Numerical animation of a North Atlantic right whale

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Abstract

Studies on large cetaceans, such as blue, sperm and right whales, are extremely limited because these animals are too large to maintain in captivity or restrain in the wild. Therefore, modeling approaches are the only ways to explore many aspects of their biology. This study describes a new technique that can be used to model the swimming motion of a North Atlantic right whale, *Eubalaena glacialis*, through the animation of a three-dimensional right whale geometry. This animation was carried out by generating a discretization for the body and treating it as a viscoelastic material modeled by a spring-mass system. In this sense, nodes of the triangulation that form the whale body are treated as beads of uniform, unit mass, and the connecting edges are treated as springs. Initial velocities for upstrokes and downstrokes were prescribed, with some intuition, to mimic the animal's natural motion. The animation was then carried out, updating the node positions and velocities over time from the initial equilibrium position by solving a set of differential equations. This process enables realistic motion of any geometry to be incorporated into a flow solver and, because it can be adapted easily for use with other marine animals, presents the potential for many important applications in the study of cetacean kinematics, energetics and physiology.

Key words: spring-mass system, explicit methods, right whale, caudal oscillation, thunniform locomotion, animation

1. Introduction

Numerical simulations of fluid movement have revolutionized the study of fluid dynamics and allow the flow of fluids to be studied in a much wider range of

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situations than those possible by either theoretical or experimental approaches. Although these simulations are often used to improve the design of human-made structures, they are especially useful in modeling systems that are too large or too small for inclusion in a experimental facility. Some examples include the movement of water masses in estuarine systems [6] and the flow of water around marine vertebrates and their appendages [15]. In the case of a marine animal, such as a swimming whale, movement of the fluid is indelibly linked with the animal's movement; the fluid is accelerated around the animal by oscillations of the body and caudal fin [20]. Although many marine animals frequently employ short periods of passive gliding, during which they rely on momentum for forward motion, they cannot move forward without additional force. The swimming motion itself changes the resistive forces experienced by animals, generally increasing the amount of energy the animal uses in comparison to a passive gliding position [20] and in others decreasing the energetic expenditure because it uses forces of the fluid to move [12]. Regardless, animal motion changes the forces experienced by a static body, and most animals spend a significant portion of their lives actively swimming. Therefore, realistic motion should be incorporated into any studies that aim to estimate the amount of energy that an animal spends on moving, usually described as its cost of locomotion.

A limited amount of work on large cetaceans has been possible because of their size and marine lifestyle. Therefore, computer-based modeling is an important tool in exploring many aspects of their biology and has not been widely applied in this way. North Atlantic right whales (*Eubalaena glacialis*) are one of the world's most endangered species with a worldwide population of fewer than 400 individuals. Averaging 13 meters in length and 40 tons in weight [14], these animals are far too large for any manipulative empirical studies of their kinematics or energetics. Therefore, the ability to model the movement of fluid around a swimming right whale is a novel and important tool for the field of biology. Although the deliberate hunting of these whales stopped almost 75 years ago, the population is still not increasing, and individuals are still regularly killed by human interactions primarily by becoming entangled in fishing gear or by being struck by ships [10]. For these reason, this species has been the focus of considerable conservation efforts, many of them based on identifying the limitations to their recovery. The influence of hydrodynamic forces on right whale mortality has been investigated [9], but no work has related the relationship between hydrodynamics and energetics. Although a wide variety of flow solvers are currently available to model the hydrodynamic forces encountered by different shapes, the forces that are experienced by a living, moving whale cannot be determined without a method to animate its swimming motion.

Similar to all other cetaceans, right whales swim by oscillation of their caudal fin and the latter half of their body. This movement results in a sinusoidal motion with the magnitude of the motion decreasing from the posterior end of the animal (the fluke tips) to the animal's center of mass (at roughly 40% of the total body length) and increasing slightly from the center of mass to the anterior end (the tip of the rostrum). The flukes and head of the animal oscillate in phase with each other, while the center of the animal, best represented by its flipper tips, oscillates almost exactly out of phase [5] to the flukes and head. Figure 1 shows the positions of these points along the body of a right whale. This motion, which is known as thunniform swimming, appears in many different marine organisms from four separate evolutionary lineages, including tunas, cetaceans, some sharks, and, most probably, the extinct icthyosaurs and is typically used by animals that swim at high speeds and propulsive efficiencies [2]. Because this swimming mode is present in a variety of marine organisms, the ability to model this motion should be applicable to a wide range of biological researchers.

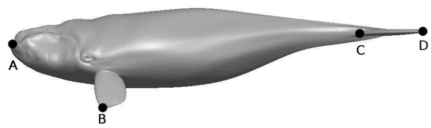

Figure 1: Key points along the body of a right whale that were used to model the swimming motion: rostrum (A), flipper tips (B), tail base (C) and fluke tips (D).

We note that the problem of aquatic locomotion has been studied from a more mechanical perspective [13, 8, 7], and that work in this area has important applications such as in the development of alternative propulsion systems for unmanned underwater vehicles that mimic the natural swimming motion of fish, like the robotic tuna of [1]. The numerical studies presented here do not require the level of aquatic fluid mechanics presented in these works, and instead follow more closely to simpler mechanical models presented in the various simulation studies which utilize elastic models based on spring mass systems such as found in [19, 21, 17, 18].

2. Body Discretization

A three-dimensional geometry of a right whale was developed with Lightwave 3D software to illustrate an encounter between a recreational fishing vessel and a submerged right whale. Initial model construction was based on two-dimensional photographs of portions of live right whales and advice from right whale researchers. However, because the final purpose of this study and subsequent ones requires that the whale geometry is anatomically accurate, further modifications were performed to incorporate quantifiable measurements into the geometry. Necropsy reports were used to obtain measurements of recently stranded right whales, and additional previously published measurements were obtained from [14]. Because of the severe deformation of certain portions of the body after death and the relocation of the carcass to land for measurement, additional measurements were obtained through aerial photogrammetry, as described in [16], which allowed the head proportions and body widths of the whale geometry to be refined. All measurements were categorized according to the age of the individual they were obtained from, and those taken from individuals older than eight years old, which were considered adults, were scaled to a uniform body length of 15 meters.

The resulting proportional measurements were applied to the existing whale geometry in Blender version 2.48 software. A triangular mesh was used to depict the whale's surface, and individual mesh nodes were selected and moved individually with the software's edit mode. Only nodes on the left side of the whale's y-axis were altered, and the right side of the animal was then modified by mirroring those changes made to the left side, so that the whale was entirely symmetrical about the y-axis. Right whales are almost entirely symmetric about this axis, except for the pattern of callosities, or the white, rough, keratinized skin that appears in specific places on the head of a right whale, that is known to differ between individuals [11]. For the purposes of this study, callosities were simplified into smooth skin so no adjustments had to be made.

3. Modelling and Numerical Method

The discretized whale body, as described above, is a triangulation consisting of 11 272 nodes connected by 22 510 edges. The body is treated as a viscoelastic material, and is modeled by a spring-mass system. This is accomplished by treating the nodes as beads of uniform, unit mass, and the connecting edges as springs. Animated motion of the whale is carried out by the solution of the system of differential equations

$$\frac{dX}{dt} = V$$

$$\frac{dV}{dt} = F$$

where X, V and F denote position, velocity and force vectors respectively. For time discretization, a simple forward Euler method is used, yielding the equations

$$X_i^{n+1} = X_i^n + \Delta t V_i^n$$

$$V_i^{n+1} = V_i^n + \Delta t F_i^n$$

where F_i represents the total spring force exerted on node i by the nodes connected to it and is given by

$$F_i^n = \sum_{j=1}^{N_j} \left\{ \mu(V_j^n - V_i^n) + k_j \left[(X_j^n - X_i^n) \left(1 - \frac{l_{i,j}}{||X_j^n - X_i^n||} \right) \right] \right\} - \nu V_i^n$$

Here, j indexes the nodes connected by an edge to node i, N_j is the maximum number of connected nodes, $l_{i,j}$ is the initial length of the edge connecting nodes i and j, μ is a damping constant and ν is a fluid resistance constant. The addition of the damping and fluid resistance terms to the spring term allow the user some added control over the simulation. The damping term is of particular importance, since [17] shows that it is necessary for stability when utilizing first order explicit methods.

Unlike traditional spring systems, here we use a local spring constant, k_j, of a connected node where the constants are assigned to nodes rather than the connecting edges. This idea also differs from the use of a universal spring stiffness (such as that used by [19]) but has been used in image processing, by [18] for example. This way of allocating spring constants has several advantages including reduced storage since there are fewer nodes than edges, and ease of implementation. Due to the extreme deformation in the fluke, this method cannot realistically treat its movement, and this area is instead treated like a swinging gate with the tail base acting as the hinge. Angles are defined between the tail base and the fluke tips for approximately 30 points throughout a complete cycle of the swimming motion, and piecewise linear interpolation provides values for timesteps in between. These angles were obtained from video recordings of a captive bottlenose dolphin swimming horizontally in a tank, as described by [3]. Points on its rostrum, flipper tips and fluke tips, such as those shown on a right whale in figure 1, were marked to clearly trace the movement of the whole body throughout the cycle of its fluke stroke. The nodes between the fluke tips and tail base are then shifted and rotated in accordance with the angle data throughout the swimming motion.

As discussed in [21] and [17], spring systems are prone to instabilities, particularly with explicit methods such as the one described here, so small time steps must be used. In fact, through some simple stability analysis we find that the numerical solution is stable at timestep n if $\Delta t \, ||F_i^n|| \leq 1$ for each node i, and thus we see that the larger the resulting forces from e.g. large spring constants or displacements, the smaller the timestep needs to be. The explicit Euler method has however been used succesfully for numerous other applications such as in [19]. The choice of an explicit method over an implicit one is particularly important for the intended application here, as incremental changes in the geometry are computed and then used by the flow solver in a time marching fashion, thus eliminating the need to store the whale geometry at each timestep.

3.1. Velocity Profile

The most important aspect of the animation is the choice of appropriate initial velocities for the upward and downward motion of both the tail and head. A process is used here in order to develop these in which a pivot point is chosen, and velocity profiles are defined for both the head and tail areas by simple functions. To provide a full motion cycle, the whale is initially at an equilibrium position with its tail flat, and the upward velocity is first used as the initial condition for the ODE system, which is solved forward in time until the tail reached its desired peak. At the peak, the current velocities are negated so that after an equal amount of time the whale is returned to its equilibrium position. This motion is then repeated for the downward motion, providing a full stroke cycle. Once the animation is produced, it is evaluated and unrealistic areas are marked for improvement. The velocity profiles in these areas are modified accordingly, and the process is repeated until satisfactory realistic motion is acheived.

3.2. Spring Constants

The choice of spring constants also plays an important role in the animation. Stiffer springs, i.e. those with higher constants, make it harder for individual nodes to separate from each other and can be used in areas where less motion is desired or where a particular node (or nodes) needs to be pulled towards another one. We have found that lower spring constants work better in areas where a node's target displacement from equilibrium is large. As such, the whale here is treated with high constants in the pivot region (i.e. the back of the head and thoracic region) that is mainly stationary and low spring constants in the tail and head where much more deformation occurs.

3.3. Damping and Fluid Resistance Constants

The effects of the damping and fluid resistance constants on motion can cause undesired effects if not chosen properly. For example, the damping term causes the motion to start slowly and increase in speed as the ODE system is evolved, which in this case causes the tail to unrealistically accelerate. In contrast, the fluid resistance constant causes deceleration and thus can be used to balance acceleration from the damping term. Here, the damping constant was chosen to be as small as possible while still maintaining stability of the system, and the fluid resistance constant was then altered accordingly to eliminate any acceleration effects.

4. Results

The numerical procedure described above has been successfully carried out to produce a smooth, seamless animation. Visualization is acheived by animating data files produced throughout a single stroke cycle using Tecplot 360. Some animation frames are provided here that show the whale body at the extreme positions of each cycle. Particularly, figure 2 shows the starting equilibrium position, which is also the end position for the second upstroke cycle, figure 3 shows the peak of the upstroke half of the cycle, figure 4 shows the whale's tailstock returning to the equilibrium position at the end of the first downstroke cycle and figure 5 shows the bottom of the second downstroke cycle.

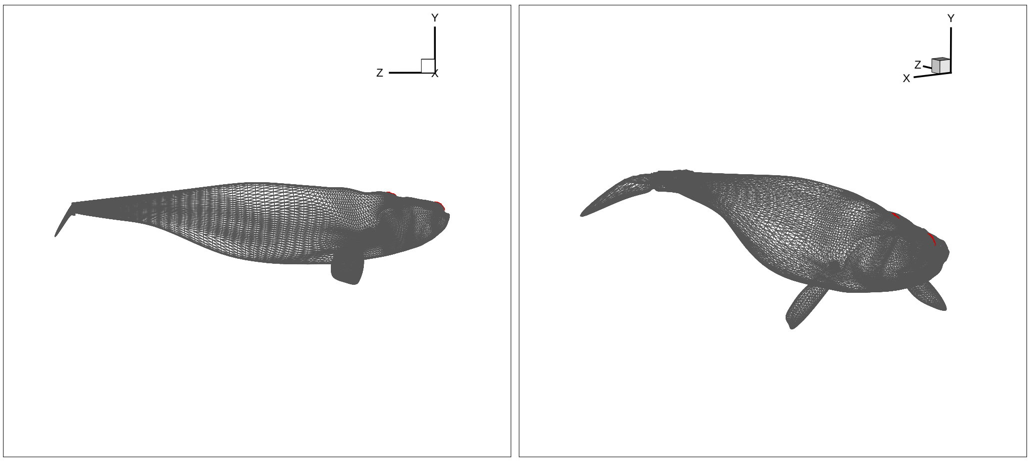

Figure 2: The whale at equilibrium position from side (left) and angled (right) views.

5. Conclusion

In order to reliably and accurately model fluid flow and its interaction with a living animal, swimming movements must be added to a static model geometry. The process described here does that, allowing the whole-body swimming motion of a right whale to be realistically incorporated into a flow solver. In addition to the broad-scale movements, this method also allows minor changes in the whale's external shape, such as deformation of the fluke tips, to be modeled. Fluke tip deformation has been shown to significantly alter the flow and noticably reduce the hydrodynamic forces experienced by a swimming dolphin [4], demonstrating that these small changes in shape may not be neglible when calculating the hydrodynamic forces of the entire body. The combination of an accurate swimming motion as described here with the use of a numerical simulation of fluid movement provides a unique tool for studying the movement

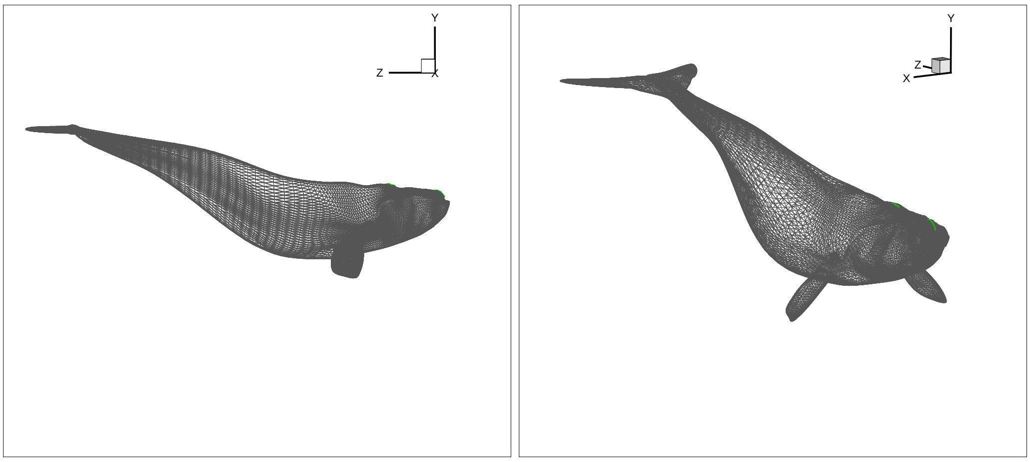

Figure 3: Tail upstroke at peak position from side (left) and angled (right) views.

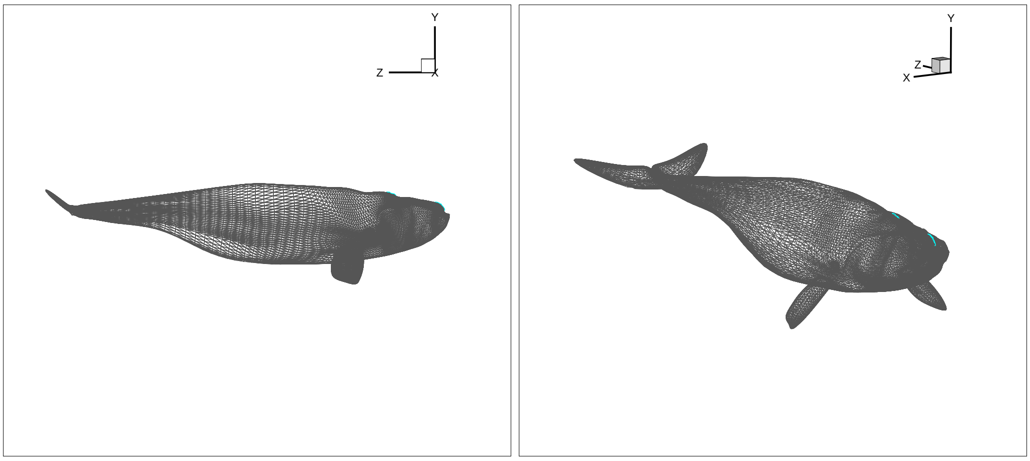

Figure 4: Tail downstroke at middle position from side (left) and angled (right) views.

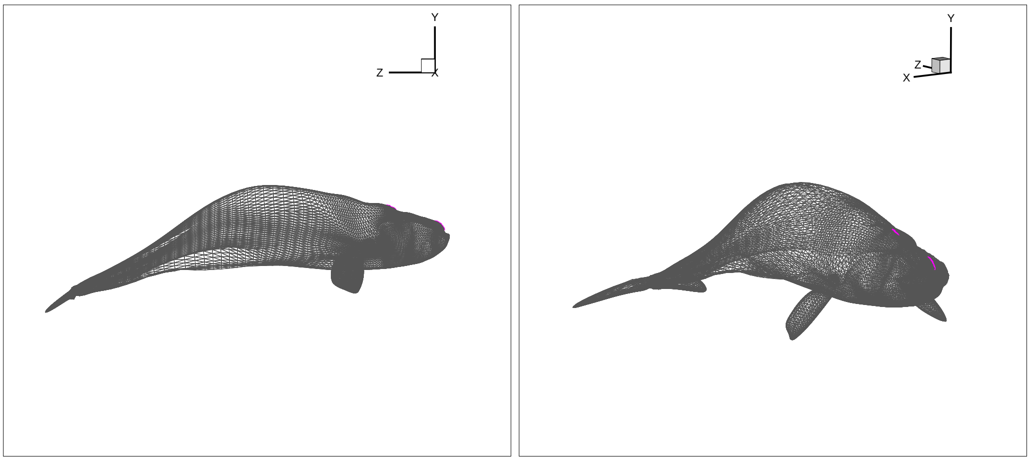

Figure 5: Tail downstroke at bottom position from side (left) and angled (right) views.

of fluids in situations previously inaccessible by experimental methods.

A method has been presented here for the realistic simulation of a swimming North Atlantic right whale and provides guidance for the future animation of swimming marine mammals and any other animals that move by body oscillation. The results show that a simple, computationally cheap, explicit method can be used to replicate the movement inherent in marine locomotion. An animal's forward movement is directly related to its ability to overcome the resistive force of the fluid around it, and the amount of resistance it must overcome directly relates to the amount of energy it must use to do so. The propulsive movements of many organisms, from nematodes to whales, consists of phased oscillations of the body and tail, making the ability to accurately replicate this motion attractive to a wide range of researchers.

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References

[1] J. M. Anderson, N. K. Chhabra, Maneuvering and stability performance of a robotic tuna, Integ. and Comp. Biol. 42 (2002) 118–126.

[2] R. W. Blake, Fish locomotion, Cambridge University Press, 1983.

[3] F. E. Fish, Power output and propulsive efficiency of swimming bottlenose dolphins (*Tursiops truncatus*), Journal of Experimental Biology 185 (1993) 179–193.

[4] F. E. Fish, M. K. Nusbaum, J. T. Beneski, D. Ketten, Passive cambering and flexible propulsors: cetacean flukes, Bioinspiration & Biomimetics 1 (2006) S42–S48.

[5] F. E. Fish, J. E. Peacock, J. J. Rohr, Stabilization mechanism in swimming odontocete cetaceans by phased movements, Marine Mammal Science 19 (3) (2003) 515–528.

[6] J. L. Hench, R. A. L. Jr., Transient tidal circulation and momentum balances at a shallow inlet, Journal of Physical Oceanography 33 (4) (2003) 913–932.

[7] E. Kanso, J. Marsden, C. Rowley, J. Melli-Huber, Locomotion of articulated bodies in a perfect fluid, J. Nonlinear Sci. 15 (2005) 255–289.

[8] E. Kanso, J. E. Marsden, Optimal motion of an articulated body in a perfect fluid, in: 44th IEEE Conference on Decision and Control, Serville, Spain, 2005.

[9] A. R. Knowlton, F. T. Korsmeyer, J. E. Kerwin, H. Y. Wu, B. Hynes, The hydrodynamics effects of large vessels on right whales, Tech. Rep. 40EANFF400534, National Marine Fisheries Service (1995).

[10] A. R. Knowlton, S. D. Kraus, Mortality and serious injury of northern right whales (*Eubalaena glacialis*) in the western north atlantic ocean, Journal of Cetacean Research Management Special Issue 2 (2001) 193–208.

[11] S. D. Kraus, K. E. Moore, C. A. Price, M. J. Crone, W. A. Watkins, H. E. Winn, J. H. Prescott, The use of photographs to identify north atlantic right whales (*Eubalaena glacialis*), Reports of the International Whaling Comission (special issue) 10 (1986) 145–151.

[12] J. C. Liao, D. N. Beal, G. V. Lauder, M. S. Triantafyllou, Fish exploiting vortices decrease muscle activity, Science 302 (5650) (2003) 1566–1569.

[13] J. B. Melli, C. W. Rowley, D. S. Rufat, Motion planning for an articulated body in a perfect planar fluid, SIAM J. Applied Dynamical Systems 5 (4) (2006) 650–669.

[14] M. J. Moore, A. R. Knowlton, S. D. Kraus, W. A. McLellan, R. K. Bonde, Morphometry, gross morphology and available histopathology in north atlantic right whale (*Eubalaena glacialis*) mortalities (1970 - 2002), Journal of Cetacean Research Management 6 (3) (2004) 199–214.

[15] V. V. Pavlov, R. P. Wilson, K. Lucke, A new approach to tag design in dolphin telemetry; computer simulations to minimise deleterious effects, Deep-Sea Research Part II: Topical Studies in Oceanography 54 (2007) 404–414.

[16] W. L. Perryman, M. S. Lynn, Evalution of nutritive condition and reproductive status of migrating gray whales (*Eschrichtius robustus*) based on analysis of photogrammetric data, Journal of Cetacean Research Management 4 (2002) 155–164.

[17] M. Servin, C. Lacoursiere, N. Melin, Interactive simulation of elastic deformable materials, in: SIGRAD 2006 Conference Proceedings, 2006.

[18] J.-K. Shen, B. J. Mastuszewski, L.-K. Shark, C. J. Moore, Deformable image registration using spring mass system, in: Proceedings of Medical Image Understanding and Analysis, 2006.

[19] N. Tamura, T. Nakaguchi, N. Tsumura, Y. Miyake, Spring-bead animation of viscoelastic materials, IEEE Computer Graphics and Applications 27 (6) (2007) 87–93.

[20] P. W. Webb, Hydrodynamics and energetics of fish propulsion, Bulletin of the Fisheries Research Board of Canada 190 (1975) 1–159.

[21] C. A. Wüthrich, J. Augusto, S. Banisch, G. Wetzstein, P. Musialski, C. Toll, T. Hofmann, Real time simulation of elastic latex hand puppets, in: WSCG 2006 Proceedings, Plzen, Czech Republic, 2006.