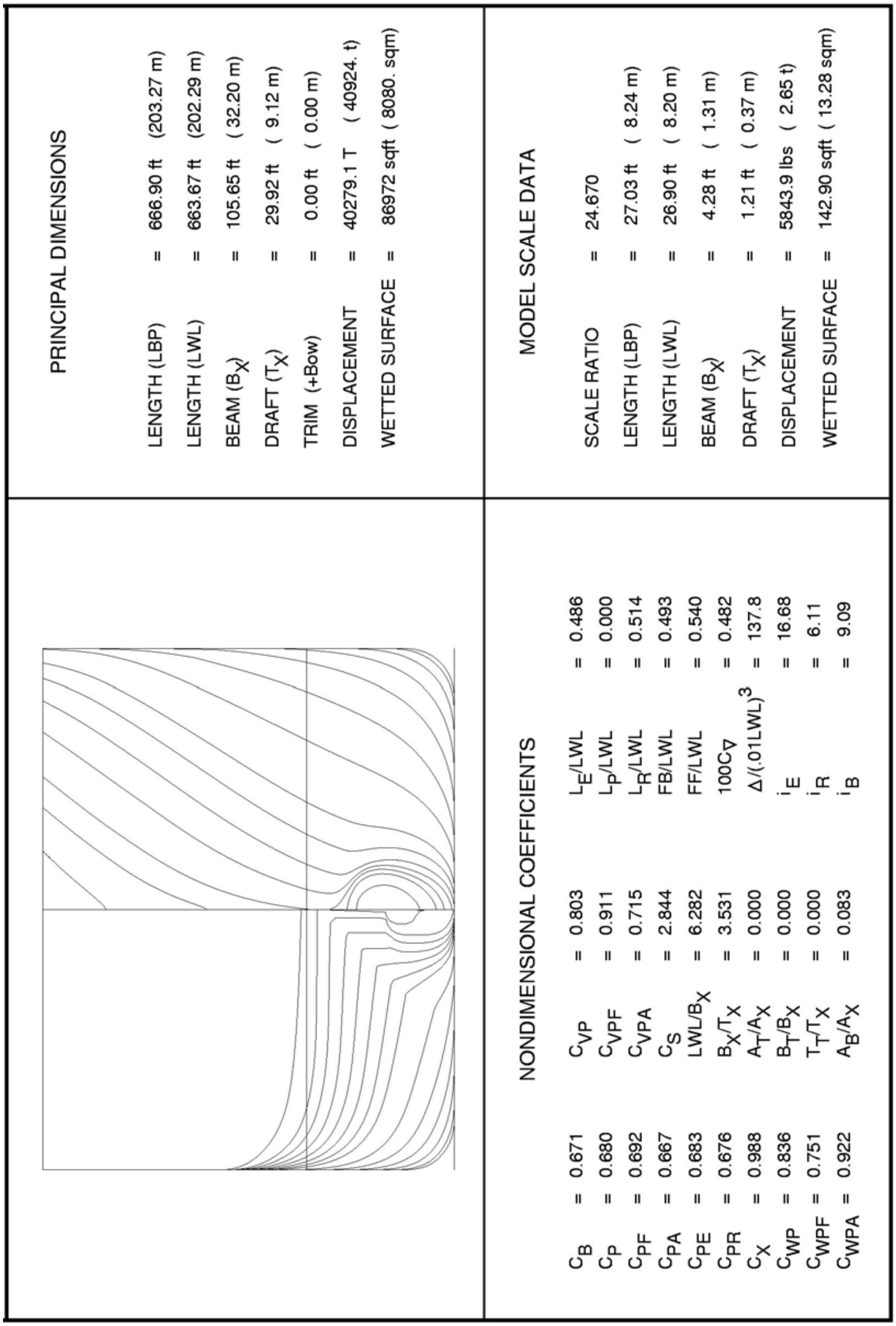
	Model	Full Scale
Length Overall (cm)	54.91	1354.6
Length to Base of Tail (cm)	44.78	1104.7
Maximum Width (cm)	12.37	305.2
Flipper Length (cm)	13.69	337.7
Fluke Width (cm)	19.69	485.8
Maximum Girth (cm)	39.51	974.7
Mass (kg)	3.097	46500
Volume (cm^3)	3380.82	5.08E+07
% Reserve Buoyancy	8.30%	10.71%

Table 2 – Experimental Matrix

Ship Speed (kts)	Centerline			20ft Offset			40ft Offset			60ft Offset		
	↓↑	←→	↘↗	↓↑	←→	↘↗	↓↑	←→	↘↗	↓↑	←→	↘↗
5	●	●	●	●	●	●	●	●	●	●	●	●
10	●	●	●	●	●	●	●	●	●	●	●	●
15	●	●	●	●	●	●	●	●	●	●	●	●
20	●	●	●	●	●	●	●	●	●	●	●	●
25	●	●	●	●	●	●	●	●	●	●	●	●

THIS PAGE INTENTIONALLY LEFT BLANK

Figures



PRINCIPAL DIMENSIONS

LENGTH (LBP)	= 666.90 ft	(203.27 m)
LENGTH (LWL)	= 663.67 ft	(202.29 m)
BEAM (B_X)	= 105.65 ft	(32.20 m)
DRAFT (T_X)	= 29.92 ft	(9.12 m)
TRIM (+Bow)	= 0.00 ft	(0.00 m)
DISPLACEMENT	= 40279.1 T	(40924. t)
WETTED SURFACE	= 86972 sqft	(8080. sqm)

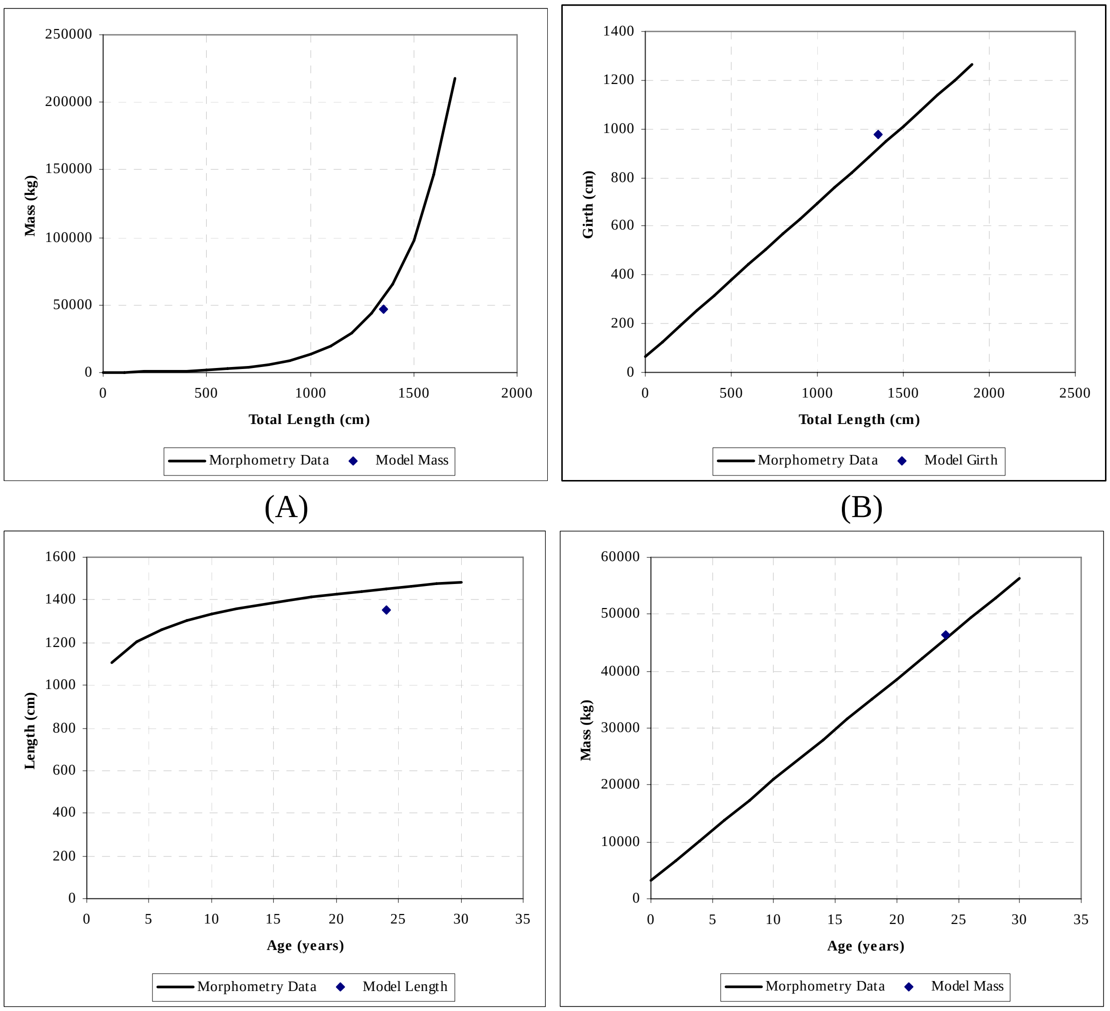
MODEL SCALE DATA

SCALE RATIO	= 24.670	
LENGTH (LBP)	= 27.03 ft	(8.24 m)
LENGTH (LWL)	= 26.90 ft	(8.20 m)
BEAM (B_X)	= 4.28 ft	(1.31 m)
DRAFT (T_X)	= 1.21 ft	(0.37 m)
DISPLACEMENT	= 5843.9 lbs	(2.65 t)
WETTED SURFACE	= 142.90 sqft	(13.28 sqm)

NONDIMENSIONAL COEFFICIENTS

C_B	= 0.671	C_{VP}	= 0.803	L_E/LWL	= 0.486
C_P	= 0.680	C_{VPF}	= 0.911	L_P/LWL	= 0.000
C_{PF}	= 0.692	C_{VPA}	= 0.715	L_R/LWL	= 0.514
C_{PA}	= 0.667	C_S	= 2.844	FB/LWL	= 0.493
C_{PE}	= 0.683	LWL/B_X	= 6.282	FF/LWL	= 0.540
C_{PR}	= 0.676	B_X/T_X	= 3.531	$100C_\nabla$	= 0.482
C_X	= 0.988	A_T/A_X	= 0.000	$\Delta/(.01LWL)^3$	= 137.8
C_{WP}	= 0.836	B_T/B_X	= 0.000	i_E	= 16.68
C_{WPF}	= 0.751	T_T/T_X	= 0.000	i_R	= 6.11
C_{WPA}	= 0.922	A_B/A_X	= 0.083	i_B	= 9.09

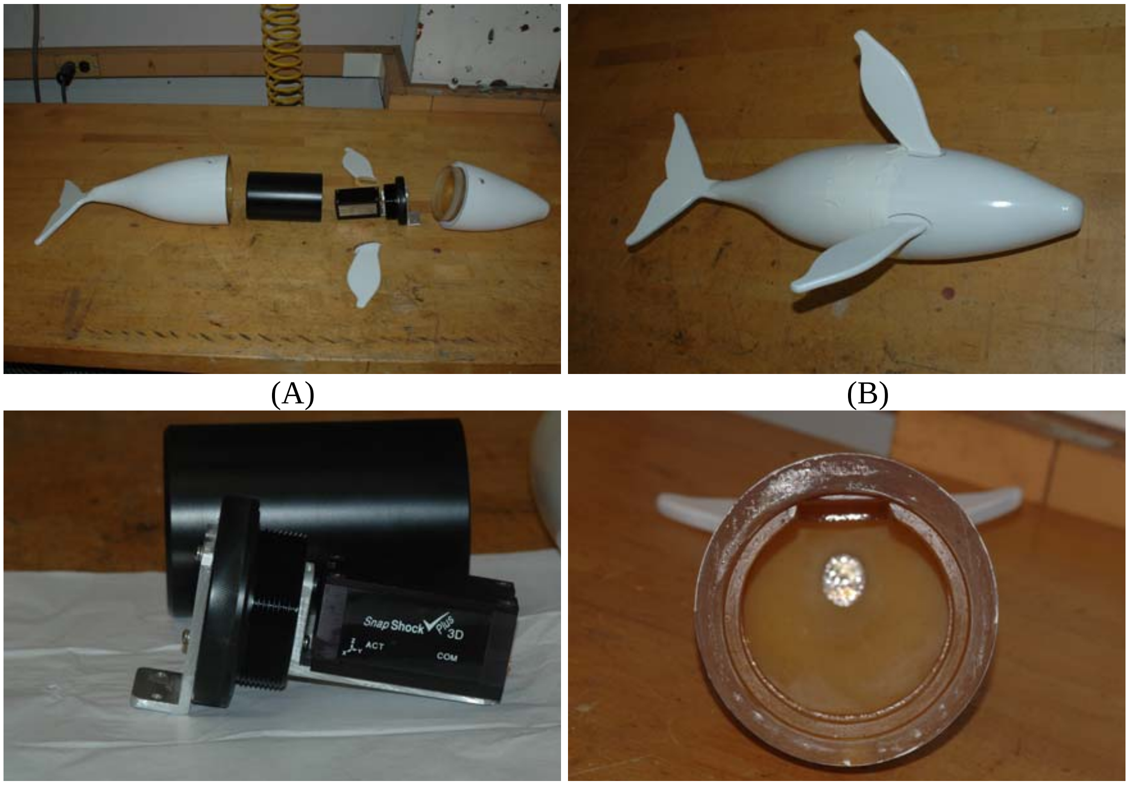
Figure 1 – Particulars of Model 5665



(A) (B)

(C) (D)

Figure 2: Whale model dimensions as compared to trendlines derived from morphology data from whale necropsies (A) Length vs Mass (B) Length vs Girth (C) Age vs Length (D) Age vs Mass



(A) (B)

(C) (D)

Figure 3 – Whale Model: (A) Overview of whale model components (B) Assembled whale model (C) accelerometer and instrument casing (D) Interior view of whale afterbody showing alignment tab for instrument casing

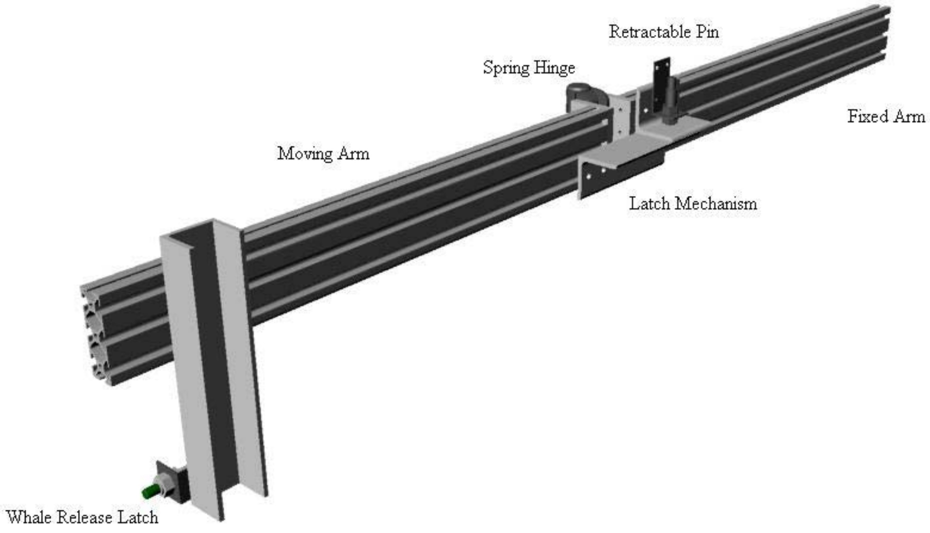


Figure 4 – Release Mechanism

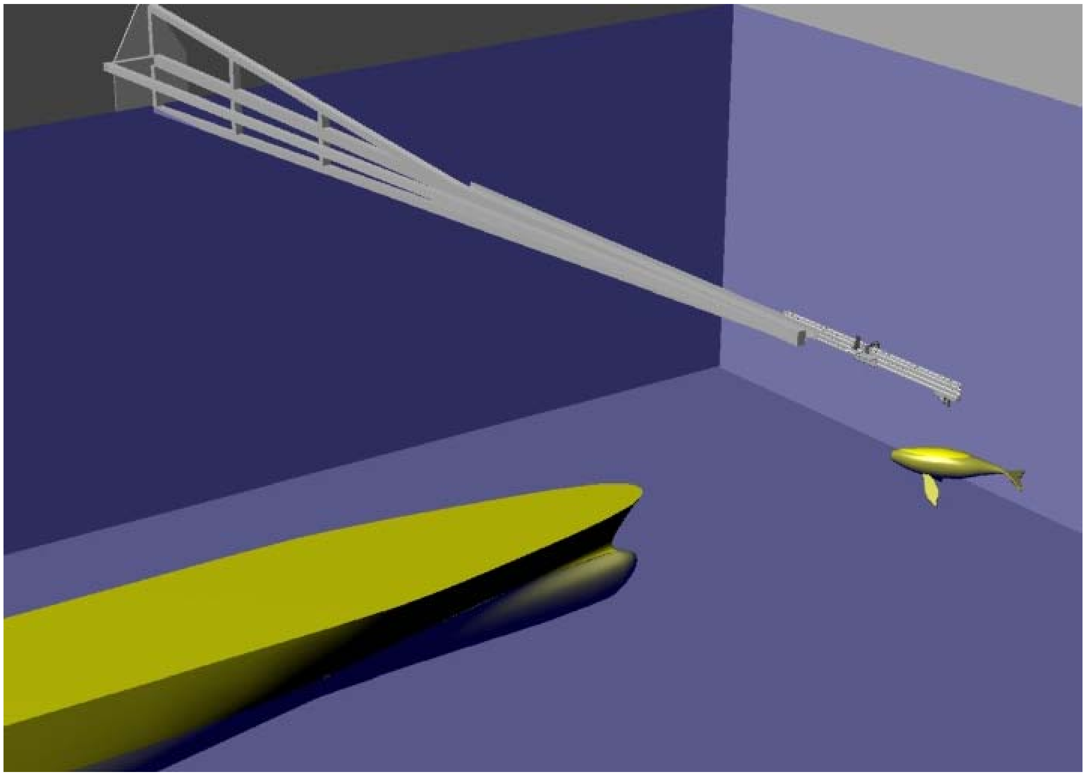


Figure 5 – Test Arrangements Overview

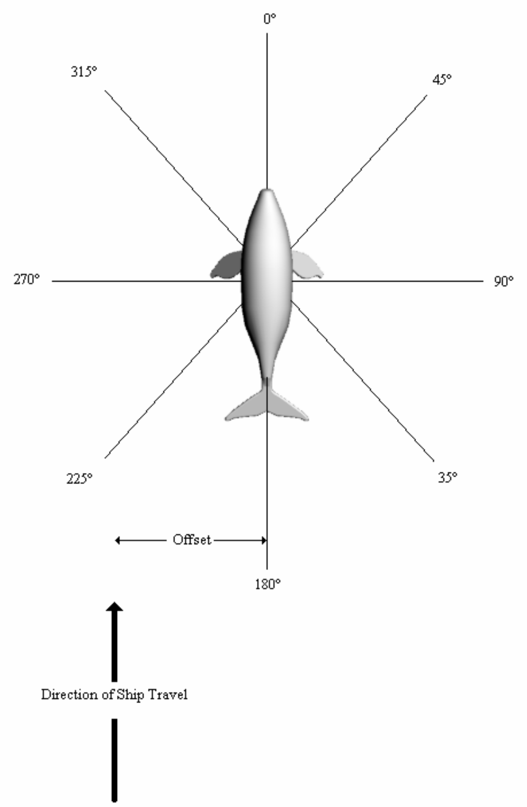
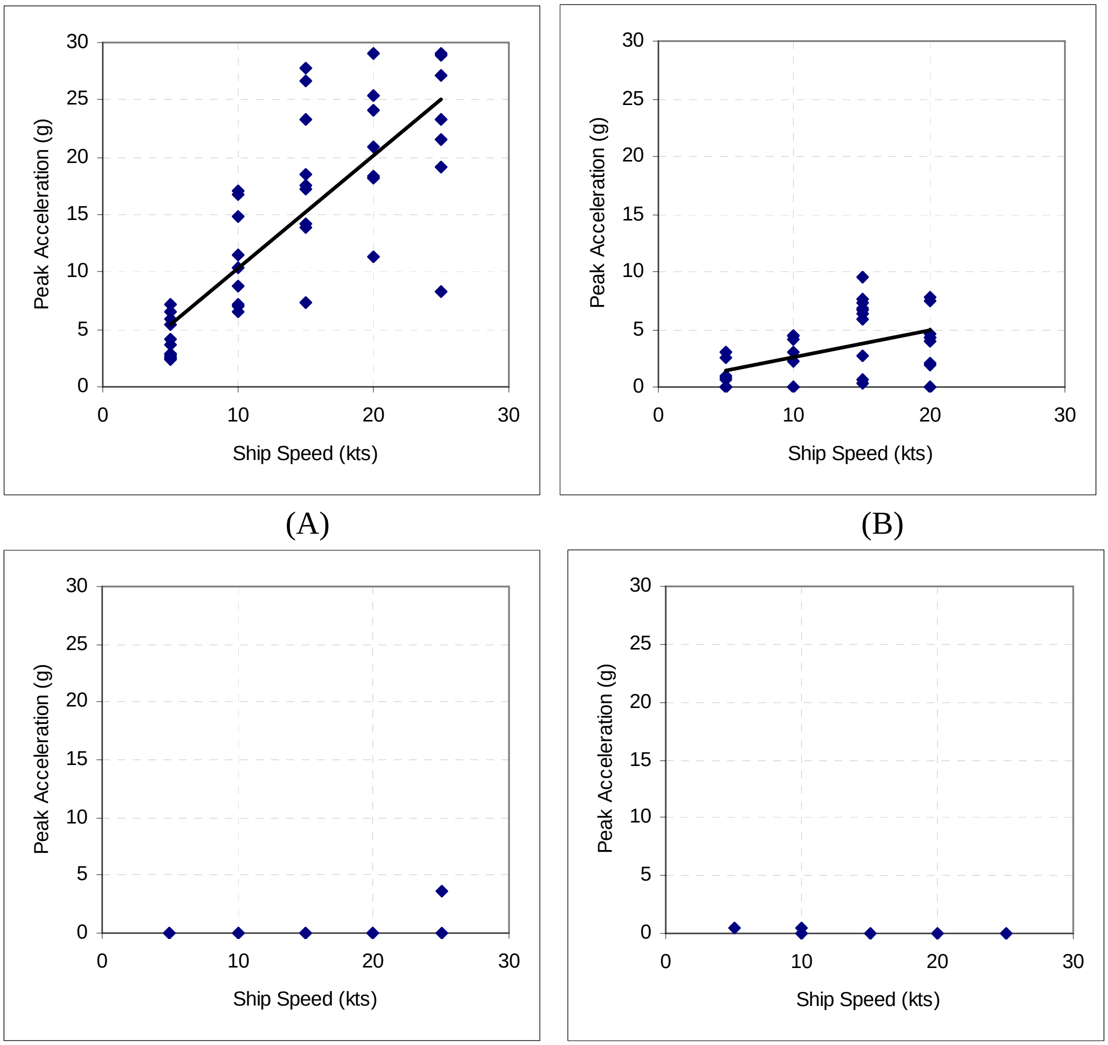


Figure 6 – Test Geometry

Figure 7 – Photos of Test in Progress



(A) (B)

(C) (D)

Figure 8 – Acceleration Magnitude versus speed for all orientations at (A) Centerline, O/B$_{1/2}$=0 (B) 20ft, O/B$_{1/2}$=0.38 (C) 40ft, O/B$_{1/2}$=0.76 (D) 60ft, O/B$_{1/2}$=1.14 offset distances

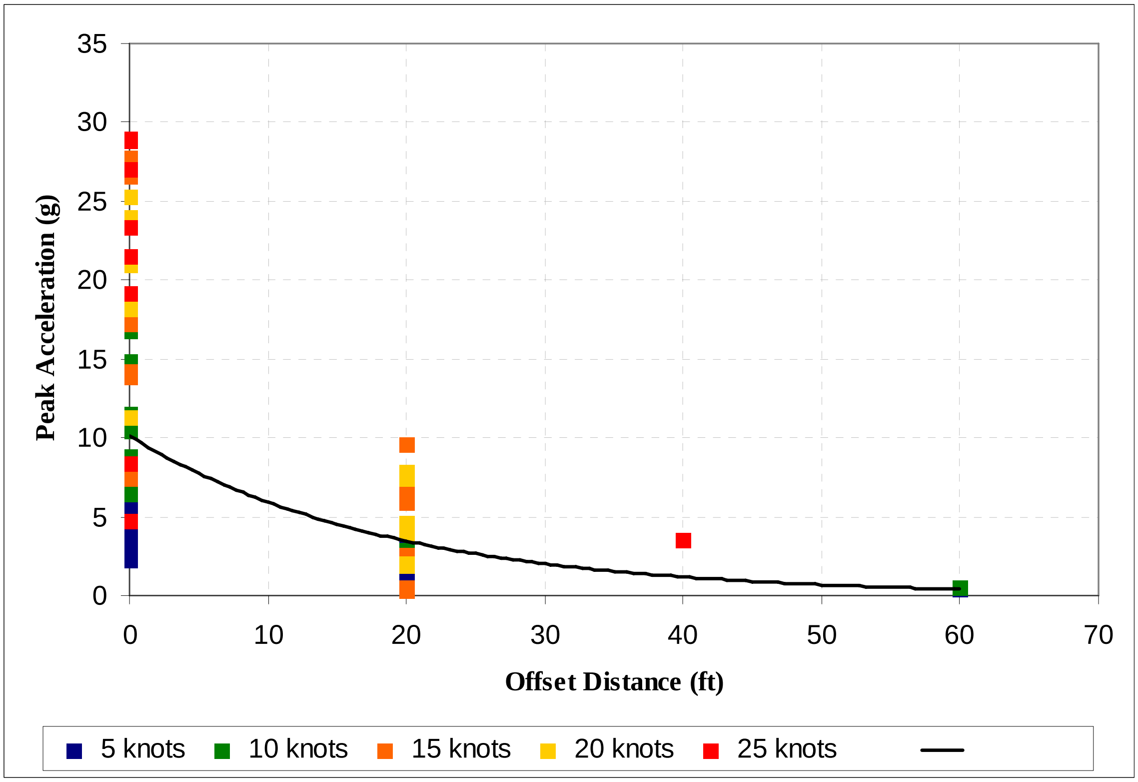
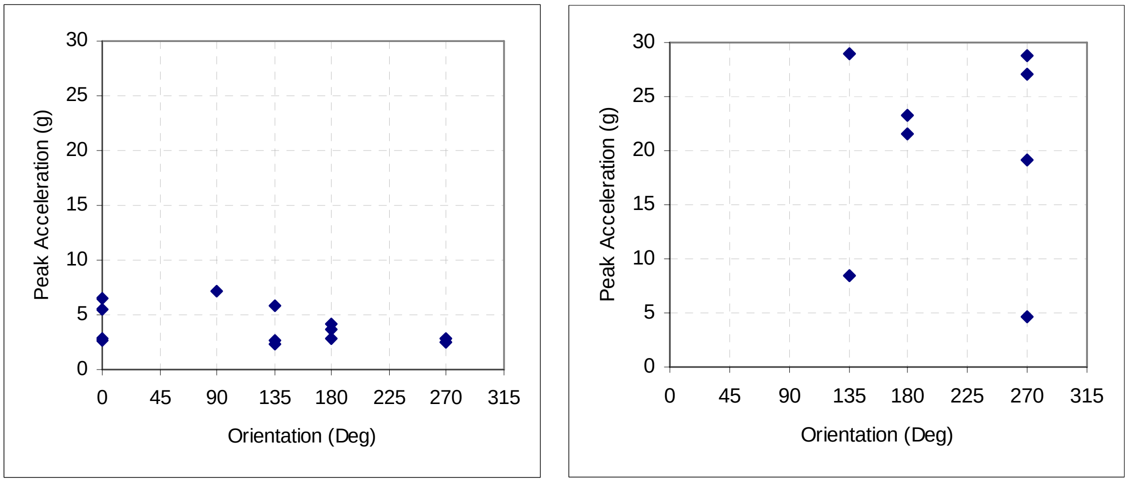


Figure 9 – Acceleration Magnitude versus offset distances for all speeds and orientations



(A) (B)

Figure 10 – Acceleration Magnitude versus orientation for (A) 5 knot (B) 25 knot ship speeds

(A) (B)

Figure 11 – Propeller impact damage to whale model. (A) Initial strike on forward left quarter of whale (B) Subsequent strikes near centerline on afterbody. Damage to fin attachment point is not due to propeller strike

Figure 12 – Propeller Injuries to North Atlantic Right Whales. Note angle of propeller wounds relative to whale centerline. Photos courtesy of NOAA and Center for Coastal Studies.

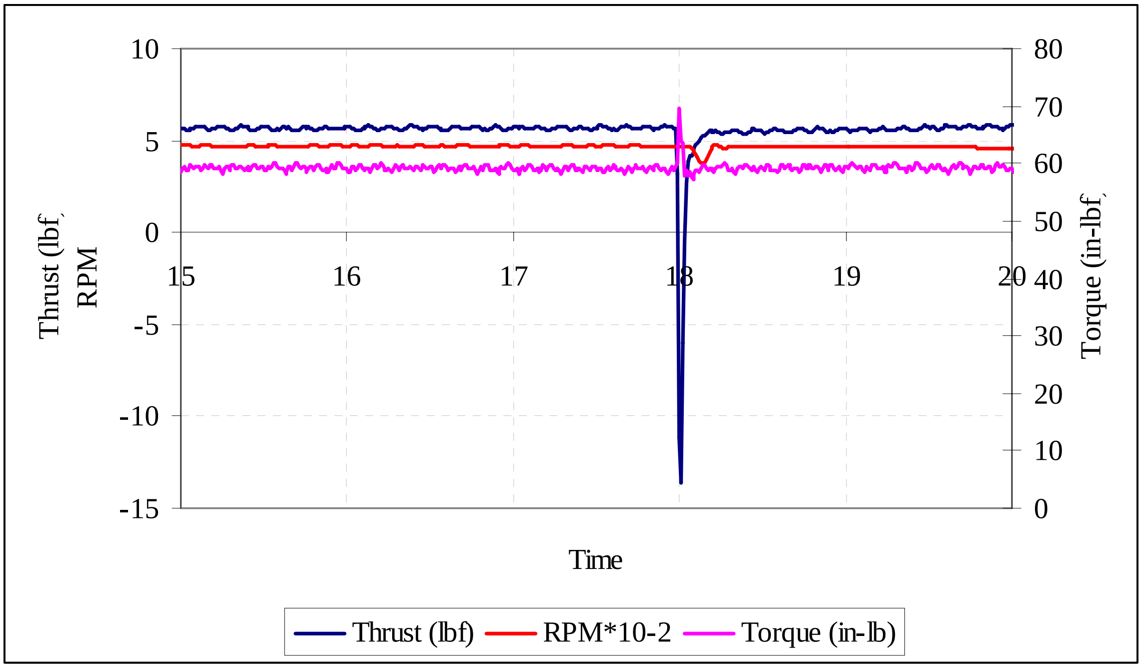


Figure 12 – Instrument Records of Prop Strike

THIS PAGE INTENTIONALLY LEFT BLANK

References

1. Jensen, A.S. and G.K. Silber. 2003. *Large Whale Ship Strike Database*. U.S. Department of Commerce, NOAA Technical Memorandum.

2. Ward-Geiger et al. 2005. *“Characterization of Ship Traffic in Right Whale Critical Habitat.”* Coastal Management Vol. 33.

3. Clyne, H. and J. Kennedy. 1999. *“A simulation of interactions between the critically endangered North Atlantic Right Whale (Eubalaena glacialis) and shipping using dynamically variable temporal granularity to minimise run time.”* Masters thesis (MSc), Napier University, Edinburgh. Abstract and summary located at http://www.nero.noaa.gov/shipstrike/Clyne99summary.pdf

4. Knowlton, A. R., F.T. Korsmeyer, J.E. Kerwin, H.Y. Wu and B. Hynes. 1995. “*The Hydrodynamic Effect of Large Vessels On Right Whales.*” NMFS Contract No. 40EANFF400534. http://www.nero.noaa.gov/shipstrike/WhatsNew/Knowlton et al,1995.pdf

5. Knowlton, A. R., F.T. Korsmeyer, B. Hynes. 1998. “*The Hydrodynamic Effect of Large Vessels On Right Whales Phase II.*”. NMFS Contract No. 46EANF60004. http://www.nero.noaa.gov/shipstrike/WhatsNew/Knowlton et al,1998.pdf

6. Moore et al., *“Morphometry, gross morphology and available histopathology in North Atlantic right whale (Eubalena glacialis) mortalities (1970-2002)”* Journal of Cetacean Research Management, Vol 6.

Appendix A - Tabular Data

Qualitative Assessment of Impact Severity

🔴	Severe
🟠	Moderate
🟢	Light
☐	Miss

Blank acceleration records indicate accelerations below instrument threshold

Ship Speed (kts)	Whale Offset (ft)	Whale Orientation (deg)	Collision	Max Accel X (g)	Max Accel Y (g)	Max Accel Z (g)	RMS Max (g)
5	0	0	🔴	-2.921	4.250	1.741	5.443
5	0	0	🔴	2.954	5.683	1.365	6.549
5	0	0	🔴	0.588	0.964	2.682	2.910
5	0	0	🔴	0.331	0.651	2.526	2.629
5	0	90	🔴	-7.232	0.288	-0.204	7.241
5	0	135	🔴	-2.512	0.728	0.233	2.626
5	0	135	🔴	-2.240	0.548	0.194	2.314
5	0	135	🔴	-3.846	-4.358	0.737	5.859
5	0	180	🔴	-0.496	-1.977	3.622	4.156
5	0	180	🔴	0.306	-1.293	2.428	2.768
5	0	180	🔴	0.546	-1.532	3.311	3.689
5	0	270	🔴	2.797	-0.214	-0.221	2.814
5	0	270	🔴	2.433	-0.346	-0.262	2.471
10	0	90	🔴	-9.094	4.867	1.586	10.436
10	0	90	🔴	2.698	-2.528	5.306	6.467
10	0	135	🔴	-7.083	-0.507	0.000	7.101
10	0	135	🔴	6.686	2.067	-0.654	7.029
10	0	135	🔴	14.663	-6.457	-5.126	16.822
10	0	180	🔴	11.518	-9.298	-1.365	14.865
10	0	180	🔴	3.293	-6.976	4.325	8.844
10	0	180	🔴	10.360	-4.802	-1.153	11.477
10	0	180	🔴				
10	0	180	🔴				
10	0	270	🔴	15.043	-4.283	-6.990	17.132
15	0	135	🔴	16.864	-16.587	-12.158	26.596
15	0	135	🔴	16.839	-11.818	-10.980	23.319
15	0	135	🔴	16.839	-16.579	-14.668	27.813
15	0	180	🔴	0.629	-16.595	-5.846	17.606
15	0	180	🔴	-7.265	-16.579	-3.516	18.439
15	0	180	🔴	6.156	-16.060	-1.652	17.279

Ship Speed (kts)	Whale Offset (ft)	Whale Orientation (deg)	Collision	Max Accel X (g)	Max Accel Y (g)	Max Accel Z (g)	RMS Max (g)
15	0	180	🔴	3.244	-6.465	-1.529	7.393
15	0	270	🔴	13.562	0.321	-4.121	14.178
15	0	270	🔴	0.455	-4.744	13.024	13.869
20	0	90	🔴	-15.689	7.610	-5.184	18.192
20	0	135	🔴	16.806	-16.595	-9.092	25.308
20	0	135	🔴	-5.999	-2.685	9.173	11.285
20	0	135	🔴	16.814	-16.620	-16.736	28.966
20	0	180	🔴	6.297	-16.612	4.276	18.273
20	0	180	🔴	15.805	-13.433	-2.919	20.947
20	0	180	🔴	16.856	-16.579	-4.440	24.056
20	0	270	🔴	16.756	-4.274	-5.715	18.212
25	0	135	🔴	16.847	-16.686	-16.736	29.023
25	0	135	🔴	2.185	4.390	-6.786	8.372
25	0	180	🔴	-11.808	-16.620	6.974	21.547
25	0	180	🔴	-16.053	-16.645	2.992	23.318
25	0	270	🟠	2.094	-3.163	-2.804	4.717
25	0	270	🔴	16.632	-16.636	-16.736	28.870
25	0	270	🔴	16.922	-16.711	-12.902	27.057
25	0	270	🔴	-7.555	-16.653	-5.707	19.156
5	20	45	🟠				
5	20	45	🟠	0.554	0.346	-0.417	0.775
5	20	90	🟠	-1.589	-1.985	0.294	2.560
5	20	135	🟠	0.000	-2.685	-1.194	2.939
5	20	135	🟠	-0.530	-2.775	-1.112	3.036
5	20	180	🟠	0.223	-0.947	0.213	0.996
5	20	180	🟠	0.521	-0.214	-0.221	0.605
5	20	270	🟠				
5	20	270	🟠				
5	20	270	🟠				
10	20	0	🟠	2.590	0.461	-1.357	2.960
10	20	45	🟠				
10	20	90	🟠	-1.341	1.705	0.491	2.224
10	20	135	🟠	-1.026	-3.896	-1.987	4.492
10	20	135	🟠	-0.571	-3.648	-1.660	4.048
10	20	180	🟠	-3.376	-1.614	-2.387	4.438
10	20	180	🟠	-3.550	-1.557	-2.289	4.502
10	20	180	🟠				
10	20	270	🟠				
15	20	0	🟠	3.202	5.518	3.696	7.373
15	20	45	🟠	-2.383	-0.214	-1.112	2.638
15	20	90	🟠	-5.494	-5.098	-1.390	7.623
15	20	135	🟠	-2.532	-4.826	-2.314	5.921
15	20	135	🟠	-0.869	-8.730	-3.835	9.575
15	20	180	🟠	-5.759	-1.754	-3.115	6.778
15	20	180	🟠	-5.453	-2.495	-2.870	6.648
15	20	180	🟠	-5.370	-2.042	-2.870	6.422
15	20	270	🟠	0.480	0.247	0.204	0.577

Ship Speed (kts)	Whale Offset (ft)	Whale Orientation (deg)	Collision	Max Accel X (g)	Max Accel Y (g)	Max Accel Z (g)	RMS Max (g)
15	20	270	🟠	-0.199	0.000	-0.213	0.291
20	20	0	🟠	3.343	1.005	-2.469	4.276
20	20	90	🔴	-6.065	-2.751	-4.096	7.819
20	20	135	🟠	-1.829	-3.031	-1.880	4.008
20	20	135	🟠	-2.300	-2.932	-2.060	4.258
20	20	180	🟠	-3.848	-1.532	-2.118	4.652
20	20	180	🟠	-6.231	-1.787	-3.573	7.402
20	20	270	🟠	-0.364	-2.001	-0.294	2.055
20	20	270	🟠	-0.348	-1.837	-0.384	1.909
5	40	135	🟢				
5	40	180	🟢				
10	40	135	🟢				
10	40	180	🟢				
15	40	135	🟢				
15	40	180	🟢	3.053	-16.571	-7.865	18.595
15	40	180	🟢				
20	40	135	🟢				
20	40	180	🟢				
25	40	135	🟢				
25	40	180	🟢	0.662	-3.179	-1.513	3.582
5	60	180	☐	-0.348	0.000	0.213	0.408
10	60	180	☐				
10	60	180	☐	0.414	0.222	-0.213	0.516
15	60	180	☐				
20	60	180	☐				
25	60	180	☐				

DISTRIBUTION

Number of Copies	Office	Individual	Total Copies
5	National Marine Fisheries Service 1315 East-West Highway Silver Spring, MD 20910	Gregory Silber	5
2	NAVAIR Engineering Station Lakehurst, NJ 08733	Michael Benulis	7
1	5300	Hung Vo	8
1	5010		9
1	5060	Dave Walden	10
1	DTIC		12
1	3452 (Library)	PDF Only	12
2	5200	5200 Office Files	13
13	5200	Slutsky, Karafiath, Day	26