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Note on the swimming deceleration of a dolphin

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A series of decelerative swimming motions of a dolphin were recorded underwater showing that the animal decelerated more rapidly than could be accounted for by frictional drag. The theory of swimming slender bodies was used to calculate the mean thrust on the dolphin produced by the observed motions. It is shown that the dolphin is decelerating by producing a swimming thrust opposite to the direction of swimming.

Both recent theory and historical observation confirm that marine animals propel themselves through water by various undulatory motions. For example, fish accelerate with these motions as well as maintain a constant speed for long periods of time. The theory of swimming bodies (e.g. Lighthill 1960) also predicts that deceleration can be produced by swimming motions, a fact verified by 'swimming plates' in the laboratory (e.g. Kelly 1961, p. 442). This note is a measurement of deceleration produced by the swimming motions of a porpoise.

A simple experiment was carried out with a porpoise swimming the length of a 15 × 7 m tank. A lure fish was dropped into the water alternately from either end of the tank. The mammal accelerated very rapidly (to a speed of over 6 m/sec) and continued swimming in a deceleration fashion toward the bait. Because the lure was near a wall, the porpoise had to approach the bait with low terminal speed. It is apparent (see figure 1) that the above swimming behaviour minimizes transit time to the bait, as the fixed distance can be covered in a shorter time than swimming toward the lure with constant acceleration and arriving at the wall with equal low terminal speed. The conclusions drawn in this note are based on film taken of the porpoise while executing this manœuvre.

In 1960 Lighthill formulated a theory of swimming of slender fishes in terms of hydrodynamical theory of slender body motion in a fluid. The swimming motions of a porpoise approximate to that of a slender body and the simplest comparison of experiment with theory can be made in terms of this formulation. Only the barest essentials of the theory are given here.

The motion of fluid around the propoise is due to a longitudinal mean swimming speed, U, and small lateral body displacements $h(x,t)$. Each elemental cross-section of the porpoise has an inertial mass $\rho A(x)$ which is the sum of the mass of the slice of the porpoise (of same density as water) and the water moving with it.

The lateral velocity of this water mass is approximately

$$V = \frac{\partial h}{\partial t} + U\frac{\partial h}{\partial x}. \tag{1}$$

The lift L on the driving element of the body is equal to the rate of change of momentum of the fluid flowing about it,

$$L = -\left\{\frac{\partial}{\partial t} + U\frac{\partial}{\partial x}\right\}\rho A V. \tag{2}$$

The porpoise does work at a rate which is the sum of the work done by all its body elements,

$$W = -\int_0^l \frac{\partial h}{\partial t}\{L(x,t)\}\,dx. \tag{3}$$

Over many cycles the average rate of work is

$$\overline{W} = \rho U A(l)\left\{\overline{\frac{\partial h}{\partial t}\left(\frac{\partial h}{\partial t} + U\frac{\partial h}{\partial x}\right)}\right\}_{x=l}, \tag{4}$$

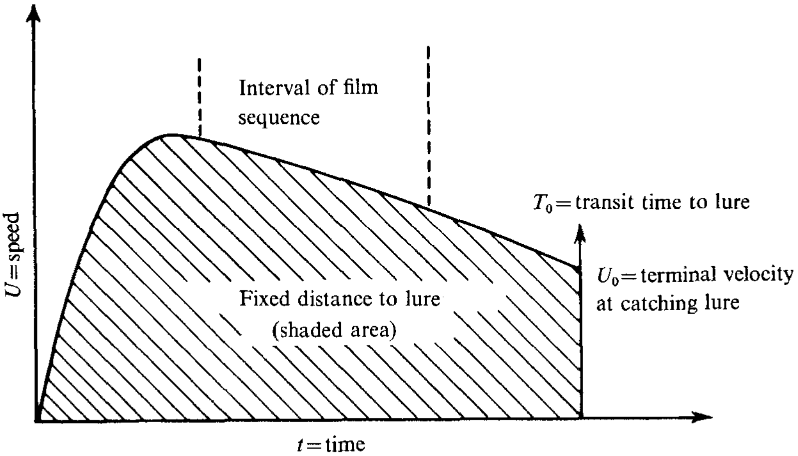

FIGURE 1. Characteristic speed *vs.* time graph of porpoise transit to lure.

where the bar denotes the time average over many cycles. In the above derivation l is the length of the porpoise and terms of order $l/\Delta T U$, $\Delta U l/U^2 \Delta T$ have been neglected, with ΔT the time of averaging and ΔU the change of mean velocity in this time. Furthermore, the condition $\partial h/\partial t < U$ is to hold.

Lighthill points out that (4) is the product of lateral velocity $\partial h/\partial t$ of the tail trailing edge with the rate of shedding of lateral momentum $(\rho V A)U$ behind the fish. Not all this work can be used for driving the porpoise. There is a vortex trail shed behind the animal, which has lateral motions of kinetic energy $\frac{1}{2}\rho A(l)\,V^2(l)$. The mean rate of shedding this energy is the work used to excite these lateral motions in the vortex trail and must be subtracted from (4) to obtain the work available to drive the animal. Let $\overline{P}$ be the mean thrust, then

$$\overline{P}U = \overline{W} - \tfrac{1}{2}\rho\overline{U V^2(l)}A(l), \tag{5}$$

whereby

$$\overline{P} = \tfrac{1}{2}\rho A(l)\left\{\overline{\left(\frac{\partial h}{\partial t}\right)^2 - U^2\left(\frac{\partial h}{\partial x}\right)^2}\right\}_{x=l}. \tag{6}$$

The mean thrust from (6) can be either positive or negative; it is negative when the horizontal momentum of the wake is less than that of the mean flow outside the wake. In this latter case an external force must be applied to push the animal through the water with velocity U or the animal will decelerate.

It was found that in most of the experiments the porpoise was decelerating, and the mean value of (6) proved to be negative. Furthermore, the mean value of $\bar{P}$ calculated from (6) (see table 1) was the larger portion of the mean force required to produced the observed behaviour, i.e. the force required to accelerate or decelerate the inertial mass of the animal; the viscous drag was generally the smaller fraction. This result might be somewhat fortuitous because the approximations made in the theory hold marginally and the interpretation of the films is not unique. Also, the shape of the porpoise (figure 2) departs from a 'slender' body near the tail flukes, an important area with regard to the animal's movements. Nevertheless, the validity of these calculations is established by the internal consistency of the total picture; i.e. when a large deceleration was indicated $\bar{P}$ was calculated to be a negative value (run no. 1, 14, 30, 35, 50) and when acceleration or a near equilibrium situation was apparent $\bar{P}$ was calculated to be a smaller positive value (run no. 2, 28). The required thrust is on the average within 20 % of the calculated thrust (table 1).

Run no.	Mean speed (cm/sec)	Change of speed (cm/sec)	Duration of run ($\frac{1}{50}$ sec)	Calculated mean available thrust (kg)	Mean turbulent drag (kg)	Required mean thrust (kg)
1	396	−122	34	−15·4	−6·4	−18·6
2	457	+30	29	+16·3	−8·2	+17·3
14	457	−244	34	−14·1	−8·2	−36·3
28	579	−91	33	+4·5	−13·6	−14·9
30	396	−183	38	−4·1	−6·4	−24·5
34	457	−213	25	−37·7	−8·2	−43·6
50	427	−122	22	−43·1	−7·3	−42·2

TABLE 1. Comparison of required and available thrust for deceleration.

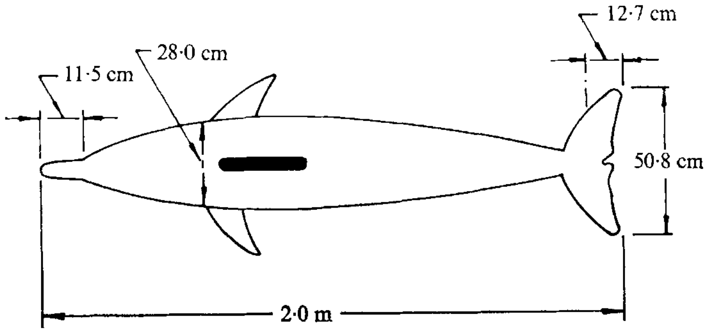

FIGURE 2. Schematic of physical characteristics of 'Dixie'. Weight, 90 kg; inertial mass (□), 108 kg; $gA(l)$ = inertial mass per unit length of tail section, 94 kg; turbulent drag coefficient (+), 0·0024. □, Lamb (1932, p. 85); +, Lang (1963).

A large commercial marine exhibit gave their consent to the use of their animals and tanks in the taking of approximately 600 ft. of underwater 16 mm black and white film. The animal used was a dolphin (*Tursiops truncatus*), a young female named Dixie measuring approximately 2 m in stretched straight position and weighing approximately 90 kg. The span of her tail measured approximately 51 cm, and the mean chord length was 12·7 cm (see figure 2).

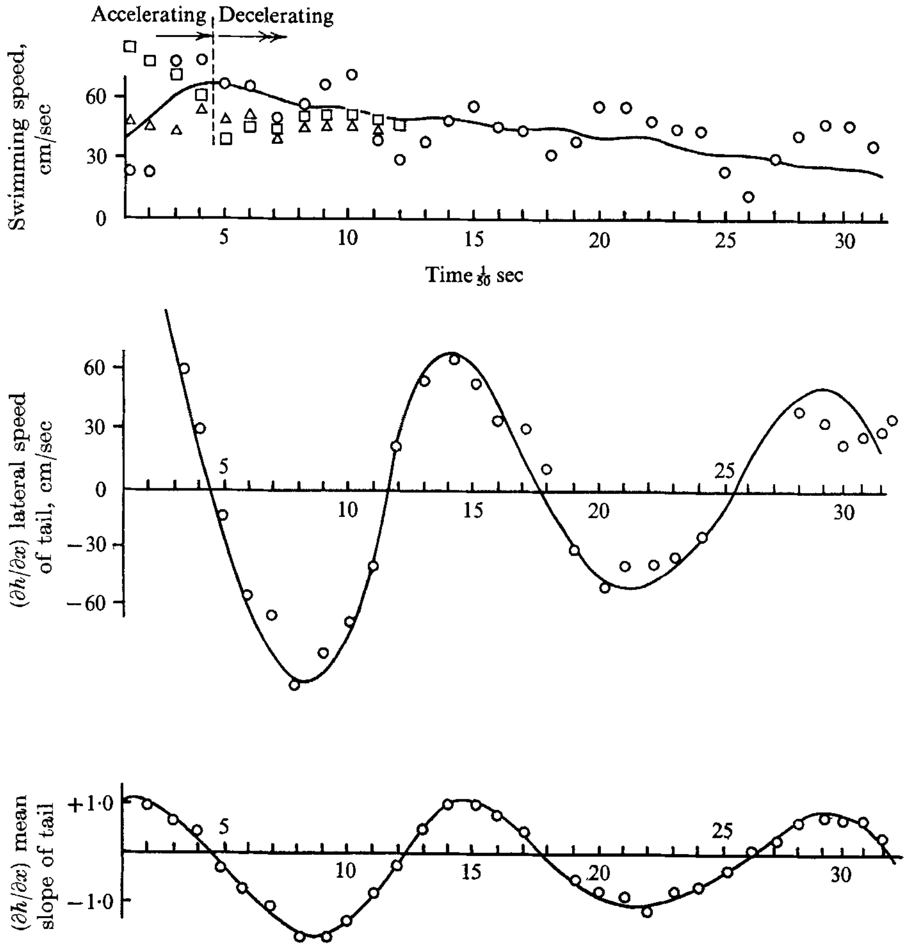

FIGURE 3. Swimming characteristics of 'Dixie' no. 50. ○, rate of tail advance; △, rate of nose advance; □, rate of pectoral advance; —, swimming speed.

The films were taken in a tank with dimensions 15 × 7 m and approximately 3 m in depth. Dixie showed considerable interest in both diver and camera, and could apparently hear the camera mechanism when operated as she would immediately react by turning toward the camera and peering intently at the underwater housing at close range. Eventually she ignored the sound and seven usable sequences, lasting approximately $1\frac{1}{2}$ sec each, were obtained when her trainer would throw fish in one end of the tank and then the other.

Several techniques were attempted, the most successful was when the camera was held stationary as Dixie swam through the film frame from edge to edge.

In this manner, almost two full swimming cycles were eventually obtained. The film speed was calibrated to give 50 frames/sec.

The selected films were projected to a convenient size and the tail (of fixed length), pectoral, dorsal fin and nose outlines were transferred on to graph paper which allowed a calculation of the forward velocity by measuring the average advance rate of tail, dorsal, pectoral and nose outline in each frame (this average yields the mean motion of the centre of mass of the animal). The length of the nose was used to fix a length scale. The change in angular deflexion of Dixie to the film plate was also determined by measurement of change in her relative dimensions from frame to frame and was found to be insignificant. The centre of each uniform tail section and stream tail angle was determined, and measurements of $\partial h/\partial t$ and $\partial h/\partial x$ were taken directly from these graph paper plots.

The velocity *vs.* time for a typical run is plotted in figure 3 along with the characteristics $\partial h/\partial t$, $\partial h/\partial x$ of the tail motion used in calculating the available mean thrust. Figure 2 displays the physical characteristics of Dixie. Table 1 contains the calculated values of available thrust from (6) and the mean thrust required to decelerate the inertial mass of Dixie the observed amount. Thrust is positive in the direction of motion. Table 1 also contains the estimated turbulent skin friction drag, based on the mean velocity of the run.

In runs 1, 14, 30, 34 and 50 a negative mean force is required to decelerate the inertial mass of Dixie. At worst, the skin friction drag is of turbulent nature. There is a good reason to believe that the actual frictional drag for a dolphin lies between the turbulent and laminar value (Lang 1963), whereby the turbulent drag is an over-estimation of the viscous force. Because the turbulent frictional drag is much less than the required decelerative force, it is clear that the dolphin in this sequence of runs decelerates by drawing momentum out of the mean flow using swimming motions like those normally used in overcoming frictional drag or accelerating. Runs 2 and 28 approximate the equilibrium situation where some thrust is used to overcome the viscous drag.

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