THE HYDRODYNAMIC EFFECTS OF LARGE VESSELS ON RIGHT WHALES: PHASE TWO

Amy R. Knowlton[1], F. Thomas Korsmeyer[2], and Brodie Hynes[2]

[1] New England Aquarium
Central Wharf
Boston, MA 02110

[2] Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

Final Report
May, 1998

In fulfillment of Contract No. 46EANF60004

National Marine Fisheries Service
Northeast Fisheries Science Center
166 Water Street
Woods Hole, MA 02543

INTRODUCTION

The impact of ship collisions on North Atlantic right whales has been defined as a major factor contributing to their apparent lack of recovery (NMFS 1991). A minimum of 15 right whales are known to have died from ship collisions between 1972 and 1997, with eight of these mortalities occurring in the 1990's (Knowlton and Kraus, In prep.). This number is underestimated as some carcasses were not retrieved or adequately necropsied to determine cause of death, and some number of floating carcasses go undetected. With an estimated population size hovering between 300-350 individuals, these human related mortalities need to be minimized to allow the population to attain the highest possible recovery level.

The documented right whale/ship strike interactions have occurred all along the eastern seaboard. Little is known about how or why these collisions occur, or what could be done to reduce the chance of a ship strike. This report focuses on one possible influential factor, the hydrodynamic effects of ships on right whales. It is well documented that ships operating in proximity can induce hydrodynamic forces on each other that can lead to collisions even though the ships appear to be on courses that should not intersect. Determining whether these hydrodynamic influences could make a passing ship situation more dangerous to right whales by drawing the whale into the ship was the focus of a previous research project performed by these co-collaborators (Knowlton et al., 1995). This project expands on this previous work to further refine and elaborate on some of the initial findings.

The initial study (Knowlton et al., 1995) used an existing computer program, which computes the forces created by pressure fields as the water moves around the ship's hull, and extended it to include the calculation of the rigid-body motion of a whale due to the hydrodynamic forces. This allowed for simulation of the movement of the whale in relation to the passing ship. Three of the forces imposed on a whale by a passing ship (sway, surge, and yaw) were calculated for three different vessels with a whale placed at varying lateral offsets from the side of the vessel. Of particular interest was determining where the whale has to be in relation to the passing ship in order to avoid collision. For the situation where a passive whale at 5.5 meters below the surface was placed one ship's length in front of the approaching ship and 1.5 meters inside the maximum beam width of the ship, the initial positive sway force induced by the passing bow pushed the whale away from the ship before drawing it back in, and the whale did not collide with the ship. However, in a simulation where the whale surfaced or "appeared" in proximity to a passing ship and was not exposed to the initial positive sway force, the whale did get drawn into the ship from a distance of at least 3 meters.

A number of further analyses were carried out under the second phase of this project to gain a better understanding of a number of different whale/vessel scenarios. First, the maximum distance that a passive whale could be inside the beam without colliding with a given ship was more precisely determined. Second, the maximum distance outside the track of a given ship that a whale may "appear" and be drawn into the ship was ascertained. Third, the modeling capability was extended to include vertical forces and motions in addition to the existing horizontal forces and motions. This allowed for modeling of situations where the whale is submerged below the ship. The effect of water depth in these situations was also investigated. And lastly, the computer code was extended to allow for the inclusion of a simple behavior model for the whale. Although the first study found that the hydrodynamic effects on a passive whale were independent of ship speed, speed was identified as a factor if a whale tries to actively escape the approaching vessel, thus these behavioral scenarios were evaluated using different ship speeds.

METHODS

Computer code

A time domain, potential flow computer code, used to model ships passing in a channel of specified depth and width, was modified to simulate the hydrodynamic effects of a passing ship on a whale. In this model, free-surface effects are considered unimportant relative to other hydrodynamic effects, an assumption which increases in validity as ship speed decreases or as whale submergence increases. Details of this computer code are described in Korsmeyer et al., 1993 and Knowlton et al., 1995 and will not be elaborated on here. The code was expanded for this analysis to include vertical forces and motions. This current version of the code was verified using the same parameters described in the earlier report (Knowlton et al., 1995).

Ship and whale measurements used in simulations

The three ships chosen for the simulations were a DDG51 (a Navy destroyer: length 150 meters, draft - 9.3 meters, beam - 18 meters), an SL-7 (a cargo ship: length - 300 meters, draft - 11.5 meters, beam - 36 meters), and a VLCC (very large crude carrier: length - 300 meters, draft - 15.4 meters, beam - 50 meters). The DDG51 is a fine, low-volume hull, the SL-7 is fine at the bow and full in the midship section, and the VLCC is full throughout with a bluff bow. The whale used in the simulations was of length - 15 meters, beam - 3.08 meters, and draft - 3 meters (Table 1) (Knowlton et al., 1995).

Passive and appearing whale simulations

Simulations were conducted for each of these ships both for a passive whale placed one ship length in front of the approaching vessel at different offsets from the midline of the ship and at varying depths, and for an "appearing" whale (for example, a whale which has been diving that appears in proximity to the ship) with zero velocity situated three meters forward of the bow of the ship at varying distances from the midline of the ship and at varying depths. A water depth of 20 meters was used. The "effective beam", or the distance from the centerline at which the whale is hit by the ship was determined for these two types of situations. In describing the effective beam, the actual beam of the ship is equal to 1.0 and effective beam is described in 1/10th increments less than, equal to, or greater than 1.0 (Figure 1).

Whale under vessel simulations

A whale submerged below the draft of an approaching ship may be in danger from hydrodynamic forces, especially when in shallow water. The computer code is not able to simulate what occurs after a whale hits the sea floor or hits the ship, but calculations were carried out to describe when such events occurred. For these simulations, the whale was placed at a depth of 18 meters, the vessel used was a VLCC with a draft of 15.5 meters, and the water depths used ranged from 20 meters to 32 meters.

Incorporation of whale behavior

The role that whale behavior might play in their ability to escape an approaching ship was assessed. A whale moving perpendicularly away from the ship at an initial speed of five knots at a depth of 10 meters was simulated using the VLCC. The whale was placed at distances of 0, 12.5, 25, 33, 40, 43, and 50 meters (offsets from 0.0 to 2.0) from the centerline of the vessel at a starting point three meters forward of the bow of the approaching ship, similar to the "appearing" whale situations. Ship speeds of 10, 15, and 20 knots were tested.

Force decay and whale path

The surge, sway, and yaw forces on an appearing whale at varying distances from the VLCC ship were calculated to estimate how far away the whale had to be from the ship to not feel any effects from the passing ship. The distances tested were, from the centerline, 25, 50, 100, 200, and 500 meters.

The relative movement of the whale horizontally and vertically through the water column were simulated for the VLCC with the whale at six meters depth for both the passive and appearing whale scenarios. The effect of the orientation of the whale on these relative movements was tested.

RESULTS

Passive whale simulations

For each ship, passive whale simulations were carried out for the whale placed at offsets from the midline ranging from 0 to 1.0 at 1/10th or 2/10th increments and whale depths ranging from 4 to 18 meters in 2 meter increments. A 1/10th increment of offset is equal to 0.9 meters for the DDG, 1.8 meters for the SL-7, and 2.5 meters for the VLCC. The results of these simulations are summarized in Table 2. The data indicate that the effective beam is 0.9 for the Navy destroyer, 1.0 for the SL-7., and 0.8 for the VLCC. The depth of the whale affected the offset at which the whale would get hit. For the Navy destroyer, the highest effective beam (0.9) occurred when the whale was at a depth of 4 meters. The effective beam dropped substantially with each 2 meter increase in whale depth. For the SL-7., the effective beam of 1.0 occurred when the whale was placed at a 6 meter depth. At 4 meters and 8 meters, the effective beam only dropped to 0.9. It dropped to 0.8 when the whale was at a 10 meter depth and 0.7 at a 12 meter depth. For the VLCC, the effective beam remained at 0.8 when the whale was anywhere from 4 to 10 meters deep. The effective beam dropped to 0.6 when the whale was at depths of 12 and 14 meters, but the whale still collided with the ship at 16 and 18 meter depths at a 0.0 offset, even though a whale at 18 meters was well below the ships draft of 15.4 meters. In general, for all three vessels the collisions occurred at or near the bow.

Appearing whale simulations

Because of time constraints with this project, appearing whale simulations were only done in detail for the VLCC. Three simulations were done with interesting results. For a whale at a depth of 6 meters, the effective beam is equal to 1.6. At 10 and 14 meters, the effective beam is 1.3. Thus, considering the actual beam is 50 meters, a whale that appears as far as 15 meters (1.6 offset) outside of the beam could get drawn into the ship.

There are only a few cases where the whale avoids collision with the ship and still passes close enough to the hull to be hit by the propeller. A whale at 6 meters depth is in danger of approaching the propeller when it appears even with the bow at a lateral offset of 1.8 ship beams (20 meters outside beam). The same danger occurs for a whale depth of 10 meters and a lateral offset of 1.5 ship beams (12.5 meters outside beam). The case of the whale at a depth of 14 meters (near the draft of a VLCC) and a lateral offset of 1.3 ship beams (7.5 meters outside beam) is one occasion when a whale appears to go through the propeller.

Whale under vessel simulations

Situations with a passive whale submerged below the draft of an approaching vessel were simulated with the VLCC for a whale at a depth of 18 meters, offsets of 0.0 and 0.5, and water depths of 20, 24, 28, and 32 meters (Table 4). For all cases, the whale is driven toward the bottom. For a 0.5 ship beam offset, the whale is not only pushed down, but also away from the centerline. In a water depth of 20 meters, the whale is driven into the bottom for both lateral offsets, however what impact this has on the whale is unknown. In 24 meter water depth, the whale at 0.0 offset is driven into the bottom by the time 1/3 of the ship has passed over the whale only to be pulled back toward the hull as the stern approaches. The whale was not pulled close enough to make contact with the propeller. At a water depth of 24 meters and the whale at a 0.5 offset, the whale is not driven into the bottom. For water depths of 28 and 32 meters and a 0.0 offset, the whale is driven down to depths of 24 and 26 meters and pulled back up no higher than

22 meters depth.

Incorporation of whale behavior

For all of the passive and appearing whale simulations, the effect of the passing ship on the whale is independent of ship speed. However, if the whale tries to escape this has some bearing on whether the whale will collide with the ship. For a whale at a depth of 10 meters moving perpendicularly away from the ship at a speed of five knots, the whale at the starting point of the ships' centerline and three meters forward of the bow collides with the ship for all three ship velocities (10, 15, and 20 knots). For the moving whale positioned at 12.5 meters from the centerline (0.5 offset) and three meters forward of the bow, a collision occurred for the ship speed of 20 knots only. The collision occurred at the forward quarter of the hull. In all other cases, the moving whale avoided collision.

Force decay and whale path

The level of surge, sway, and heave forces on the appearing whale whale by the VLCC dropped inversely with distance from the centerline (Figure 2) with most of the decrease occurring in the first 100 meters. At 200 meters very little force is exerted on the whale and at 500 meters, no force is exerted on the whale.

Figure 3 shows the relative movements for a passive and appearing whale for the simulations involving the VLCC with the whale at 6 meters depth and even with the beam of the ship (1.0 offset). In the appearing whale scenario, the path is truncated as the whale collides with the ship. In the passive whale scenario, the positive sway force pushing the whale away from the ship combined with the whales' inertia result in the whale not colliding with the ship even though the negative sway force pulls it very close to the hull. The orientation of the whale had a limited effect on the relative movement of the whale but the chance of collision remained unchanged.

Animations

Animations of a subset of the computer simulations were done in order to better visualize the hydrodynamic effects on the whale. These animations can be exported in VRML and raster metafile format for use with Amtec's Tecplot Framer. Both formats have free viewers available.

These animations could be exported to a video format but this is more complicated and there would be associated costs.

DISCUSSION

This study has shown that there are hydrodynamic effects from ships that increase the danger to right whales in certain situations. Unlike the situation where two ships passing in proximity can draw each other into a collision, the hydrodynamic effect of a ship on a passive right whale is more akin to its effect on a Styrofoam cup - it is very difficult for a ship to hit a relatively small floating object which lies just inside the beam as a pressure wave in front of the ship tends to push these objects away from the ships' hull before drawing it back toward the ship. However, right whales are not passive, at least not all the time, and during the course of their daily activities they could end up in situations where they could collide with a ship even if the whale is outside of the direct path of the vessel. Such situations could occur if a whale "appears" from a dive nearby a ship after the initial positive sway force pushing them away from the hull has already passed. The negative sway force could draw them into the ship and, in some situations, the whale could pass through the propeller.

Another situation that is dangerous to right whales is a ship with little clearance between the hull and the sea floor. In the situation described with the VLCC, even if there is 8.5 meters of clearance (24 meter water depth), the whale at the zero offset can get pushed into the sea floor. And with a 20 meter water depth (4.5 meter clearance), the whale at 0.5 offset can also be pushed into the sea floor. How this effects the whale is not known but it could cause some level of injury.

The impact of vessel speed does not change <u>if</u> the whale remains passive as the forces are independent of ship speed, i.e. greater forces would be exhibited at higher speeds but the ship is also going faster, so the relative movement of the whale to the ship remains the same. However, if the whale takes avoidance action, ship speed becomes a factor in their ability to escape especially in these "appearing" whale situations.

In summary, the hydrodynamic effects of ships on whales are as follows:

- A passive whale is not in increased danger from a passing ship from hydrodynamic forces.
- A whale which "appears" after the initial positive sway force from the ship has passed can be drawn into a ship even if it is outside of the beam of certain ships and is in increased danger from a ship in these situations.
- In general, collisions with a passive whale tend to occur towards the bow of the ship. Collisions with an appearing whale tend to occur along the length of the vessel with some situations bringing the whale close to the propeller.
- A passive whale which is submerged under a ship is in increasing danger of collision with either the ship or the sea floor as water depth decreases.
- If a whale is trying to escape the approaching ship, reduced ship speed will increase its ability to avoid collision.

Table 1. Vessel and whale dimensions. Units are meters and meters-cubed. The block coefficient is a vessel's volume divided by its length x width x depth. It is a non-dimensional quantity representing the fullness of the ship.

	Whale	DDG	SL-7	VLCC
Length	15	150	300	300
Beam	3	18	36	50
Draft	3	9.3	11.5	15.4
Volume	-	7625.4	67690.3	135145.2
Block	-	0.303	0.545	0.585

Table 2. Collision occurrence for whale at varying depths and offsets from the midline. 'C' means a collision occurred. '-' means a collision did not occur. The maximum effective beam is represented by the highest offset that a collision occurs. The shaded cells under draft represent whale depths which are less than the vessel draft.

Navy destroyer - DDG51: length - 150m , beam - 18m , draft - 9.3m

Offset→ Draft↓	0.0	0.2	0.4	0.5	0.6	0.7	0.8	0.9	1.0
4	C	C	C	C	C	C	C	C	-
6	C	C	C	C	C	C	-	-	-
8	C	C	C	-	-	-	-	-	-
10	C	C	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-	-
14	-	-	-	-	-	-	-	-	-
16	-	-	-	-	-	-	-	-	-
18	-	-	-	-	-	-	-	-	-

Cargo vessel - SL-7: length - 300m, beam - 36m, draft - 11.5m

Offset→ Draft↓	0.0	0.2	0.4	0.5	0.6	0.7	0.8	0.9	1.0
4	C	C	C	C	C	C	C	C	-
6	C	C	C	C	C	C	C	C	C
8	C	C	C	C	C	C	C	C	-
10	C	C	C	C	C	C	C	-	-
12	-	C	C	C	C	C	-	-	-
14	-	-	-	-	-	-	-	-	-
16	-	-	-	-	-	-	-	-	-
18	-	-	-	-	-	-	-	-	-

Very Large Crude Carrier (VLCC): length - 300m, beam - 50m , draft - 15.4m

Offset→ Draft↓	0.0	0.2	0.4	0.5	0.6	0.7	0.8	0.9	1.0
4	C	C	C	C	C	C	C	-	-
6	C	C	C	C	C	C	C	-	-
8	C	C	C	C	C	C	C	-	-
10	C	C	C	C	C	C	C	-	-
12	C	C	C	C	C	-	-	-	-
14	C	C	C	C	C	-	-	-	-
16	C	-	-	-	-	-	-	-	-
18	C	-	-	-	-	-	-	-	-

Table 3. Collision occurrence for an "appearing" whale placed three meters forward of the bow at varying depths and offsets from the midline. 'C' means a collision occurred. '-' means a collision did not occur. The maximum effective beam is represented by the highest offset that a collision occurs. The shaded cells under draft represent whale depths which are less than the vessel draft.

Offset→ Draft↓	1.0	1.3	1.6	1.72	2.0
6	C	C	C	-	-
10	C	C	-	-	-
14	C	-	-	-	-

Table 4. Submerged whale scenario. Ship used in simulations is a VLCC (draft 15.4 meters); whale is placed at 18 meter water depth. 'C' means a collision occurred. '-' means a collision did not occur. In these simulations the collision always occurred with the seafloor.

Offset→ Water depth↓	0.0	0.5
20	C	C
24	C	-
28	-	-
32	-	-

REFERENCES CITED

Korsmeyer, F.T., C.-H. Lee, and J.N. Newman. 1993. The computation of ship interaction forces in restricted waters. Journal of Ship Research. Vol. 37, No. 4, pp. 298-306.

Knowlton, A.R., F.T. Korsmeyer, J.E. Kerwin, H. Wu, and B. Hynes. 1995. The Hydrodynamic Effects of Large Vessels on Right Whales. Final Report to the National Marine Fisheries Service, Contract No. 40EANFF400534, 31 pp. + figures and appendices.

Knowlton, A.R. and S.D. Kraus. In prep. Mortality and serious injury in North Atlantic right whales.

NMFS 1991. Recovery Plan for the Northern Right Whale *(Eubalaena glacialis)*. Prepared by the Right Whale Recovery Team for the National Marine Fisheries Service, Silver Spring, MD. 86 pp.