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Hydrodynamics of a ship/whale collision

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ABSTRACT

All endangered large whale species are vulnerable to collisions with large ships; and "ship strikes" are the greatest known threat to one of the world's rarest whales, the North Atlantic right whale (*Eubalaena glacialis*). The magnitude of this threat is likely to increase as maritime commerce expands. Factors influencing the incidence and severity of ship strikes are not well understood, although vessel speed appears to be a strong contributor. The purpose of this study was to characterize the hydrodynamic effects near a moving hull that may cause a whale to be drawn to or repelled from the hull, and to assess the accelerations exerted on a whale at the time of impact. Using scale models of a container ship and a right whale in experimental flow tanks, we assessed hydrodynamic effects and measured accelerations experienced by the whale model in the presence of a moving vessel. Accelerations at impact were measured while the whale was at the surface, for various vessel speeds, orientations of the whale relative to the vessel path, and distances off the direct path of the vessel. Accelerations experienced by the whale model in a collision: increased in magnitude with increasing ship speed; were not dependent on whale orientation to the vessel path; and decreased exponentially with increasing separation distances from the ship track. Subsequent experiments with the whale model submerged at one to two times the ship's draft indicated a pronounced propeller suction effect, a drawing of the whale toward the hull, and increased probability of propeller strikes resulting from this class of encounter. Measured accelerations are a proxy for impact severity, but do not constitute a detailed study of injury mechanism in a living animal, though they may help inform future work. We present a heuristic map of the hydrodynamic field around a transiting hull likely involved in close whale/vessel encounters. These results may have bearing on policy decisions, particularly those involving vessel speed, aimed at protecting large whales from ship strikes worldwide.

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1. Introduction

Collisions with vessels (or "ship strikes") can result in injury and death in a number of marine vertebrate taxa, including large whales (Laist et al., 2001; Jensen and Silber, 2003; Glass et al., 2009), sirenians (*i.e.*, manatees and dugongs) (U.S. Fish and Wildlife Service, 2001; Greenland and Limpus, 2006; Lightsey et al., 2006), and turtles (Hazel and Gyuris, 2006; Hazel et al., 2007). All endangered large whale species are vulnerable to collisions with ships. Several reports provided summations of records of ship strikes involving large whales worldwide, accounting for nearly 300 incidents through 2002 (Laist et al., 2001; Jensen and Silber, 2003) and over 750 incidents through 2007 (Van Waerebeek and Leaper, 2008). These numbers are certainly minima as many other strikes likely go undetected or unreported, some collisions do not leave external evidence of collision, and in the case of some recovered carcasses, the cause of death could not be determined (Glass et al., 2009) due, for example, to advanced decomposition.

Observed injuries resulting from whale/ship collisions can include, for example, broken bones, hemorrhaging, other evidence of blunt trauma, and severe propeller cuts (Knowlton and Kraus, 2001; Moore et al., 2005; Campbell-Malone, 2007); and on occasion a vessel may arrive in port with a whale carcass pinned to its bow or riding atop the bulbous bow.

One critically endangered species, the North Atlantic right whale (*Eubalaena glacialis*), appears to be more prone, on a per-capita basis, to vessel collisions than other large whale species (Vanderlaan and Taggart, 2007) and ship strikes are considered a significant threat to recovery of the species (National Marine Fisheries Service, 2005). In a

Abbreviations: λ, Linear scale ratio (non-dimensional); ρ, Mass density of salt water taken as 1025.9 kg/m^3; *a*, Acceleration; A_I, Impact severity; *AX*, Magnitude of acceleration in the *X* direction; *AY*, Magnitude of acceleration in the *Y* direction; *AZ*, Magnitude of acceleration in the *Z* direction; *Fn*, Froude number; *g*, gravities 9.81 m/s^2 (32.2 ft/s^2); Hz, hertz; kJ, Kilojoule; *L*, Generic unit of length for dimensional analysis or characteristic length of a ship; *M*, Generic unit of mass for dimensional analysis; m, meters (3.2808 ft); *p*, Pressure (N/m^2); s, Seconds; *T*, Generic unit of time for dimensional analysis; T_{Peak}, Time of peak measured acceleration in an encounter; *V*, Velocity (given in meters per second or knots 1 knot = 0.5144 m/s).

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population estimated to contain only 300–400 individuals, there were 50 confirmed right whale deaths between 1986 and 2005, 38% of which have been attributed to ship collisions (Kraus et al., 2005). An average of 2.2 known North Atlantic right whale deaths and serious injuries from ship strikes occurred annually between 2003 and 2007 (Glass et al., 2009).

Ocean-going and coastal vessels are increasing in number, size, and speed to keep pace with waterborne commercial, industrial, and recreational activities. The number of commercial vessels engaged in maritime commerce has tripled in the last 50 years with most of the growth occurring in the 1970s (Vanderlaan et al., 2007), and continued growth of global freight transport is projected at a rate of 4% or more at least thorough 2020 (Corbett and Winebrake, 2007). Thus, the threat of ship strikes to whales may also increase.

A number of steps have been taken in North American waters and elsewhere to reduce the occurrence of ship strikes of whales and other marine mammal species. The depleted status of the North Atlantic right whale and its vulnerability to ship strikes has prompted the U.S. National Oceanic and Atmospheric Administration (NOAA) to establish recommended shipping routes in key right whale aggregation areas and modify a vessel Traffic Separation Scheme servicing Boston (Bettridge and Silber, 2008). NOAA also issued vessel speed restrictions in certain locations along the U.S. eastern seaboard to reduce the threat of ship strikes to North Atlantic right whales (National Marine Fisheries Service, 2008), and established a seasonal Area to be Avoided in the Great South Channel. The U.S. National Park Service limits the number of entries and speed of cruise ships in Glacier Bay National Park, Alaska, to reduce the likelihood of fatal strikes of humpback whales (U.S. National Park Service, 2003). In Canadian waters, Bay of Fundy shipping lanes were recently moved (International Maritime Organization, 2003; Vanderlaan et al., 2008) to reduce the co-occurrence of vessels and right whales. Spain issued a notice in 2007 to mariners requesting that vessels in the Strait of Gibraltar restrict their speed, and has repositioned a Traffic Separation Scheme off Cabo de Gata, to reduce the incidence of whale strikes (International Whaling Commission Ship Strikes Working Group, 2006). In an analogous effort, vessel speed restrictions have also been established in Florida to reduce small craft collisions with manatees (*Trichechus manatus*) (Laist and Shaw, 2006).

Uncertainties exist regarding factors contributing to ship strikes, particularly in the seconds prior to a collision, including possible ship detection and avoidance by the whale and the role of the flow field about the vessel at various vessel speeds. In assessing records of ship strikes of whales, several studies concluded that vessel speed is an important factor in contributing to the severity or lethality of the strike (Laist et al., 2001; Pace and Silber, 2005; Vanderlaan and Taggart, 2007). Vanderlaan and Taggart (2007) also suggested, based on elementary momentum theory considerations, that the fate of the whale in a ship strike is a function of both vessel speed and whale mass. With regard to detection and avoidance, Nowacek et al. (2004) found that right whales showed little overall reaction to the playback of sounds of an approaching ship, and Laist et al. (2001) suggested some collisions may involve only a last second flight response by the whale. However, the role of hydrodynamic effects associated with a moving vessel and the impact accelerations potentially experienced by a whale during a collision have received little consideration, except by way of computer simulation (Knowlton et al., 1995; Knowlton et al., 1998; Raymond, 2007).

The goals of this study were to characterize the flow field near a moving hull, assess accelerations experienced by a whale in a collision or close encounter, and determine the influence of vessel speed on both. Using a scaled ship model proportional to the specifications of a commercial container ship and a proportionally-scaled right whale model, we quantified impact accelerations at various (appropriately scaled) hull speeds in an experimental setting to provide a better understanding of the hydrodynamic conditions affecting a whale when struck or in close proximity to a moving vessel. The results have implications for efforts to lessen the threat of ship strikes to endangered whales, particularly as they pertain to vessel speed and other aspects of vessel operations.

2. Materials and methods

2.1. Study location and facilities

We conducted two series of trials at the experimental flow tank facilities at the Carderock Division of the Naval Surface Warfare Center, Bethesda, Maryland (David Taylor Model Basin). The first set of trials, to determine interaction effects around the hull while the whale model was stationary at the surface, were conducted in a towing basin measuring 15 × 383 × 3 m with an electro-hydraulically driven carriage capable of towing a ship or submarine model at speeds of up to 12 knots (Stahl 1995) (Fig. 1a). The second set of trials, to determine effects on a submerged whale model, were conducted in a circulating water channel with a test section measuring 18.3 × 6.7 × 2.7 m (Fig. 1b) in which the same vessel model was held stationary and water and whale model were forced past it. The two basins and the types of techniques used in this study have been employed for over 60 years to study vessel flow dynamics and to model the types of relationships described in this paper.

2.2. Hydrodynamic scaling

We used scaled models of both whale and ship to approximate real world relationships between the two. Well established scaling rules for hydrodynamic model testing have been developed over the past century and a half, allowing for the prediction of full scale responses based on model scale experiments (Lewis 1988). The physical basis of modern ship model experimentation was developed in the mid-19th century by William Froude (Froude 1888). Froude's experiments determined that the similarity criterion for the wave patterns involving a ship and a model varied with the square root of the linear scale ratio λ. Equivalent speeds are commonly described by the nondimensional Froude Number, $Fn = \frac{V}{\sqrt{gL}}$ where V is ship speed, g is the gravitational constant, and L is a characteristic length, typically taken as length between perpendiculars for displacement hull vessels. From this relation, it follows that time also scales as $\lambda^{1/2}$. Mass is related to volume by Archimedes law, and scales as λ^3 for equivalent fluid densities. Because atmospheric pressure and fluid characteristics such as viscosity and surface tension are difficult or impossible to vary in a model experiment, phenomena that depend on these characteristics will not scale directly. Most notably, Reynolds Number, describing the relationship between viscous and inertial forces in a flow, will not be equivalent between model and ship scale in a typical Froude scaled experiment. In the case of a collision between a ship and a whale, it can be safely assumed that the viscous aspects of the encounter are less significant than the kinematic or inertial, allowing us to neglect the difference between model and full scale Reynolds Number. Dynamic pressure, defined as $\frac{p}{\rho V^2}$, is the same at ship and model scale when taken relative to a local reference pressure to remove the effects of atmospheric pressure. Acceleration is also equivalent, as shown by the following simple analysis: acceleration has units of length per time squared, as in $a = \frac{L}{T^2}$. From the Froude scaling criteria given above, $L_{Ship} = \lambda L_{Model}$ and $T_{Ship} = \lambda^{1/2} T_{Model}$ so $a_{Ship} = \frac{L_{Ship}}{T^2_{Ship}} = \frac{\lambda L_{Model}}{(\lambda^{1/2} T_{Model})^2} = a_{Model}$. Note that the scale factors cancel, so accelerations are equivalent at ship and model scales. Similarly, momentum has units of mass times velocity, so $mv_{Ship} = \frac{M_{Ship} L_{Ship}}{T_{Ship}}$ and $MV_{Ship} = \frac{M_{Ship} L_{Ship}}{T_{Ship}} = \frac{\lambda^3 M_{Model} \lambda L_{Model}}{\lambda^{1/2} T_{Model}} = \lambda^{7/2} MV_{Model}$, leading to a momentum scaling factor of $\lambda^{7/2}$. Therefore, water flow velocities scale

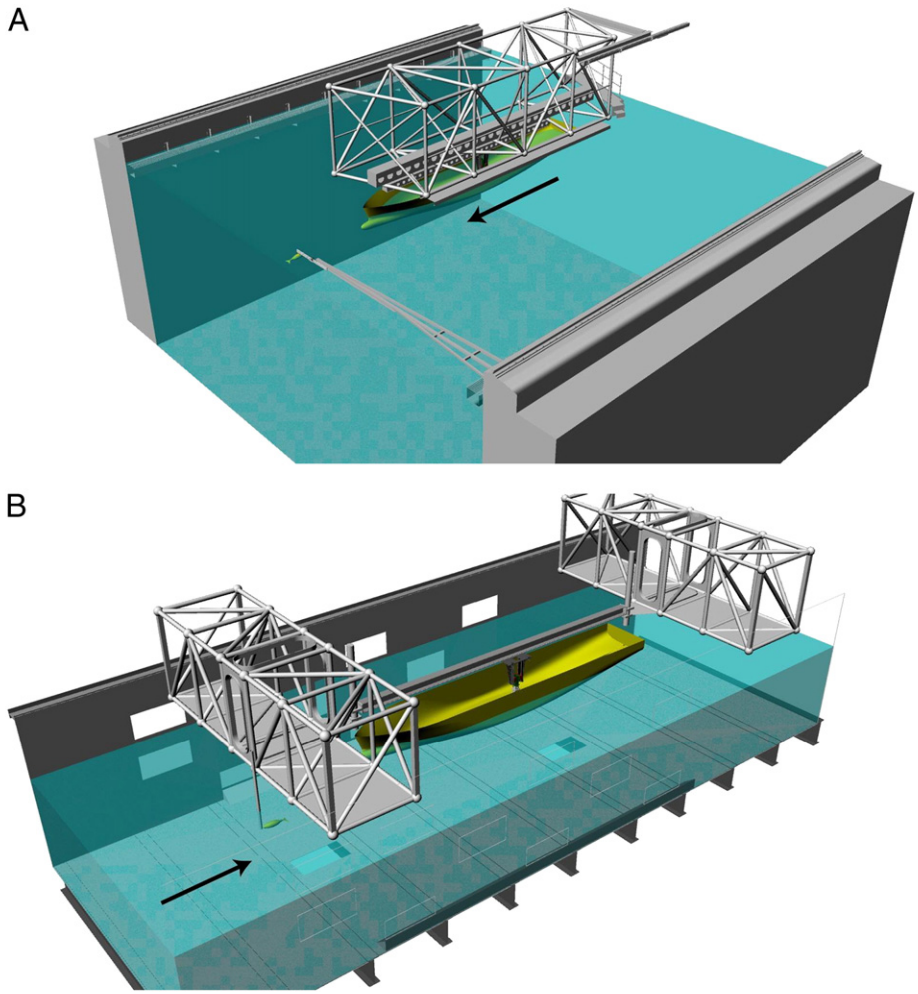

Fig. 1. (A) Rendering of test basin, center carriage structure, and whale release mechanism used in the initial (surface) test series. Direction of carriage motion is indicated by an arrow. (B) Rendering of circulating water channel, gantry structures, and whale release mechanism used in the second (submerged) test series. Direction of water flow is indicated by an arrow.

to real world scenarios at a ratio of 1:4.97. Physical properties such as viscosity and surface tension are sufficiently small relative to inertial and other forces that they may be discounted. Based on these well established similarity criteria, the scale model experiment is assumed to capture the major physical phenomena of a full scale encounter.

2.3. Ship and whale models

The ship model was selected from the inventory of existing hydrodynamic test models. The model was selected for its resemblance to a "Panamax" type vessel (210 m length, 32 m breadth, 8 m draft, 34,000 long tons displacement), representing a broad range of modern commercial container ship types with an elliptical bow bulb,[3] fine entrance lines with pronounced flare, a full midships section, and a dry transom stern. The scale ratio of the selected model was $\lambda = 24.67$, setting the general characteristics of the full scale ship (Table 1). A single skeg-supported propeller (using a stock propeller design) and a spade type rudder were fitted to the model. During testing, the propeller was powered by an electric motor run at the ship self-propulsion point in order to simulate the pressure and velocity fields due to an operating propeller. The ship model was instrumented for towing force and trim, and the drive train was fitted with a dynamometer to measure thrust and shaft torque and a magnetic pickup to measure shaft rotation rate.

A model right whale was designed using morphology derived from Moore et al. (2005) (Table 2, Fig. 2). Relative proportions and gross morphology were set for an adult whale, and a three-dimensional computer model of the whale was prepared using a commercial software package (Rhinoceros 4.0, Robert McNeel & Associates). To facilitate model construction, it was necessary to simplify the shape of the jaw and cross-sectional profile of the body. The whale's tail flukes and pectoral fins were designed as separate pieces to facilitate replacement during the testing process. The model was constructed to approximate a posture an adult whale might adopt while at rest at the surface (Fig. 3).

The size of the whale model was set at 54.91 cm length overall, corresponding to the typical length of an adult right whale (13.7–

Table 1
Particulars of ship model.

	Model	Full scale
Length overall (cm/m)	851.2	210.0
Waterline length (cm/m)	778.3	192.0
Beam (cm/m)	130.5	32.2
Draft (cm/m)	32.4	8.0
Displacement (kg/tonne)	2240.3	3455.0

[3] The bulbous bow is a structural feature situated just below the water line and is a characteristic of many cargo, naval, and passenger vessels. First developed in the early 1900s and further developed after WWII, it improves vessel fuel efficiency by modifying water flow around the hull to reduce drag.

Table 2
Particulars of whale model.

	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
Surfaced mass (kg)	2.788	41,850.0
Neutral buoyant mass (kg)	3.097	46,500.0

16.7 m) and to scale correctly with the ship model, *i.e.*, the physical dimensions of both the vessel and whale models scaled to real world dimensions at a ratio of 1:24.67. The physical model was constructed directly from the computer model from a thermoplastic resin using a stereolithography machine. The model surface was hand sanded and finished.

The resin was rigid in comparison to a living whale. This affected the collision dynamics after impact, most notably because little or none of the impact energy was expended in deforming or otherwise damaging the structure of the whale model. This would obviously not be true of a collision involving a living animal because the tissue of a living organism would absorb some of the energy of the impact; but it was a necessary experimental compromise. Our focus was on appropriate physical scaling of the whale–vessel size relationship. However, proper scaling of structural and tissue rigidity and resiliency of living right whales is not known and therefore was beyond the technology of small model construction in the context of our experiments. Nonetheless, the rigid model was considered to adequately represent a living whale in the moments leading up to the collision and the accelerations experienced by the model were regarded as establishing an upper bound for an impact with a living animal.

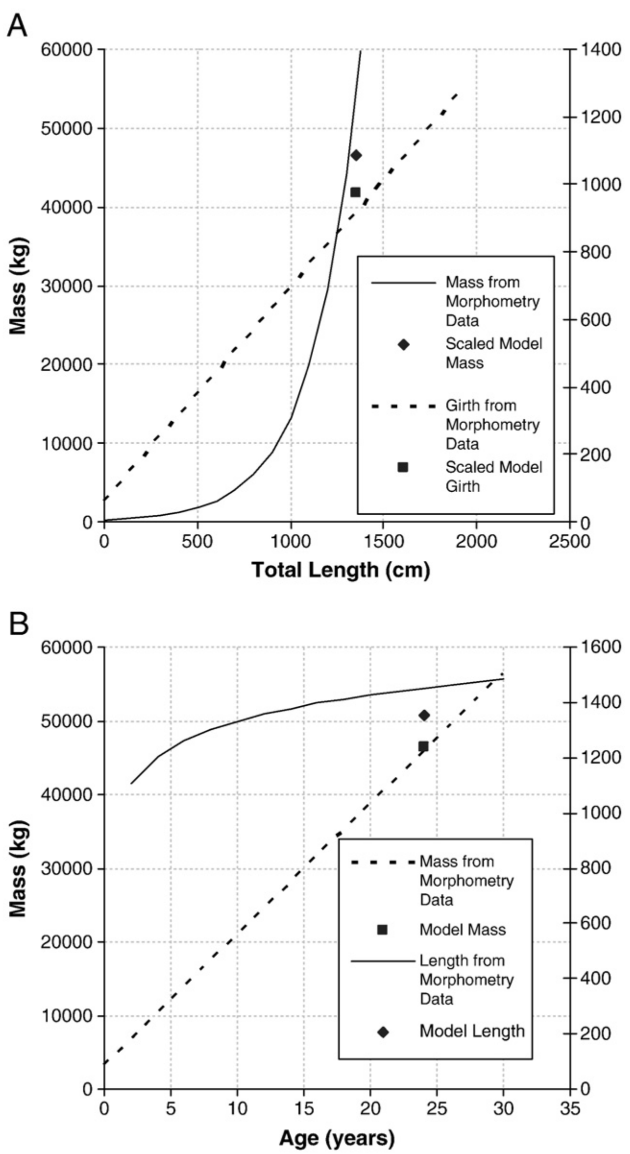

Fig. 2. Whale model dimensions as compared to trend lines derived from whale necropsy morphological data including (A) length versus mass and length versus girth; (B), age versus length and age versus mass (Moore et al., 2005).

Right whales are known to be slightly positively buoyant (Nowacek et al., 2001), but we know of no specific mass properties data from living animals. The reserve buoyancy of the whale model for the surface trials was set at 10% of the total mass as a reasonably accurate approximation (based on field observations) of a living whale while at rest at the surface. For the submerged trials, the whale model was ballasted as nearly as possible to neutral buoyancy.

The instrument package selected for the whale model was a single triaxial accelerometer with an internal data collection capability (Fig. 4). The axes of the accelerometer were aligned with the principal axes of the whale model, such that the y direction was longitudinal (positive from tail to head), x was to starboard, and z was upward. Accelerations were thus measured in a whale-fixed coordinate system, rather than a world- or ship-fixed system that possessed an external position reference point. For the purposes of measuring the magnitude of impacts, this system was suitable for characterizing some impact features to the whale model only, but did not provide a quantitative measure of the whale model's movements during the encounter. The latter information was reconstructed from video data.

The accelerometer was set to activate when the whale model's acceleration in any direction exceeded 0.1 gravities (gravity (g) = 9.81 m/s^2) or its velocity at model scale exceeded 0.3048 m/s. Upon activation, the instrument recorded acceleration as a function of time for 1.5 s (at a rate of 1200 Hz) or until a subsequent event again triggered the accelerometer.

For the surface trials, video was recorded from three angles: looking directly down at the bow of the ship model, a wide shot of the bow and area ahead of the model from the side, and looking directly forward from behind the model. For the submerged trials, video was recorded from above the waterline looking at the bow quarter of the model, below the waterline looking at the bow and stern from beside the model, and from directly below the propeller. In both cases, accelerometer data were time-stamped via an internal clock, which was synchronized with the time codes of video recording equipment and ship model instrumentation system.

2.4. Vessel speeds, offsets, and depths during trials

Two experimental series were conducted: Series One involved the whale model at the free surface; Series Two involved the whale model submerged.

2.4.1. Series One: surface lateral offsets

In the first series, the hull was connected to a towing carriage that pulled it toward the stationary, free floating whale model. In this case, the goal was to assess hydrodynamic responses of the whale model at a variety of lateral offset distances and orientations relative to the ship track (Fig. 1a).

A release mechanism was designed such that the whale model could be held stationary in the tank at a desired offset distance and orientation. The mechanism was released and retracted by a remotely

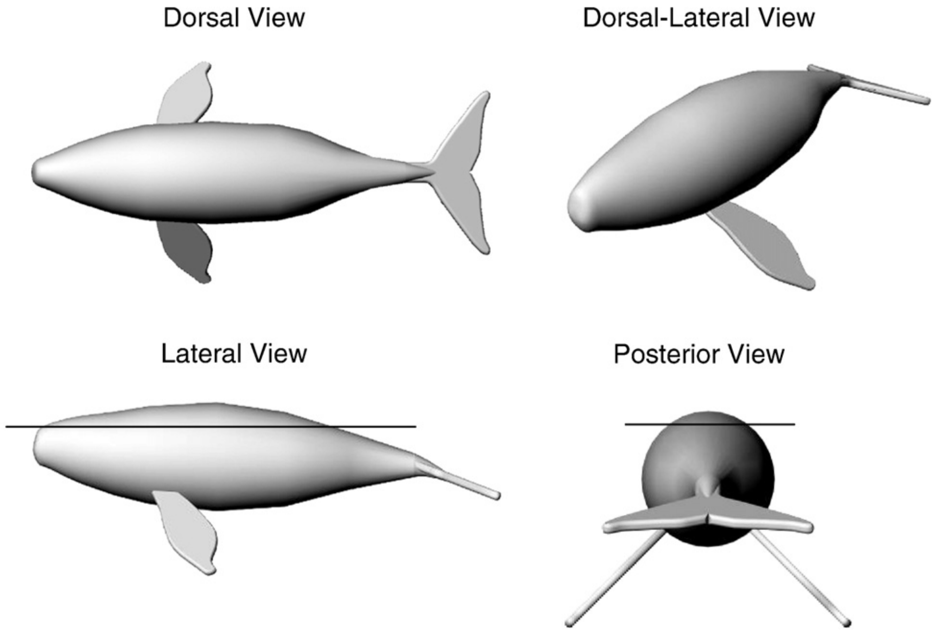

Fig. 3. Computer rendering of whale geometry used in the experiment. This computer model was used to generate the physical model using a stereolithography machine. The approximate waterline for the surface experiments is shown in the lateral and longitudinal views.

actuated solenoid as the ship model approached the release point, leaving the whale model free floating at the time of collision. In each trial, the whale model was released immediately prior to approach of the ship model and the model was run past the position of the whale. Ship data and video were obtained throughout the encounter, from before contact to well after the whale model was clear of the ship.

Ship speeds were set at equivalents of 5–25 full scale knots in 5 knot increments, which covers the operating speed range of almost all commercial cargo vessels. Tests were performed at arbitrarily set distances off the ship track line that were scaled such that they corresponded to distances of 0, 20, 40, and 60 ft (0, 6.1, 12.2, and 18.3 m, respectively) if models were full-sized (Fig. 5). Trials were

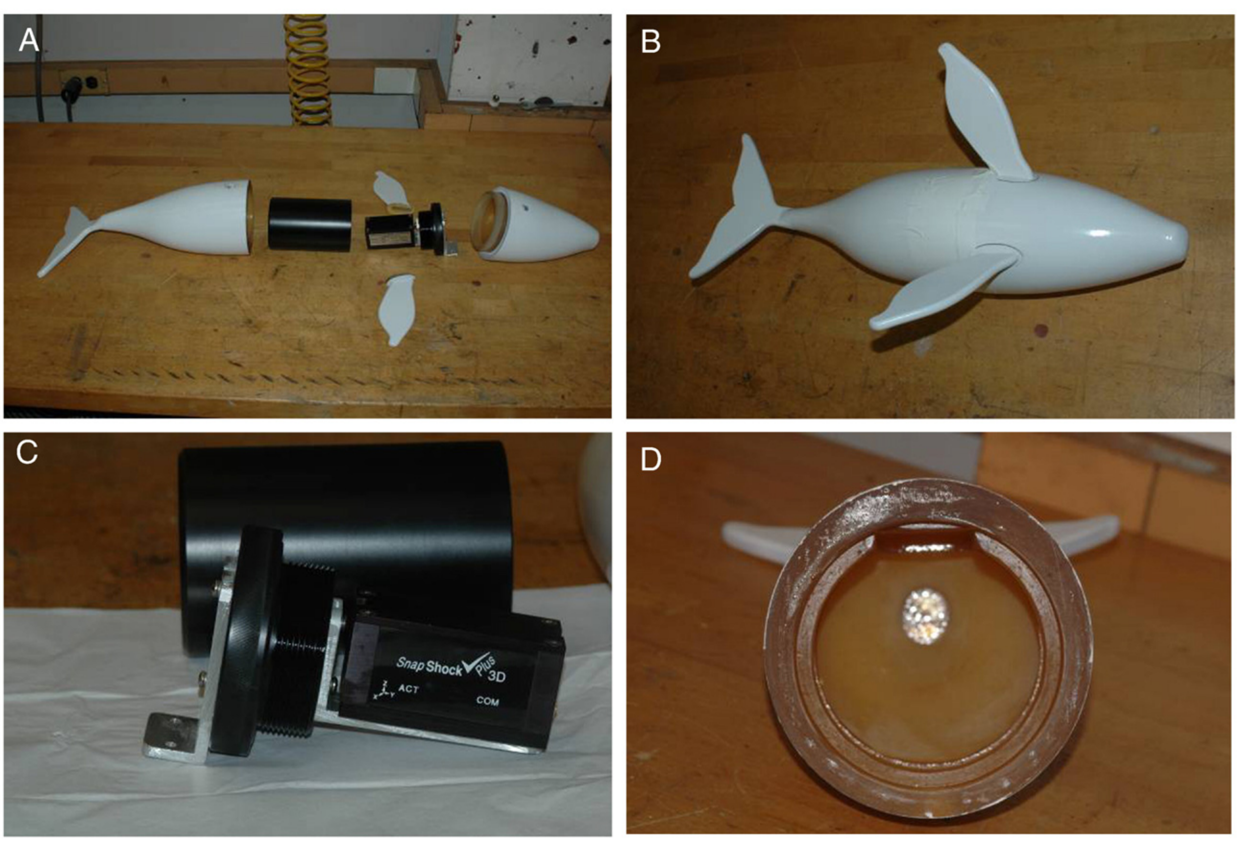

Fig. 4. Whale model: (A) exploded overview of whale model components, (B) assembled whale model, (C) accelerometer and instrument casing, (D) interior view of whale afterbody showing alignment tab for instrument casing.

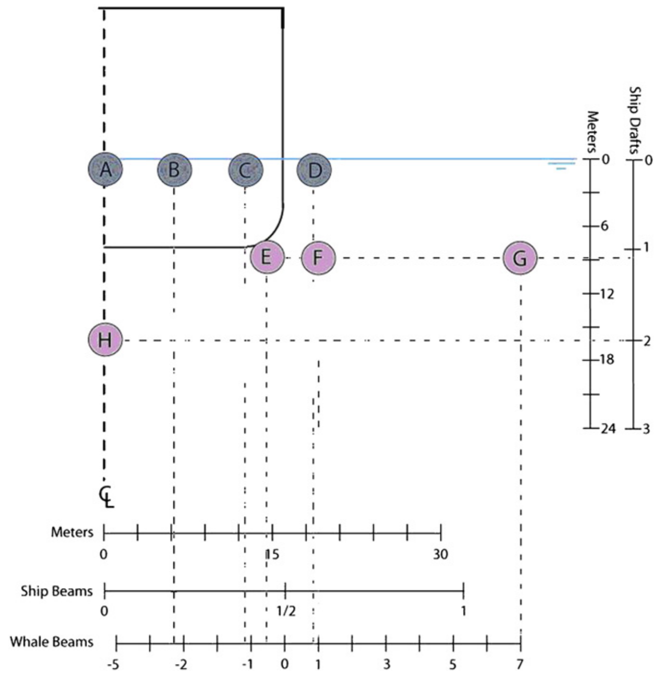

Fig. 5. Release positions of the whale model relative to the ship track for the surfaced and submerged series of experiments. Positions A through D relate to the surface trials of Series One; positions E through H relate to the submerged trials of Series Two.

also run using whale orientation angles ranging from 0 to 315° in 45° increments such that 0° indicates an overtaking encounter and 180° indicates a head-on collision. Approximately three trials were made at each test condition.

2.4.2. Series Two: submerged whale tests

In the second experimental series the hull was held stationary and the submerged whale was released into the flow that was moving toward the vessel at various water speeds. This is comparable to the use of wind tunnel testing in aerodynamics, using a model-fixed frame of reference in which the flow moves past the body, and is hydrodynamically equivalent to the towing tank approach used in the surface experiments. The goal was to determine if the hull, effectively traveling at various speeds, acted to attract the submerged whale model. New requirements for enhanced underwater camera coverage to collect video data and the need for a mechanism to release the model at depth led to the decision to use a circulating water channel for the second series of experiments (Fig. 1b). The tank is equipped with numerous viewing ports and fixed photo lighting.

In this case, the whale model was submerged at 1.2 and 2.0 times the ship's draft at lateral offsets of 0.0, 4.5, 6.0 and 12.0 whale beams (0.0, 14.5, 19.2, 38.0 m, respectively) from centerline and released into the flow toward the fixed hull at full scale ship speeds of 5, 10, and 15 knots (Fig. 5). Safety issues with the test facility precluded testing at the 20 and 25 knot ship speeds in this configuration.

The same whale model and instrumentation design was used in the submerged experimental series (dimensions provided in Table 2), with the exception of a slight shortening of the pectoral fins to better represent the morphology of actual animals. The weight of the whale model was increased by the addition of ballast to set the whale model at approximately neutral buoyancy.

2.5. Acceleration measurements

Impacts were identified by cross-referencing video of the encounter with activations recorded by the whale's onboard accelerometer. Severity (A_I) was measured in terms of the root mean square value of the directional components (in the x, y, or z directions) at the instant of the peak measured acceleration (T_{Peak}) such that:

$$A_I = \sqrt{AX^2_{TPeak} + AY^2_{TPeak} + AZ^2_{TPeak}}.$$

For cases where the encounter was not sufficient to activate the accelerometer (*i.e.*, if acceleration was <0.1 g and speed <0.3048 m/s), A_I was arbitrarily set to zero.

This system gave a reasonable measure of the relative magnitude of impact in cases where actual contact between the whale model and ship's hull or propeller were observed, though it did not take into account the length of the encounter or successive peaks in the acceleration record. The duration and rise time of accelerations experienced by a living whale are important parameters for understanding the biomechanics of ship strike induced injuries; however, any resulting traumas are also heavily influenced by the structural properties of a living animal and other factors and are therefore beyond the scope of the present rigid-body experiment. Therefore, these results may help establish some parameters for such detailed collision analysis, but are not substitutes for it.

2.6. Statistical analyses

A Pearson Product-Moment Correlation Coefficient was used to test the relationship between ship speed and acceleration impact A_I.

3. Results

3.1. Series One: accelerations experienced in the centerline position

Collisions were observed in all cases when the whale model was directly in the ship's path (0 m offset) and at full scale offset distances of 6.1 m from the centerline. Numerous collisions produced accelerations measured at over 5 g at vessel speeds of 5 knots, over 10 g at vessel speeds of 10 knots, and over 15 g at vessel speeds of 15, 20, and 25 knots (Fig. 6). Accelerations were closely related to, and varied linearly with ship speed. We found statistically significant correlations between vessel speed and acceleration impact at the centerline ($n=47$, $r=0.740$, $P<<0.0001$) and at 6.1 m offset distances ($n=30$, $r=0.418$, $P=0.0218$).

For centerline conditions (0 m offset) below 15 knots, the whale model tended to roll up and over the bow bulb, with the most severe impact coming when the stem above the bulb subsequently hit the whale. After the initial impact, the whale model was either carried along on the stem or slid off the bow and passed closely down the side of the ship.

At ship speeds of 15 knots and above, there was a marked increase in the apparent intensity of centerline impacts. In approximately one-third of high speed centerline trials, the initial impact pinned the whale model to the ship's bow bulb, followed by the ship riding over the whale, forcing it below the surface. In some instances, the whale model resurfaced along the waterline and passed along the side of the ship, but in others it remained below the hull for a considerable portion of the ship's length. One 25-knot trial with the whale at the centerline of the ship track in which the whale was forced under and traveled beneath the hull produced the only propeller strike observed during the surfaced test series.

3.2. Series One: accelerations experienced in offset positions

As the whale model's position was moved laterally away from the centerline of the ship track, the point of contact moved back along the ship's waterline, and glancing blows were more common than direct impacts. Acceleration at impact declined exponentially with increasing offset distance, to the point that very few encounters registered on the accelerometer in the 12.2 m and 18.3 m offset distances (*i.e.*, at or near

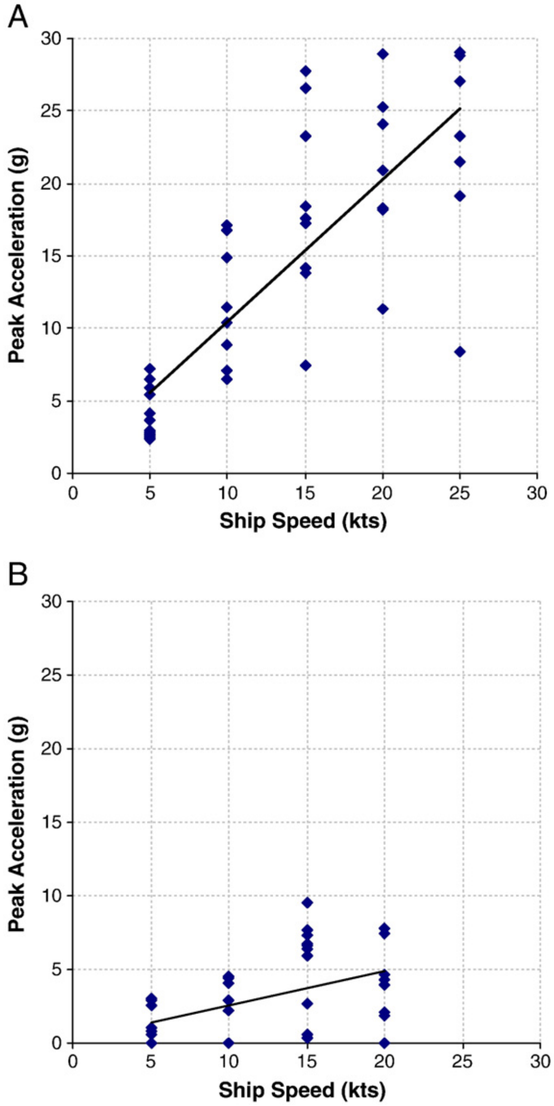

Fig. 6. Impact acceleration versus nondimensional ship speed for the centerline (A) and 6.1 m (B) offset conditions at all orientations.

the maximum beam of the ship) (Fig. 7). At these distances, the effects on the whale were too light to reliably activate the accelerometer and too few to make a good determination of speed dependency.

At the 20- and 25-knot speeds, the ship generated a significant bow wave, but the whale model responded only with one cycle of

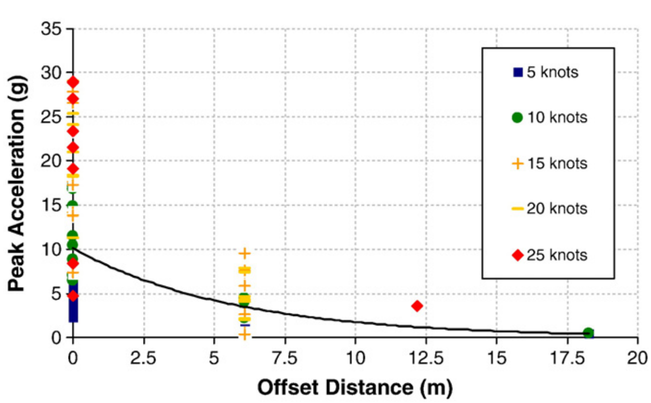

Fig. 7. Impact acceleration versus offset distance for all ship speeds and orientations.

vertical movement, but no lateral deflection away from the ship. This movement was also observed at 12.2 m and 18.3 m full scale offset distances — cases in which the whale model encountered the first crest of the divergent wave system before the hull itself.

In all trial conditions, as the whale model passed along the stern of the ship it entered the influence zone of the propeller. Propeller suction was sufficient to cause the whale model to orient toward the propeller, but not sufficient to draw it into the blades. This behavior appeared to be somewhat speed dependent, with a greater heading change observed at higher ship speeds. Arbitrarily increasing propeller speed beyond the self-propulsion level also increased the rate and magnitude of the observed response, although the primary effect was still orientation rather than inward movement. The whale model frequently passed within 1–2 propeller diameters of the blades.

In all cases, the orientation of the whale model did not appear to affect accelerations it experienced, except in cases where the orientation effectively changed the offset by placing an extremity of the model in the path of ship's stem.

For both the 0 m and 6.1 m offset conditions, we observed significant scatter in the measured accelerations (Fig. 6A), although visually, test conditions appeared to be extremely repeatable. Because the whale model data were measured in a whale-fixed coordinate system (*i.e.*, relative to the whale, only), it is difficult to relate the measured accelerations to the model's movements in an earth- or ship-fixed system. It is possible that the accelerometer mounting was susceptible to impact induced high frequency vibration at certain angles, which would account for some of the variation.

3.3. Series Two: responses of the submerged whale model

The behavior of the submerged whale model in the presence of the ship model at 5–10 knots was characterized by inboard motion toward the stern of the ship. This movement was accompanied by a change in orientation of the whale model such that the head of the whale rotated inboard toward the ship. This motion was consistent with the orientation behavior during the surface trials, and likely resulted from suction from the acceleration of flow along the ship's afterbody and the working of the propeller. This behavior appeared to depend at least partially on depth, with a greater orienting effect being observed when the whale model was at or near the depth of the propeller. The inboard suction was sufficient to draw the whale model to within one body length of the propeller from the outboard-most position (G) (Fig. 5) in low speed trials. Lateral motion was substantially more apparent than vertical.

At the outboard position (F), the lateral motion toward the centerline and orientation of the whale model toward the propeller were also observed, which was consistent with the propeller as the origin of the lateral force. Vertical motion, however, was more pronounced, with the whale model tending to be driven downward starting at approximately one quarter of the ship length from the bow. In approximately half the trials undertaken at the inboard spacings the whale model finished a run laterally in line with the propeller but below it vertically.

At the inboard position (E), the whale model was also observed to be driven down in approximately half of the observed trials. Conversely, in cases where significant vertical deflection did not occur, the whale model was drawn rapidly onto the centerline and passed down the hull just below the skin of the ship. In some cases, the whale model was observed to bump and scrape down the ship rather than pass just below it. When moving past the after part of the hull, the whale model tended to pass along either the bottom or side of the skeg, and approach the propeller very closely.

A limited number of trials were conducted with the whale model submerged at two ship drafts directly on the ship centerline (H). These trials resulted in the whale model passing closely down the centerline of the ship and approaching or striking the propeller. In general, the behavior was not notably different from the inboard position (E). In those cases, vertical deflection was moderate, and exclusively in the downward direction, and there was significant danger of propeller strike.

At positions (E) and (H), over 50% of the trials were judged to have resulted in a propeller strike. At the outboard positions (F) and (G), no propeller strikes were observed, although a number of close encounters were observed. Based on these results, we predict that under the experimental conditions, the critical lateral offset distance to avoid contact with the propeller lies approximately at one-half beam of the ship, between positions (E) and (F).

In one 10 knot trial at position (E), the whale model rode up over the bow bulb, sustaining a heavy impact with the bulb and stem. This result was very similar to the response observed at positions (A) or (B) in the surface testing series, and illustrates a continuity of results between the two experimental sequences.

4. Discussion

4.1. Factors likely involved in whale/vessel collisions

Large whales are relatively agile, acoustically aware, and at times can be easily disturbed by noise and other stimuli (see, for example, Richardson et al., 1995). It therefore seems reasonable that a whale could detect and avoid an oncoming vessel; nonetheless, ship strikes are rather common. Except in the very near-field, whales may not regard an approaching ship as a threat, or may be engaged in a vital activity (*e.g.*, feeding and mating) on which they are intently focused, and thus fail to engage in an avoidance response. Right whale vulnerability to ship strikes is probably related, at least in part, to slow swimming speeds, positive buoyancy, and a largely coastal distribution that exposes them to various activities near human population centers (National Marine Fisheries, 2008).

Terhune and Verboom (1999) postulated that right whales either have difficulty detecting ships that are relatively near or choose not to avoid them. Using a multi-sensor acoustic recording tag to measure the responses of right whales to passing ships Nowacek et al. (2004) observed little or no response by right whales to playback sounds of approaching vessels or actual vessels, regardless of vessel speed or acoustic characteristics. Ships and ship noise are fairly ubiquitous in most seas, particularly in areas of high human activity therefore, whales may habituate to the presence of ships. For whatever reason, a whale may suddenly and unexpectedly find itself directly in front of a ship or, in the case of highly buoyant right whales (Nowacek et al., 2001), emerging from a dive with little maneuverability.

Given that field trials involving full scale vessels and living whales are not possible (or at least highly ill advised), we endeavored to address some uncertainties (heretofore only studied using computer simulations) in whale/vessel interactions in an experimental setting using an inanimate object. Our study incorporates neither a whale's behavioral response nor the absorptive aspects of an actual living (or simulated, *e.g.*, Raymond, 2007) organism. The use of a rigid-body whale model, while a necessary experimental compromise, will tend to overstate acceleration experienced by the whale because no energy is lost in deforming the model as would be the case with a living animal. Therefore, whereas this study provides some insight into the physical forces at play in a collision or close encounter, it is not a substitute for detailed biomechanical analysis of a ship strike using more intensive modeling of the structural properties of a whale (*e.g.*, Tsukrov et al., 2009).

4.2. Impact characterization of a ship-whale collision

To our knowledge, no study directly links the physical and operational characteristics of a vessel to the nature and consequences of an impact experienced by a whale involved in a collision or close encounter. Generally, the extent of a trauma suffered in a collision is dependent on angle of incidence, the size of the area of impact, contact duration, integrity of the tissue contacted, and vessel mass (Campbell-Malone, 2007; Raymond, 2007), or a combination of these. Our trials do not account for most of these variables nor certain additional factors (*e.g.*, a whale's possible behavioral reaction or movements), and therefore our findings cannot be used to completely characterize the nature of an impact or resulting injury in a collision. However, to the extent both a diminished duration of impact onset (Raymond, 2007) and increased acceleration experienced by a whale may be important determinants in the nature and severity of a collision, we conclude that the role of these two variables is enhanced by increasing vessel speeds. In a related study, Clifton (2005) concluded that typical speeds of small watercraft were capable of generating sufficient kinetic energy (ca. 18–20 kJ; occurring at vessel velocities of 13–15 mph) to result in fatal bone fractures in manatees, although caution should be used when making comparisons to whales as manatee bones are denser, but perhaps more fragile than those of whales, and the vessels studied were smaller than those observed here.

Our findings regarding the relationship between vessel speed and accelerations experienced by the whale model are consistent with other studies that concluded vessel speed is an important factor in the fate of a whale in a vessel/whale collision (Pace and Silber, 2005; Vanderlaan and Taggart, 2007). Vanderlaan and Taggart's (2007) elementary momentum theory analysis in a perfectly inelastic collision assumed that the mass of the ship was orders of magnitude greater than the mass of the whale (a reasonable assumption for oceangoing cargo vessels, if not for coastal fishing and pleasure craft) and that for those conditions, vessel speed and whale mass were the primary variables affecting momentum transfer to the whale. Therefore, numerical results involving the role of vessel speed from the method proposed by Vanderlaan and Taggart are consistent with the results of the model experiment to within an order of magnitude.

4.3. Hydrodynamic zone of influence

Our results conform to the basic hydrodynamics of a moving vessel in that the upstream disturbance is extremely localized. This means that the whale model ahead of the ship experienced no forces induced by the vessel until contact was imminent. Thus in the absence of action on the part of the whale, the probability of a collision is largely dependent on the position of the whale relative to the ship's track.

We provide a heuristic map of the hydrodynamic field around a hull that likely is at play in a close whale/ship encounter (Fig. 8). As such, our qualitative results prompt us to classify the space about the ship track into three categories: a high danger (lethal) zone in which any encounter, absent a behavioral response by the whale, appears likely to lead to either a propeller or bow strike; a moderate danger (conditional) zone in which the whale model passes within less than two body lengths of the stem or propeller disk; and a low danger (safe) zone giving at least two body lengths of clearance.

These delimiters are qualitative, and necessarily somewhat imprecise, but provide approximations of the hydrodynamic environment experienced by a whale in proximity to a ship. The conditional zone in a hydrodynamic context indicates the importance of buoyancy and ship-speed effects in comparing the results of the two experimental series, but also encompasses much of the uncertainty associated with whale behavior.

Response of the whale model to the ship's bow wave was less than expected. Potential flow simulations (Knowlton et al., 1995; Knowlton et al., 1998) predicted a 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 beam of the ship. In contrast to the computer simulations, the observed response to the bow wave in both experimental series was vertical rather than lateral.

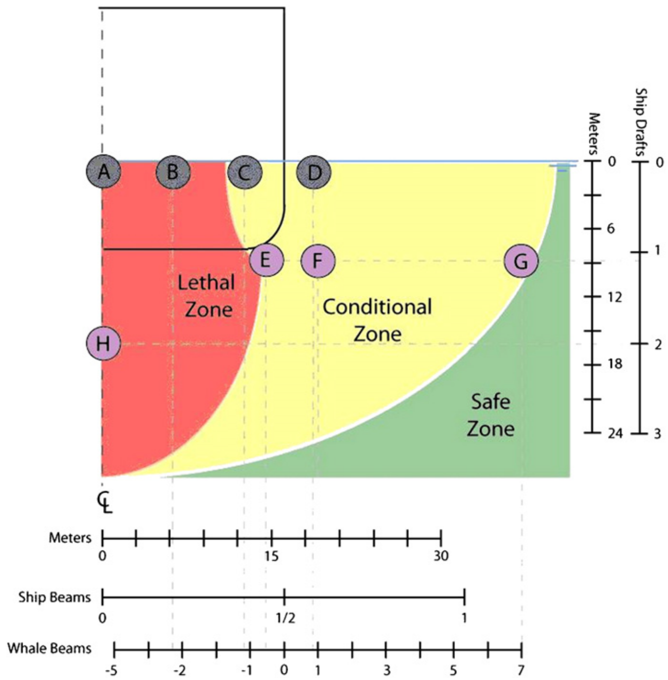

Fig. 8. Approximate delineation of critical zones about the ship track. Within the lethal zone, the whale model is judged likely to experience either a violent impact with the hull or a propeller strike. The conditional zone indicates the area in which for one or more conditions the whale model passed within one body length of the propeller or a near-miss from the bow. While these zones are defined by observation of the hydrodynamic response of the inert whale model, much of the uncertainty associated with whale behavior is believed to be critical in roughly this same area.

In the surface experiments (Series One) at position (D) the whale model encountered the first crest of the diverging wave system before the hull itself. In this case the model response was a single cycle of vertical motion. In the submerged experiments (Series Two), the tendency of the whale model to be driven down at the inboard lateral positions is due to the high pressure region at the ship's bow. The selected ship model includes a modern bulbous bow design that tends to reduce the magnitude of the wave system about the ship. It is possible that an encounter with a vessel with a traditional stem bow design (as used in the Knowlton et al. simulations) might yield a larger deflection due to effects of the bow wave.

4.4. Bow versus propeller strikes

Databases of ship strikes involving all whale species (Jensen and Silber, 2003; Van Waerebeek et al., 2007) contain a number of records (ca. 10–20% of all records) of dead whales pinned to, or having ridden up onto, the bow of a large vessel. Therefore, if our trials are analogous to real-world scenarios, this consequence could have occurred at any vessel speed when the whale was on the centerline of ship's path. In offset conditions, accelerations measured when the whale was within one-half beam width (*i.e.*, 15.6 m in this experiment) were still substantial and possibly sufficient to deliver a fatal or near fatal blow. We believe that in a real-world collision, these strikes may still result in potentially substantial tissue damage, and may be represented in actual ship strike records as generalized blunt trauma.

Likewise, observations of propeller strikes comprise approximately 20% of the recorded real-world ship strikes (Jensen and Silber, 2003; Glass et al., 2009). Whereas, these records may not be a faithful representation of all ship strikes, as many others likely go undetected, we regard the numbers reflected in the databases as reasonable approximations of actual proportions. In the model experiments, propeller strikes were observed in two situations. At ship speeds of 15 knots and greater, the whale model could be sucked under the ship model after being struck by the bow. This behavior resulted in one actual propeller strike of our model and several near-misses in Series One trials.

During the submerged test series, propeller strikes were observed in approximately half of the inboard trials (positions E and H). These results suggest that a majority of propeller strikes occur in cases where the whale is below the surface at the time of the encounter in which it is drawn laterally toward the hull, and may correspond to real-life scenarios. It should be noted as well that some propeller strike records involve small craft — a vessel class not addressed in our study.

The frequency of propeller strikes observed during testing may also be affected by 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. In most of the conditions considered in testing, a significant number of trials resulted in the whale model passing within one body length of the ship's propeller. For the inert whale model, these conditions are near-misses with no significant accelerations measured, but it is easy to envision the behavioral response of a living animal leading to propeller strikes in a number of these conditions, whereby a “startle” response may actually move a whale toward the propeller. This also is a probable scenario if a whale was attempting to dive — a typical flight reaction in response to a strong stimulus (see, for example, Richardson et al., 1995) — but was still under the influence of the vessel's drawing forces.

Whale buoyancy (set at 10% in the Series One and neutrally buoyant in the Series Two trials) may also be an important determinant of collision dynamics in bow-on encounters. Notably, there are taxonomic differences in relative buoyancy among whale species and right whales are particularly buoyant in this regard (Nowacek et al., 2004). The tendency of the whale to be driven under versus struck by the bow bulb may be affected at least in part by this factor and may vary with the species involved.

4.5. Relevance to policy decisions

Steps have been taken by governments and wildlife management entities to reduce the incidence of whale/ship collisions that include limits on vessel speed. Our findings on the role of vessel speed in such incidents, both in regard to the dimensions of the zone of influence created by a ship and the magnitude of an impact, have application to the study of physiological injury from collisions (*e.g.*, Campbell-Malone, 2007; Tsukrov et al., 2009) and policy-driven management actions regarding vessel speed restrictions. In addition to having a role in reducing the severity of impact lowered vessel speeds may have the added advantage of providing greater opportunity for either whale or (in some rare instances) mariner avoidance reactions. Therefore, our results add to a growing body of literature indicating that vessel speed restrictions are a meaningful management tool (where other alternatives such as vessel routing to avoid whale aggregation areas are not feasible) in reducing the threat of ship strikes to all large whale species.

5. Conclusion

When the whale model was hit by the ship's stem, measured accelerations were dependent on ship speed in an approximately linear relationship. Observed severity of collisions was such that direct impact with the ship's stem or propeller appears likely to result in serious injury to the whale. For cases with the whale model at the surface, the primary collision type was a strike by the bow of the ship model; and when directly on the ship's track, this would likely manifest itself in a real-life scenario with the pinning of the whale atop the bulbous bow. With the whale model submerged, the primary collision type was a propeller strike, with significant lateral drawing action due to the propeller.

The overall danger zone about a moving ship appears to be on the order of one ship beam about the centerline of the ship track in the horizontal plane and one to two times the draft vertically if the whale is considered to act as a rigid body incapable of independent action. Accelerations experienced by the whale diminished as distance from the vessel increased; and whale orientation had little effect on the nature and severity of the encounter. Nonetheless, we conclude that, to the extent that increasing vessel speed significantly increases accelerations experienced by a whale, limits on vessel speed will reduce the magnitude of the acceleration; may increase response time for a whale attempting to maneuver away from a vessel; and appear to be reasonable actions to consider in policy decisions aimed at reducing the overall threat of ship strikes.

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