

Fish, F. E. 1999. Performance constraints on the maneuverability of flexible and rigid biological systems. Pp. 394-406. In: *Proceedings of the Eleventh International Symposium on Unmanned Untethered Submersible Technology*. Autonomous Undersea Systems Institute, Durham New Hampshire.

PERFORMANCE CONSTRAINTS ON THE MANEUVERABILITY OF FLEXIBLE AND RIGID BIOLOGICAL SYSTEMS.

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ABSTRACT - Flexible bodies possessed by fish and marine mammals have been shown to permit high levels of performance with respect to maneuverability. However, flexibility has been avoided in the construction of engineered vehicles. Mechanisms to enhance turning performance with rigid bodies were assessed for the whirligig beetle and the humpback whale. Whirligig beetles swim rapidly in circular patterns. Curved trajectories were executed as powered turns by asymmetrical rowing of the legs, or by increased drag from the abducted elytra in combination with vectored thrust generated from sculling of the wing. Minimum relative radius was 24% of body length. Maximum rate of turn was 4428 deg/s with maximum centripetal acceleration of 2.86 g. Humpback whales use elongate, winglike flippers to develop lift which is resolved into centripetal force to drive the turn. The relative minimum turning radius predicted from flipper structure was 82% of body length. Compared to vertebrates with flexible bodies, the turning performance of rigid bodied beetles and whales is constrained; however, use of appendages can enhance turning performance.

INTRODUCTION

Progress in technologies concerned with aquatic locomotion comes from the discovery and refinement of new designs. The imposition of the aquatic medium on both machines and animals requires that they contend with the same physical laws that regulate their design and performance (Fish, 1998). It is no accident that the optimal shape for drag reduction is possessed by modern submarines, fish, and dolphins, although independently developed. Animal mechanisms often have been recognized mainly after an engineered solution was developed. In comparison to engineers who can limit variables in their systems, the problem for biologists has been that the systems they study are complex. These systems are composed of structural elements for which the physical characteristics have not been fully described. In addition, the biological systems are multitasking, thus limiting optimal solutions. However, natural systems have a number of attributes that are of interest to engineers which chief among these is maneuverability (Saunders, 1951; Shaw, 1959; Watts, 1961; Triantafyllou and Triantafyllou, 1995; Anderson, 1998; Kumpf and Triantafyllou, 1998; Wolfgang et al., 1998).

Various morphologies within animal lineages have evolved which foster maneuverability (Webb, 1984, 1997; Weihs, 1993; Webb et al., 1996). Within the fish and marine mammals there are divergent body designs that suggest differences in turning performance. Of the fastest swimming marine mammals, the pinnipeds and cetaceans display considerable variation in both their morphology and propulsive mode which could affect maneuverability (Fish, 1996, 1997). Turning performance is constrained by morphology with flexibility of the body, and mobility and

position of the control surfaces determining the level of performance (Webb, 1984; Weihs, 1993; Bandyopadhyay et al., 1997; Fish, 1997). For vertebrates the possession of a flexible spine and elastic elements permits these animals to display considerable proficiency in their maneuverability.

Engineering solutions for enhanced maneuverability typically have avoided whole body flexibility. Ships, submarines, torpedoes, and submersibles have relied on hinged rudders or vectored thrust to effect turning with a rigid body (Saunders, 1957; Marchaj, 1988). The difference between biological and engineered technologies is based on the materials each uses (Vogel, 1998). Whereas engineered systems employ rigid materials such as metals, ceramics, and hard plastics, organisms are composed of flexible proteins and polymers. In cases where hard tissues (i.e. bone) are used to provide skeletal support, flexibility is provided by multiple joints with a large number of degrees of freedom. Emulation of the biological structure in biomimetic systems has provided enhanced turning performance, but not at the maximum level achieved by animals (Webb, 1983; Domenici and Blake, 1991; Anderson and Kerrebrock, 1997; Bandyopadhyay et al., 1997; Fish, 1997; Kumph and Triantafyllou, 1998).

Concerns in using flexible animals to design aquatic vehicles are associated with stability and oscillations from propulsive movements. Flexible bodies are inherently unstable compared to rigid bodies (Fish, 1997). In designing vehicles which are mainly required to move rectilinearly, the addition of flexibility requires higher levels of active control to prevent unnecessary and energetically inefficient deviations in trajectory. The oscillatory and undulatory movements of the body and tail of fish and marine mammals produce recoil movements at the anterior end (Webb, 1975). These movements are smaller than the propulsive movements due to muscle coordination, narrow necking, presence of control surfaces, and inertial mass of the body (Lighthill, 1975; Webb, 1975, 1984; Fish, 1993). Observations on dolphins show pitching displacement at the rostrum to be 1-7% of body length and nearly in phase with the fluke movements (Fish unpubl. obs.). Such movements at the anterior end are similar to those of subcarangiform fish in the order of 4-7% of body length (Webb, 1975). However, these oscillations may be beyond the tolerances of engineered sensors, although acoustic, visual, electric, and pressure sensors in animals appear to operate without difficulty.

RIGID ANIMAL BODIES- AQUATIC INSECTS

An alternative animal model utilizing a rigid body can be examined for application to autonomous underwater vehicles (AUV) to avoid the complexity associated with designing and controlling flexible body systems. Arthropods have bodies constrained by a cuticle exoskeleton. Despite this perceived disadvantage, these animals are able to execute rapid maneuvers with higher efficiency than elicited by flexible vertebrates (Webb, 1979). The body form of aquatic insects exhibits variation which is associated with a compromise between maneuverability and speed (Nachtigall, 1974; Ribera et al., 1997).

Whirligig beetles (Coleoptera, Gyrinidae) have a fixed exoskeleton which renders the body rigid and firm (Nachtigall, 1974). The body has an oval design which is unstable and extremely maneuverable both at and below the water surface (Fig. 1). The beetles propel themselves by drag-based strokes of the paddlelike middle and hind legs. The middle leg can paddle with a frequency of up to 25 Hz and the hind legs stroke twice as fast (Bendele, 1986). The animals can reach velocities of more than 0.5 m/s (Tucker, 1969).

Whirligig beetles are normally observed in groups swimming slowly or resting on the surface of ponds or calm streams (Bendele, 1986; Vulinec and Miller, 1989; Watt and Chapman, 1998). Beetles detect prey with visual and mechanoreceptors, including possible reception of reflected surface waves in a system analogous to echolocation (Kolmes, 1983). Once prey is detected the beetle will circle the prey before capturing and consuming it. When disturbed, the beetles display a fright reaction in which the insects circle at high speed. This reaction is termed 'protean behavior' (Humphries and Driver, 1967; Newhouse and Aiken, 1986) which is defined as that behavior "which is sufficiently unsystematic to prevent predicting in detail the position or actions of the actor."

The ability of beetles to turn at high speed indicates that maneuverability is not constrained by a rigid body. To investigate the turning performance of whirligig beetles (*Dineutus horni*),

swimming by 25 beetles (mean mass = 0.0695 g; mean length = 12.38 mm) was videotaped at Brown University with a Kineview – High speed video system (Model 1256P, United Technologies Adaptive, Optics Associates) at 500 or 1000 frames/s. Beetles were tested in a arena constructed of a 46 mm section of white PVC pipe with an internal diameter of 115 mm. The floor of the arena was constructed from clear acrylic plastic. The arena was filled with tap water to a depth of approximately 30 mm. Water temperature was 22°C. Swimming trials for each beetle lasted two min.

Video records were analyzed frame-by-frame with a video recorder (Panasonic AG-7300). Only those records were used in which the animal's body remained horizontal through the turn. The sequential positions of the leading edge of the head were recorded onto transparencies from the video monitor. The center of rotation of the turn was determined geometrically. This technique allowed for determination of the trajectory of the center of gravity, despite distortion in observing the actual position of the head due to refraction from surface waves. Turning radius, r , and average velocity, U , were measured, and centripetal acceleration, a_c , in g s was computed according to:

$$a_c = U^2/r \ 9.8. \quad (1)$$

Angular displacement was used to calculate the turning rate in deg/s.

Curved trajectories were executed as powered turns, whereby thrust generating actions were continuous throughout the maneuver. Asymmetrical rowing of the midlegs and hindlegs on the inside of the turn powered the turn (Fig. 2). Turns also were produced by abduction of the elytra facing the inside of the turn and vectored thrust generated from sculling of the wing (Fig. 3). Wing oscillation frequency was 46.5 Hz.

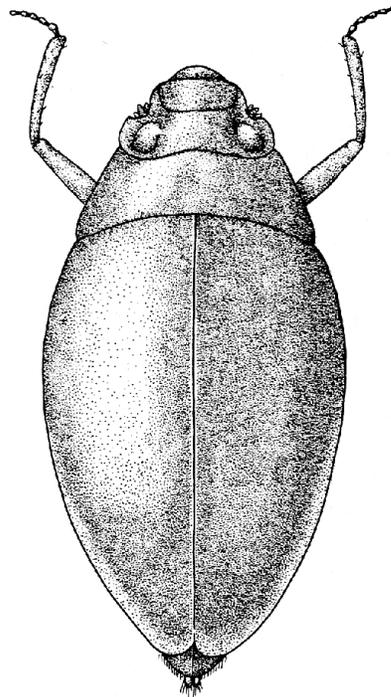


Fig. 1. Whirligig beetle showing fore legs.

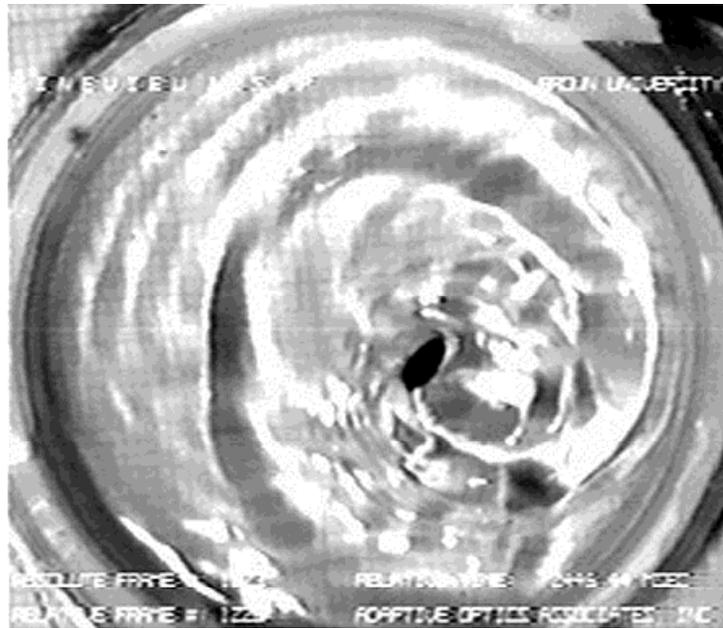


Fig. 2. Turning maneuver of whirligig beetle produced by rowing of the legs. The pattern of turning is indicated by the spiral waveform.



Fig. 3. Turning using vectored thrust produced by the wing and drag produced from the elytra. The beetle is turning to the left.

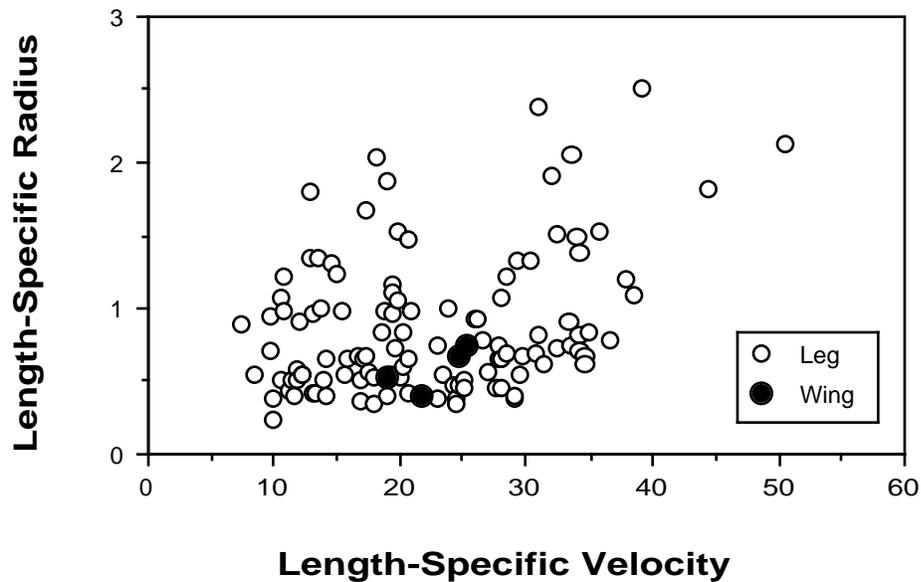


Fig. 4. Length-specific radius plotted against length-specific velocity for horizontal turning maneuvers by whirligig beetles. Open circles represent swimming by rowing of the legs; closed circles represent turns executed by drag from the elytra and vectored thrust produced by a sculling wing.

Swimming speeds varied from 0.06 to 0.55 m/s ($Re = 1.1 \times 10^3 - 6.8 \times 10^3$). These speeds represented length-specific speeds of 4.7–44.5 body lengths/s. Turning radius was not associated with swimming velocity (Fig. 4). Relative minimum radius was 24% of body length. Turning rate was linearly related to centripetal acceleration (Fig. 5). Maximum rate of turn was 4428 deg/s with maximum centripetal acceleration of 2.86 g. Turning by winged propulsion showed no difference in turning performance from legged propulsion.

RIGID ANIMAL BODIES- BALEEN WHALE

The baleen whales of the cetacean suborder Mysticete are the largest of all animals. Much of the body is inflexible because of their specialized feeding system. The whales have an expanded oral cavity which is used to gulp or skim a large quantity of water to strain through baleen plates. As a result the head can represent up to 30% of the total body length. Maneuvering appears to be restricted during feeding. Typically, whales swim rectilinearly when foraging (Ridgway and Harrison, 1985; Whitehead and Carlson, 1988; Fish and Battle, 1995). However, the humpback whale (*Megaptera novaeangliae*) is an exception to this general feeding pattern in that it undertakes maneuvers to catch prey (Jurasz and Jurasz, 1979; Hain et al., 1982).

The humpback whale is the most acrobatic of the baleen whales. Observations of swimming performance by humpback whales show them to be highly maneuverable (Tomilin, 1957;

Nishiwaki, 1972), using the extremely mobile, winglike flippers for banking and turning (Edel and Winn, 1978; Madsen and Herman, 1980). Whales use this maneuverability to feed on patches of plankton or fish schools including euphausiids, herring, and capelin (Jurasz and Jurasz, 1979; Winn and Reichley, 1985; Dolphin, 1988). Turning is widely used in feeding employed with lunging and bubbling behaviors (Hain et al., 1982).

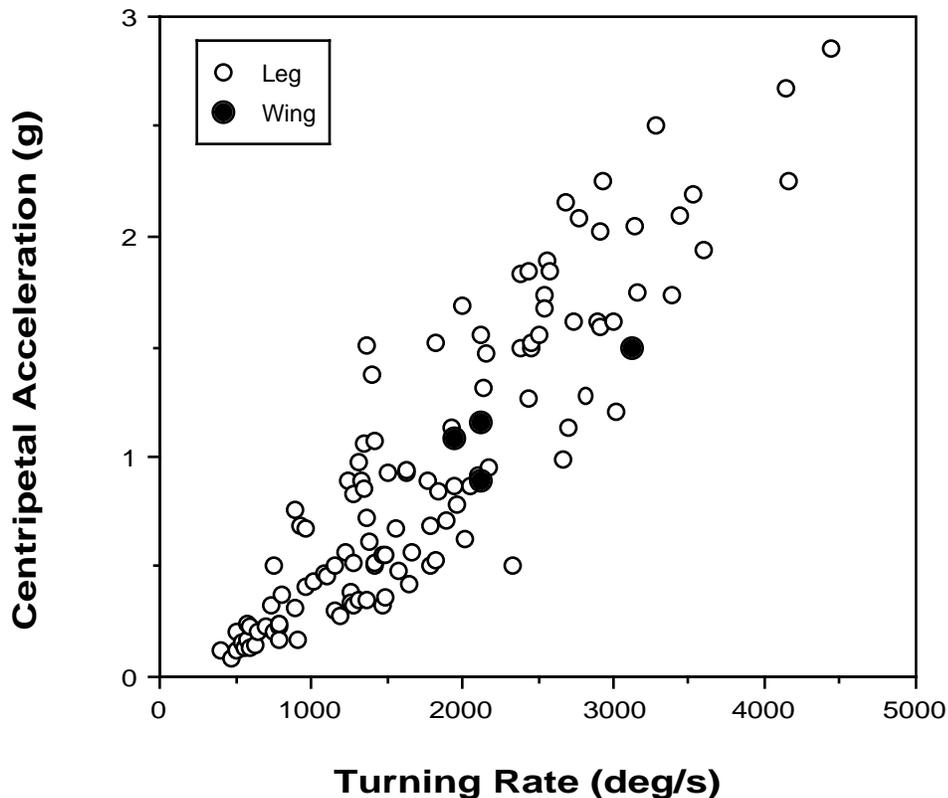


Fig. 5. Relationship between centripetal acceleration and turning rate for whirligig beetles. Open circles represent swimming by rowing of the legs; closed circles represent turns executed by drag from the elytra and vectored thrust produced by a sculling wing.

In lunge feeding, whales rush (approximately 2.6 m/s) toward their prey from below while swimming up to the water surface at a 30^o-90^o angle (Jurasz and Jurasz, 1979; Hain et al., 1982). In "inside loop" behavior, the whale swims away rapidly from the prey aggregate with its flippers abducted and protracted (Edel and Winn, 1978), then rolls 180^o making a sharp U-turn ("inside loop"), and lunges toward the prey (Hain et al., 1982). The entire "inside loop" maneuver is executed in 1.5-2 body lengths of the whale. Rapid turning maneuvers are required also for "flick feeding" which is performed in approximately 3 s (Jurasz and Jurasz, 1979).

In "bubbling" behaviors, underwater exhalations from the blowhole produce bubble clouds or columns which concentrate the prey (Winn and Reichley, 1985). Columns of bubbles arranged as rows, semicircles, and complete circles form "bubble nets" (Jurasz and Jurasz, 1979; Hain et al., 1982). Bubble nets are produced as the whale swims toward the surface in a circular pattern from a

depth of 3-5 m. At completion of the bubble net, the whale pivots with its flippers and then banks to the inside as it turns sharply into and through the center of the net (Ingebrigtsen, 1929; Hain et al., 1982). Bubble net size varies from a minimum diameter of 1.5 m for corralling euphausiids to a maximum diameter of 50 m to capture herring (Jurasz and Jurasz, 1979).

The feeding behavior of humpbacks is considered more energetically demanding than the skim feeding of bowhead whales (*Balaena mysticetus*) (Dolphin, 1987). However, faster swimming and individual foraging by finback whales (*Balaenoptera physalus*) was suggested by Whitehead and Carlson (1988) to be less advantageous for feeding success than maneuverability by groups of humpback whales.

The turning radius (r) due to the humpback whale flippers alone can be found by setting the centripetal force (F_c) acting on the whale equal to the lift force (L) generated by the flippers (Howland, 1974; Weihs, 1981) so that:

$$F_c = L \quad (13)$$

$$F_c = m_v a_c = m_v U^2/r \quad (14)$$

$$L = 0.5 \rho A_f C_L U^2 \sin \phi \quad (15)$$

where m_v is the virtual mass of the whale (body mass + water entrained to whale), U is velocity, ρ is density, A_f is the total projected area of flippers, C_L is the lift coefficient, and ϕ is the bank angle (Alexander, 1983). Turning radius is speed independent, because both centripetal and lift forces scale with the square of speed. Thus:

$$r = m_v / 0.5 \rho A_f C_L \sin \phi \quad (16)$$

Assuming neutral buoyancy, the virtual mass (m_v) is:

$$m_v = m_w + m_w \lambda \quad (17)$$

where m_v equals the sum of the whale's mass, m_w , and m_w times an added mass coefficient, λ , (0.082 for a 4:1 spheroid).

Fish and Battle (1995) computed the turning radius for a 9 m humpback whale. The whale's minimum turning radius equaled 7.4 m when ϕ equals 90° (Fig. 6). This translates into a length-specific radius of 82% of body length. The calculated minimum turning radius falls within the minimum and maximum radii for turns during bubbling behaviors (Jurasz and Jurasz, 1979).

Maximum bubble net radius (25 m) may be achieved by the humpback whale with ϕ of 17° . Considering that other surfaces of the whale (e.g., flukes, peduncle, body) are employed in turns (Edel and Winn, 1978), the actual minimum turning radius is assumed to be smaller. Fluke span is 27-38% of total body length (True, 1983; Tomilin, 1957). The relatively large size of the flukes would contribute to maneuverability by increasing the lift force. However, the restricted range of motion of flukes and body in conjunction with their use in thrust production limit their effectiveness to control maneuverability during powered swimming.

DISCUSSION

Turning is effected by dynamic forces. These forces include unsteady non-inertial forces such as body internal dynamics (i.e., redistribution of body mass) and fluid inertial reaction (i.e.,

pulsed jet), and include steady non-inertial forces such as lift and drag. In aquatic maneuvering systems, the non-inertial forces dominate.

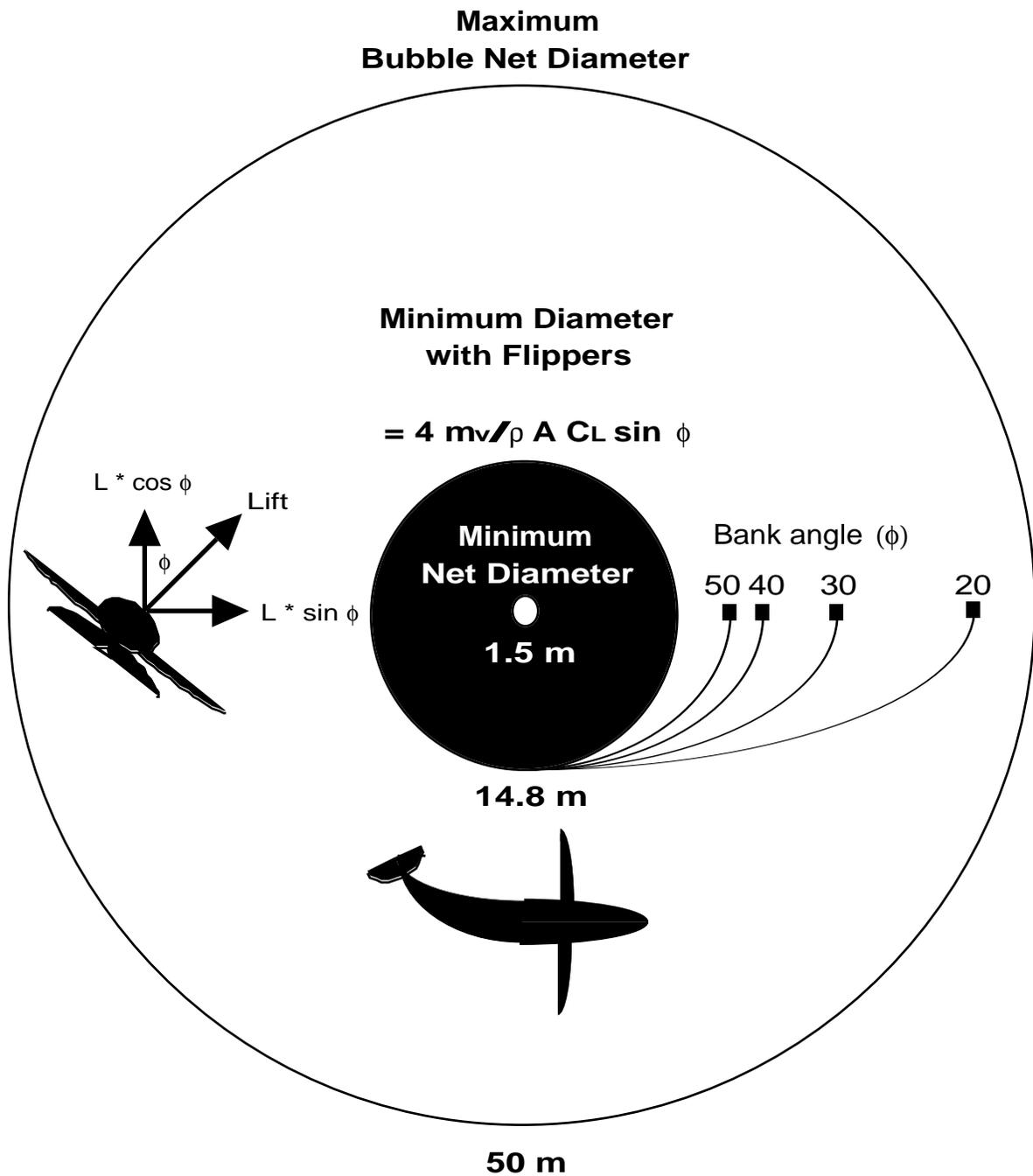


Fig. 6. Calculated and observed turning performance of the humpback whale (*Megaptera novaeangliae*). The calculated minimum turning diameter (14.8 m) for a 9 m whale is shown by the outer margin of the black circle, based on the equation shown. The margins of the turn for various bank angle are shown by curved lines. The minimum and maximum diameters of bubble nets are shown by the margin of the central white circle and the outer white circle, respectively. The lift (L)

vectors with respect to bank angle is illustrated in the inset. The silhouette indicates the dimensions of the whale.

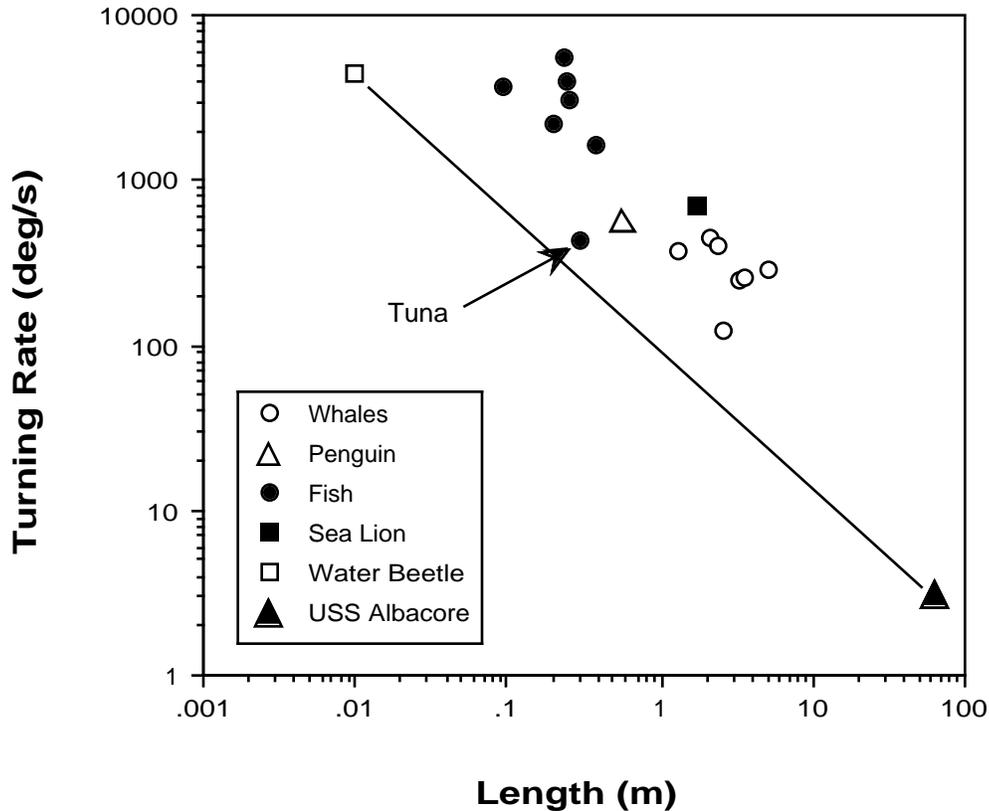


Fig. 7. Comparison of turning rate with respect to size. The line connects the beetle and submarine which both have inflexible bodies. The value for relatively stiff tuna approaches the line. Data from Webb, 1976, 1983; Hui, 1985; Miller, 1991; Blake et al., 1995; Fish, 1997.

Animals can use an asymmetrically applied drag to rotate around and turn. Appendages modified as paddles can produce this effect which works well in conditions dictated by low velocity and precise control. However, drag-based turning should be less effective in conditions of rapid movement with high velocity. The consequences of using drag-based turning is a dramatic reduction in velocity, because appendages used for propulsion become braking devices without producing thrust. Even under conditions where thrust is maintained by other appendages and non-propulsive appendages generate the drag for turning, the energy cost will be high.

Lift-based maneuvering systems have the advantage of producing a centripetal force to effect turning without incurring a large decelerating drag (Watts, 1961). This is the primary system used by ships, fish and marine mammals (Manning, 1930; Howland, 1974; Hoerner and Borst, 1975; Weihs, 1981; Webb, 1983, 1997; Marchaj, 1988; Fish and Battle, 1995; Fish, 1997). The control surface works best with a high aspect ratio, winglike morphology. The effectiveness of lift-based mechanisms varies with speed (Marchaj, 1988). Lift used by the control surfaces to create destabilizing moments varies in proportions to U^2 . However, the mass to be moved by the

destabilizing moments is proportional to mass and independent of speed (Webb, 1997). As speed decreases, the lift also decreases relative to the required force necessary to turn so that maneuvering is more difficult at low U .

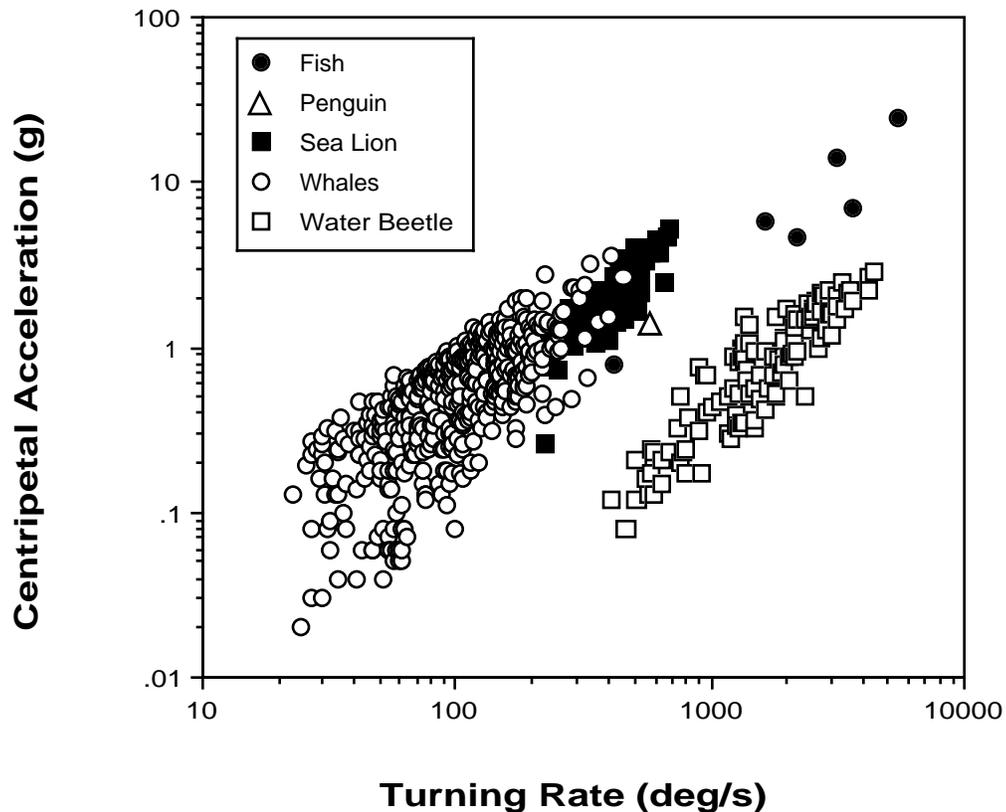


Fig. 8. Plot of centripetal acceleration as a function of turning rate. Data from Webb, 1976, 1983; Hui, 1985; Blake et al., 1995; Fish, 1997.

Despite the apparent advantages of lift-based versus drag-based turning with regard to speed, the use of rowing appendages can be beneficial for continuous turning. Propulsion is curtailed during small-radius turning maneuvers using extreme body flexibility in combination with lifting surfaces. Thus these unpowered turns are limited in duration as frictional drag on the body causes a loss of momentum. To produce continuous turns, fish and marine mammals would have to dispense with the unpowered turn and revert to a powered turn with its increased turning radius. Only by alternating bouts of powered and unpowered turns could a position be held and the turn sustained. Adjustments between the powered and unpowered turns will reduce the effectiveness of the maneuver. With rowing, the appendages can continue to generate thrust to maintain the minimum turning radius for a prolonged period. Although propulsion by paddling is less efficient than oscillating a hydrofoil (Blake, 1986; Fish, 1993, 1996), maintenance of a stable circular turn could make paddling more efficient for circular maneuvers.

Compared to vertebrates with flexible bodies, the relative turning radii of whirligig beetles and humpback whales are constrained by a rigid body morphology. Expressed as a percentage of body length, the minimum turning radius is 5.5-47% for fish, 11-17% for cetaceans, and 9-16% for sea lions (Hui, 1985; Domenici and Blake, 1997; Fish, 1997). The higher minimum turning radius for fish (47%) was found for the tuna (Blake et al., 1995). These fish are thick-bodied and relatively stiff (Webb, 1984). Submarines with inflexible hulls have turning radii of 200-300% of body

length (Maslov, 1970). Such limitations in turning performance due to body inflexibility also are shown in examination of turning rate (Fig. 7). If a line is drawn between the turning rates for the two rigid bodied swimmers (whirligig beetle and submarine), flexible-bodied swimmers are shown to have higher turning rates with respect to their size. Only the tuna approaches the line and falls far below turning rates for similarly sized fish.

Higher centripetal accelerations are generated by flexible-bodied organism compared to rigid-bodies (Fig. 8). This is largely a consequence of the tighter turning radius of flexible organisms. For these animals that turn using lifting surfaces, the high centripetal acceleration is necessary to generate sufficient force for the turn. However, high centripetal accelerations are not required by the beetles. The drag-based paddling and vectored thrust mechanism can effect turns with a pivoting action that permits a higher turning rate but with lower centripetal acceleration.

In conclusion, rigid bodies do constrain turning performance compared to flexible bodies. However, the inability to bend can be compensated for by modifying the use of appendages acting as propulsors and control surfaces. Paddle-propulsion and vectored thrust maintain continuous turning; whereas, increased size of control surfaces can enhance lifting capabilities to provided centripetal force. Under conditions dictated by simplicity design, rigid bodies could be employed in the construction of maneuverable autonomous underwater vehicles

ACKNOWLEDGMENTS

I would like to express my appreciation to G. W. Fairchild, C. S. Fish, K. Heron, C. Kovacs, K. Middleton, J. Peacock, and S. Swartz for their contributions to this project. Much of the manuscript was based on research supported from the Office of Naval Research, grant number N00014-95-1-1045 (program manager T. McMullen).

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