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Hydrodynamic Analysis of Cetacean Performance

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SYMBOLS USED IN TEXT

A	Surface area of animal, ft^2
a	Acceleration, ft/sec^2
B	Weight of water displaced by animal, lb
b_t	Tail span, ft
C_f	Drag coefficient based on wetted surface area
D	Drag, lb
D_t	Total drag of animal and collar, lb
D'	Drag area, $D' = 2D/\rho V^2 = D/q$, ft^2
F	Attractive force between bodies, lb
F_f	Force exerted by fins, lb
F_t	Force exerted by tail, lb
g	Acceleration of gravity, ft/sec^2
h	Corrected jump height, ft
HP	Horsepower output of animal, $HP = P/550$
HP_a	Horsepower calculated from acceleration data
HP_D	Horsepower calculated from drag and velocity data
l	Length of animal, ft, unless otherwise specified

M	Body moment produced by angle of attack, ft lb
m_l	Longitudinal effective mass of animal, slugs
m_w	Mass-flow rate of water accelerated when sculling, slugs/sec
P	Power, ft lb/sec
q	Dynamic pressure, $q = \rho V^2/2$, lb/ft^2
R_l	Reynolds number, $R_l = \frac{Vl}{\nu}$
T	Thrust during acceleration, lb
t_1	Time elapsed in traveling from Hoop 1 to Hoop 2, secs
t_2	Time elapsed in traveling from Hoop 2 to Hoop 3, secs
V	Speed of animal, ft/sec, unless otherwise specified
$\frac{1}{2}v_t$	Velocity induced at the tail while sculling, ft/sec
W	Weight of animal, lb
W_a	Weight supported above water when sculling, lb
ΔX	Hoop spacing, ft
z	Depth of center line of animal, ft
ρ	Mass density of water, approximately 2 slugs/ft^3
ν	Kinematic viscosity of water, approximately 1.3×10^{-5} ft^2/sec

INTRODUCTION

Observers aboard high-speed ocean craft have often seen dolphins traveling at apparent speeds of at least 21 knots, and whales at apparent speeds of at least 30 knots. An analysis of torpedoes and submarines, of roughly the same dimensions as dolphins and whales, indicates that the sea animals either are much more powerful than expected or possess some method of reducing hydrodynamic drag. Although the problem has not been resolved, evidence exists which indicates that the unusual performance is attributable to hydrodynamic rather than to physiological factors.

A wide variety of performance tests may be conducted, each of which will do

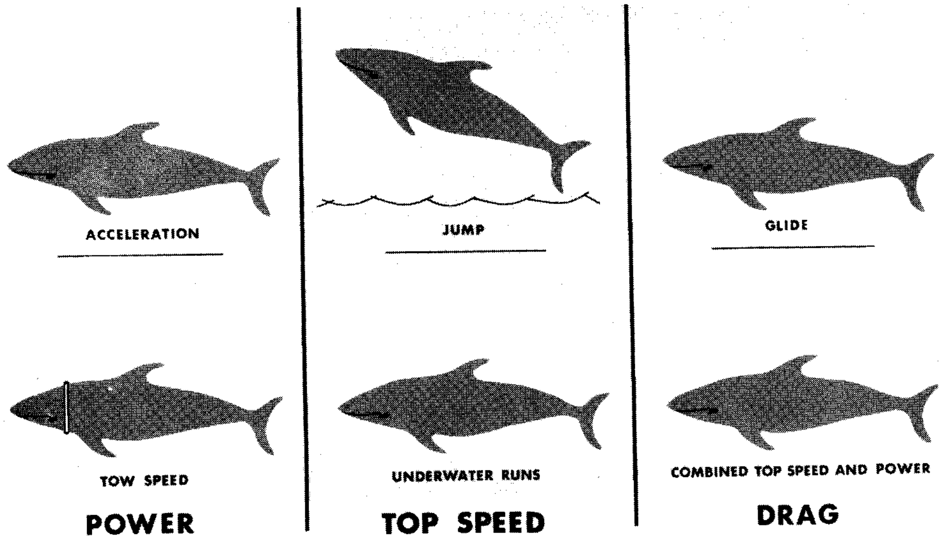

FIG. 1. Cetacean performance tests.

its share in solving the puzzle. Of prime importance is the need for accurate and more extensive data on top speed. As an aid to researchers studying performance, figure 1 presents tests that provide basic data on power, top speed, and drag. A number of these tests on cetaceans are based on the use of training techniques. In view of the many unknowns arising in such tests, different approaches may be used to cross-check the results.

Net power, for example, may be determined from acceleration runs, from runs with the animal wearing a collar or towing an object or line, or from observations of the animal supporting itself partly above the surface. Actual power would be somewhat greater than the calculated net-power output, as hydrodynamic efficiency must be taken into account. Top speed may be obtained either from instrumented runs or from measurement of jump height. Drag may be calculated directly from the measured deceleration of the animal while coasting or gliding, or indirectly by relating its known top speed and power output. A poor method of measuring drag, incidentally, is to tow the animal, as the towing device causes turbulence and interference drag, which are difficult to compensate for in analyzing the results.

A large body of evidence suggests that cetaceans and many types of fish possess unusually low drag because their boundary layers remain laminar at high speeds, and do not become predominantly turbulent, as in rigid bodies. Figure 2 shows the frictional drag coefficient as a function to the Reynolds number for both

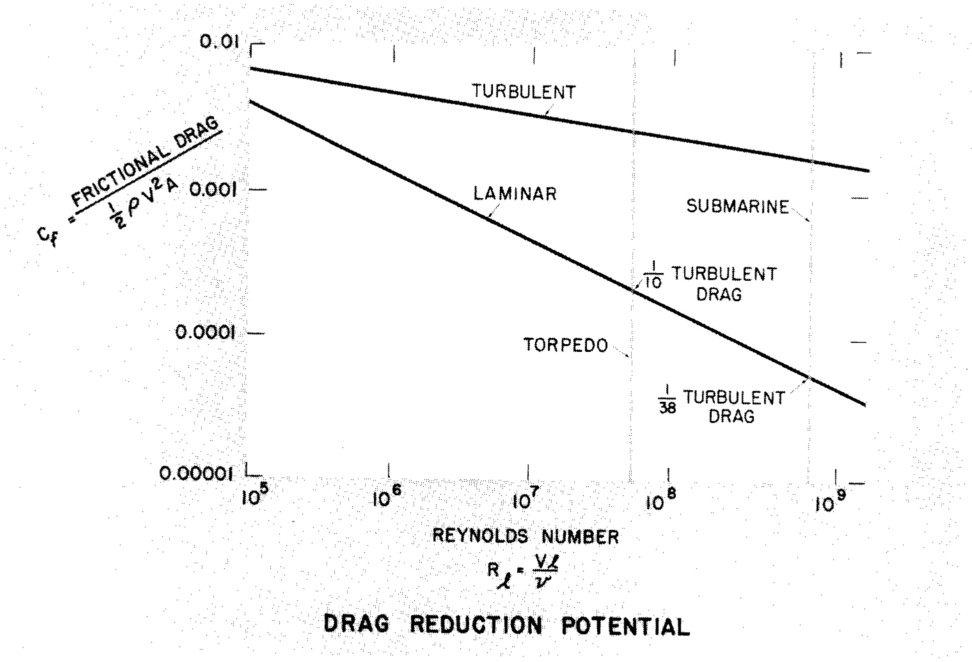

FIG. 2. Drag-reduction potential.

turbulent and laminar flows. Marked reductions in drag and power take place when a boundary layer is kept laminar. Thus dolphins and whales having a Reynolds number $R_l = \left(\frac{Vl}{\nu}\right)$, similar to a torpedo, can travel at the same speed as the torpedo with only a tenth of the power, if their boundary layers are laminar.

TESTS IN A SEAWATER TANK

To obtain more data on performance, the U.S. Naval Ordnance Test Station (NOTS) conducted a series of tests* with Notty, a trained dolphin, in a seawater-filled towing tank at the Convair Division of the General Dynamics Corporation, San Diego, California. The tank is 315 ft long, 12 ft wide, and 6.5 ft deep. A gate was placed near one end of the tank to form a pen for the porpoise. The tests took place on June 3, 4, and 5, 1960, with a water depth of 4.5 ft, and on June 15, 1960, with a water depth of 6 ft.

Notty, of the species *Lagenorhynchus obliquidens* (Pacific striped dolphin), was caught off Catalina Island in 1960 by Marineland of the Pacific, Palos Verdes, California. Her effective weight while swimming was 215 pounds, a figure including 15 pounds for the virtual weight of the water she carried along with her when moving. (For the dolphin's measurements, see fig. 3.)

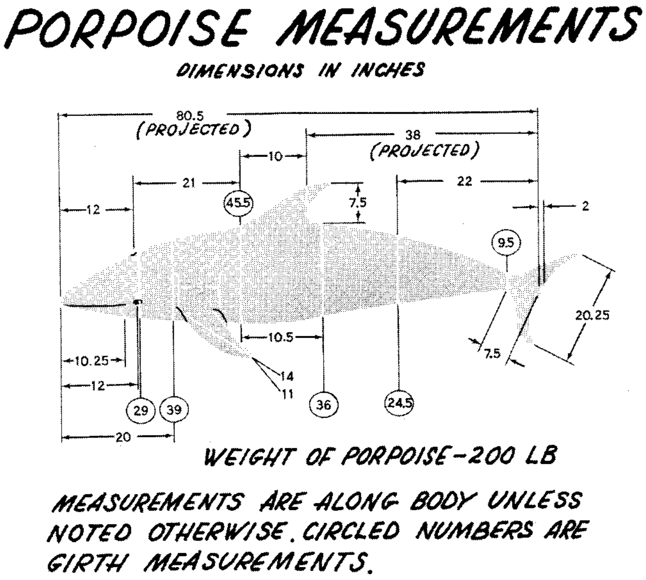

FIG. 3. Notty's measurements.

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* Funded by the Bureau of Naval Weapons and the Office of Naval Research.

Acceleration and top-speed tests, runs with collars, and glide runs through underwater hoops were made. The acceleration power, P, was calculated from the acceleration runs as thrust, T, times instantaneous velocity ($P = TV$), where thrust was the effective mass, m_l, times instantaneous acceleration ($T = m_l a$). An alternate value for power was obtained by multiplying the top speed with a collar by the estimated total drag, D_t, of both the animal and the collar ($P = VD_t$). Several collars of differing thickness were used, and were placed 18 inches behind the dolphin's nose. Top speeds, with and without collars, were measured by overhead cameras with synchronized timing. Drag was calculated from glide (coasting) runs through courses of three to five hoops. The basic drag equation is $D = -m_l a$, where a is negative because the animal is decelerating. Since the drag varies approximately as V^2, it may conveniently be expressed in terms of the drag-area coefficient,

$$D' = \frac{D}{1/2\,\rho\,V^2}$$

where ρ is the water density expressed in mass per unit volume. Solving the equations of motion for a glide through three hoops,

$$D' = (2m_l/\rho\Delta X)ln(t_2/t_1),$$

where ΔX is the hoop spacing, ln is the natural logarithm, and t_1 and t_2 are the times elapsed in traveling from Hoop 1 to Hoop 2, and from Hoop 2 to Hoop 3, respectively. Figure 4 shows Notty being trained to enter a hoop.

The detailed results of the performance tests are reported in Lang and Daybell (1963). In general, they showed no unusual hydrodynamic or physiological performance. The maximum acceleration horsepower was 2.1, as shown in figure 5. The maximum velocity without a collar was 15 knots, or 25 fps (fig. 6), at which speed $R_l \approx 13 \times 10^6$.

The drag area of the dolphin, with and without collars of differing thickness, is shown in figure 7. Tail or flipper movement was evident in all glide runs where D' was less than 0.04 ft^2, which indicates that the porpoise could have been producing thrust. Thus the data taken during these runs are invalid. Slight tail movement also probably occurred during many of the other runs, but could not be detected because of surface distortion caused by wave action. Figure 8 is the same as figure 7, except that the drag areas are plotted against collar thickness. The broken-line curve is a fairing of the maximum experimental D' data points. It is believed that this curve approximates the actual drag, as tail or body movement would probably be used in acceleration. This curve also agrees well with the predicted values. Figure 7 shows that the dolphin seldom permitted her speed to drop below 10 fps to get through the hoops; therefore, Notty probably accelerated before her speed diminished to 10 fps. It is noteworthy that the D' data points cluster and approach a maximum value, which is likely to be some kind of a fundamental, fixed parameter, such as the dolphin's drag.

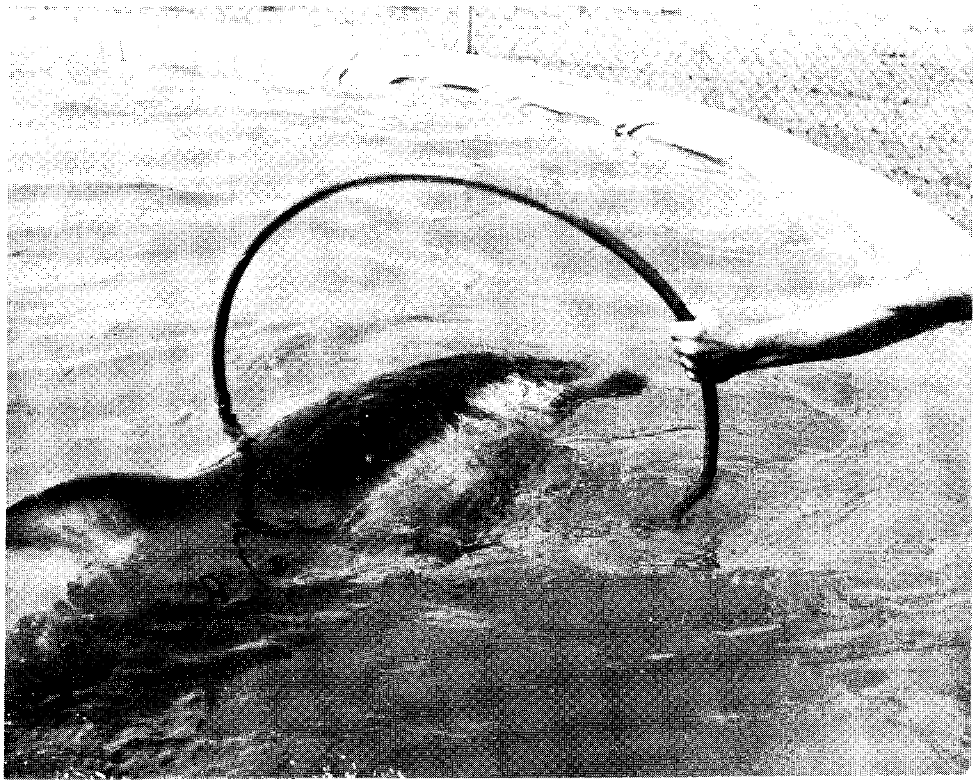

FIG. 4. Training Notty for hoop tests.

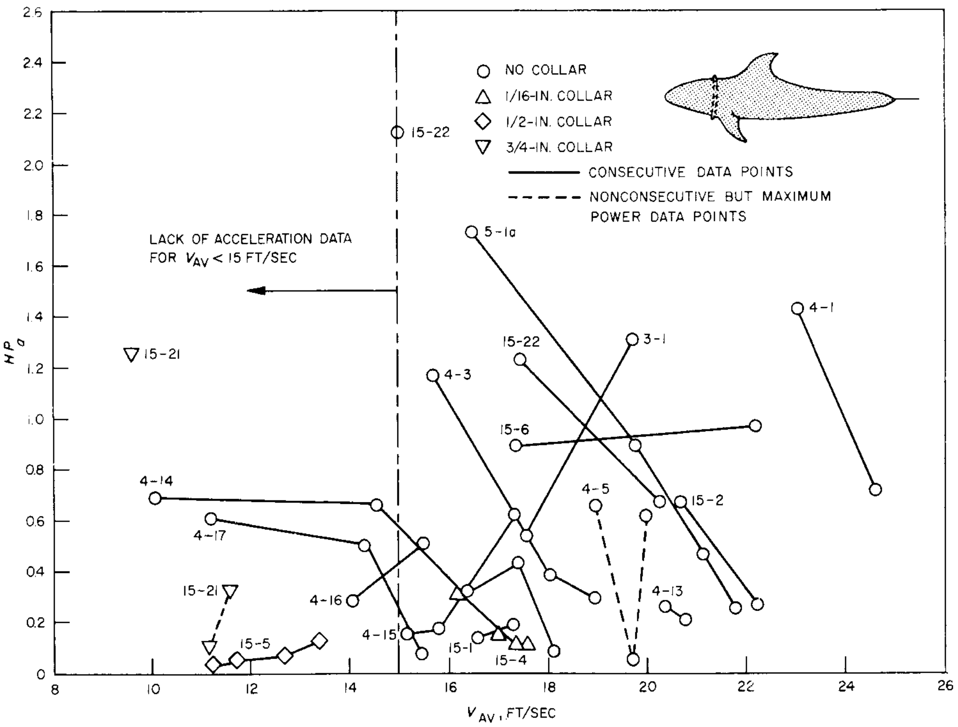

FIG. 5. Acceleration horsepower versus velocity.

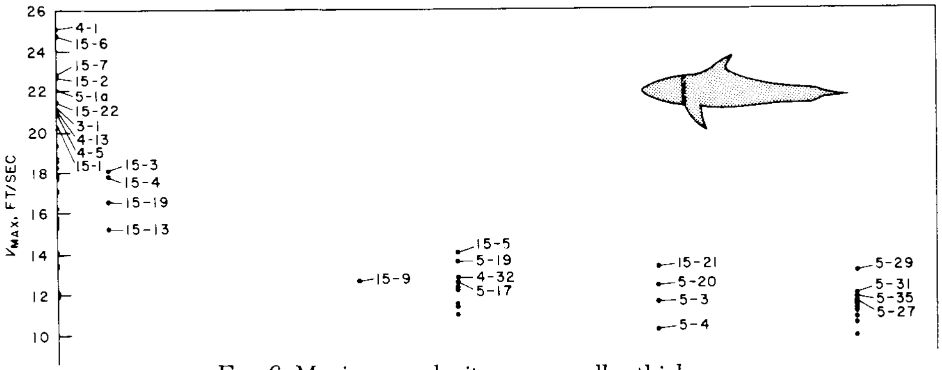

FIG. 6. Maximum velocity versus collar thickness.

The drag horsepower shown in figure 9 was established as the product of the top speed times the drag obtained from the faired experimental curve of figure 8. The recorded drag horsepower during runs was less when collars were worn than when they were not. The maximum power with collar was 0.8 hp; without collar it was 2.0 hp. The higher value agrees with the results of the acceleration runs. But why was the maximum power with collar only 0.8 hp? One possible reason is that the higher values of acceleration and drag power without collar were sustained for only 1 to 2 seconds, whereas the top-speed runs with collar lasted for several seconds. It is known that the power capability of animals declines markedly as the exertion period increases. Another possible reason for the low drag horsepower is that all the collar runs took place late in the run schedule on each day. In general, only short rest periods occurred between collar runs. Another reason may be that the faired curve of D' used in estimating power may have been too low, owing to lack of sufficient data.

In general, however, results compare with the power output of trained athletes described by Wilkie (1960), where 6 hp is reported for a fraction of a second, 2 hp for 6 seconds, 1 hp for about 1 minute, about 0.5 hp for 5 to 120 minutes, and 0.2 hp for 24 hours. This comparison with a trained athlete is considered reasonable because a cetacean is continually moving and exercising its muscles.

A factor that affected all the runs was wave drag, caused by the animal's swimming near the surface. Figure 10 shows that at a depth of 2 ft, the drag-area coefficient due to wave drag is 0.025 at 12 fps and 0.015 at 14 fps. Correcting the dolphin drag areas plotted in figure 7, it is seen that the dolphin may attain a laminar flow of about 20 per cent, which is in agreement with smooth, streamlined, rigid bodies.

These tests indicate that Notty did not exhibit unusual power. The lack of data substantiating unusual hydrodynamic capability may have been the result of excessive water turbulence, motion during glide runs, inaccuracy in wave-drag

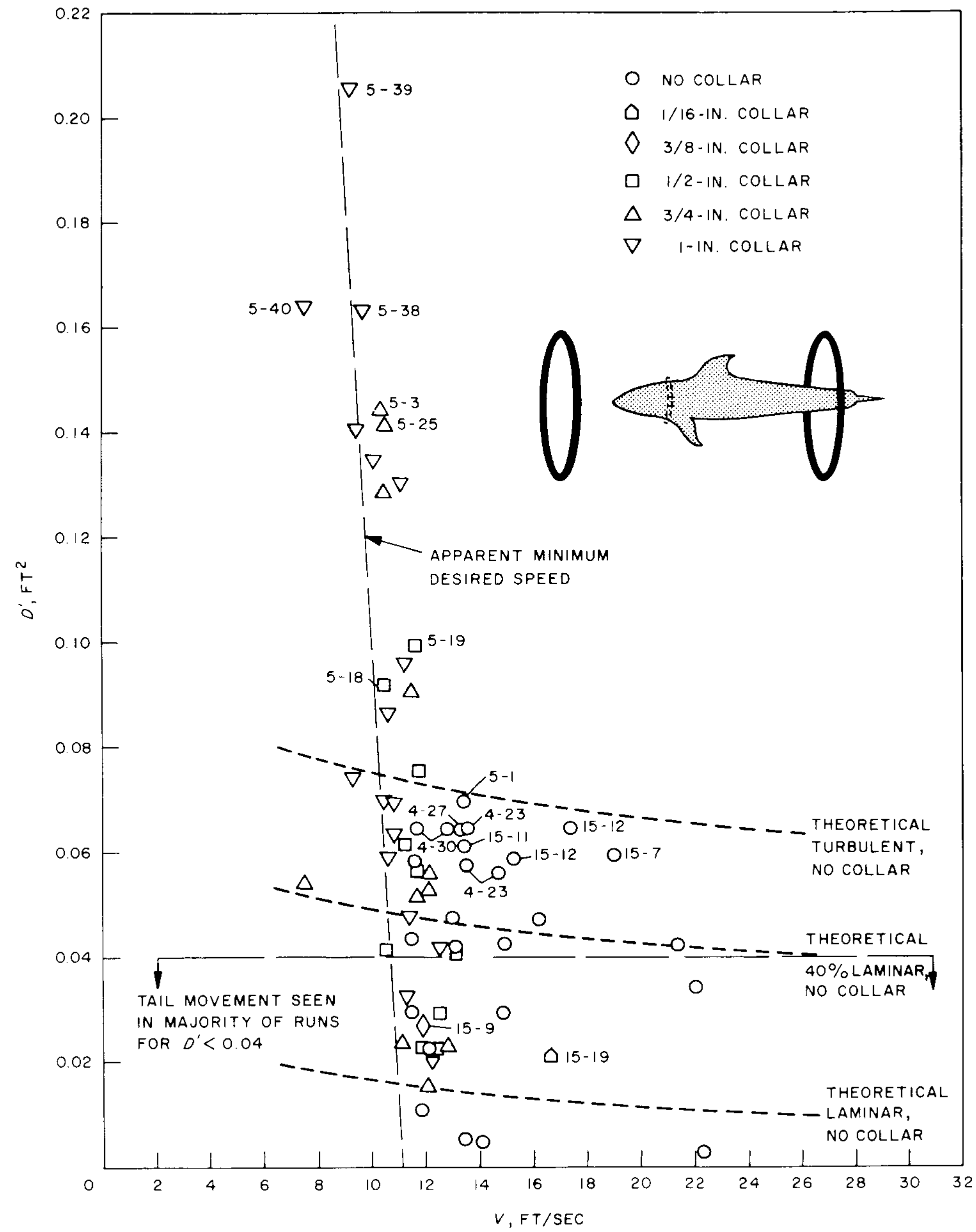

FIG. 7. Drag area versus velocity.

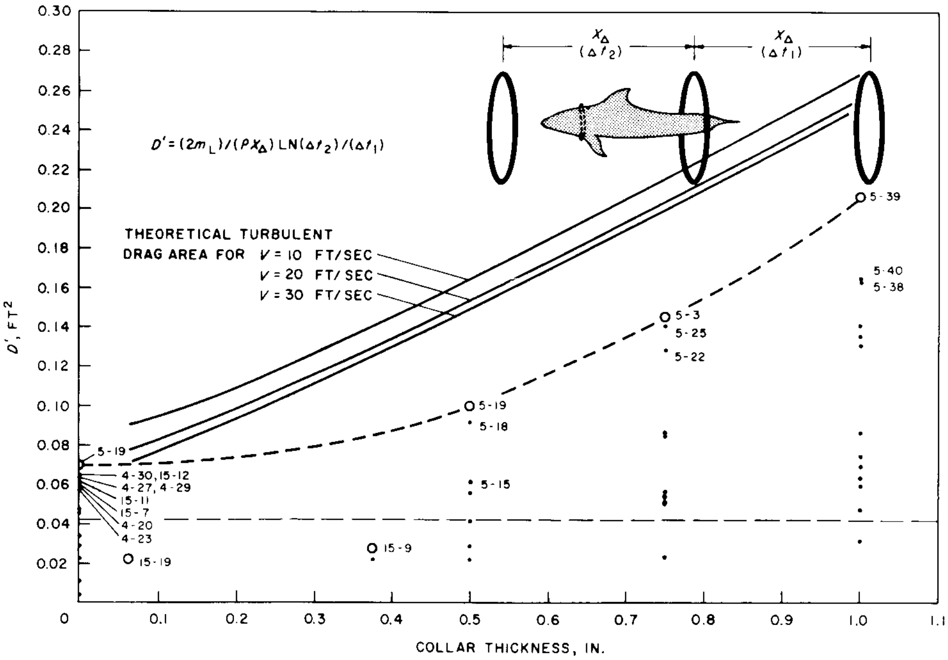

FIG. 8. Drag area versus collar thickness.

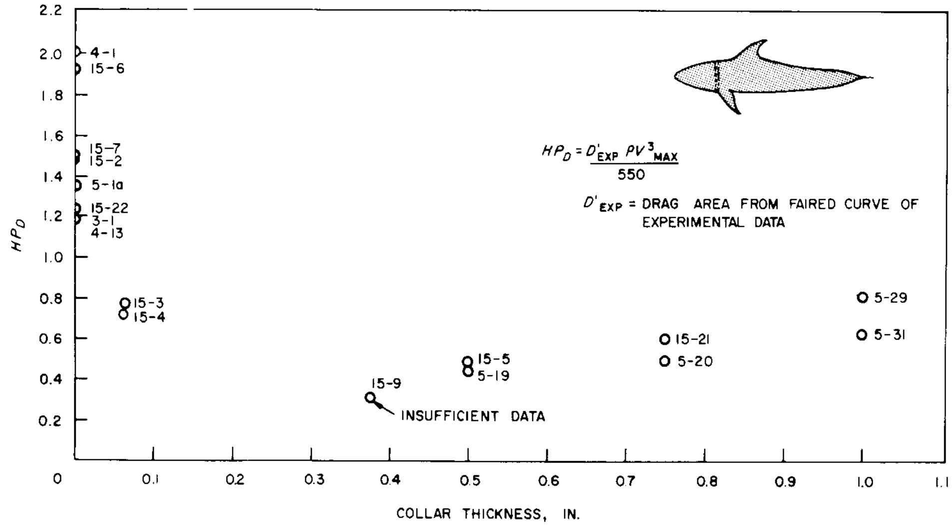

FIG. 9. Maximum drag horsepower versus collar thickness.

correction, or the small tank size and its inhibiting influence. All these factors indicate that the best location for performance runs is one that more closely approximates the natural ocean environment.

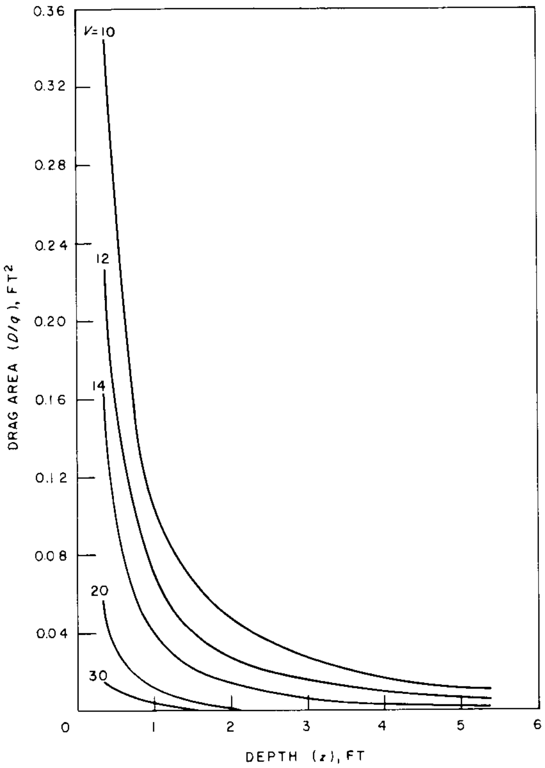

FIG. 10. Theoretical wave drag.

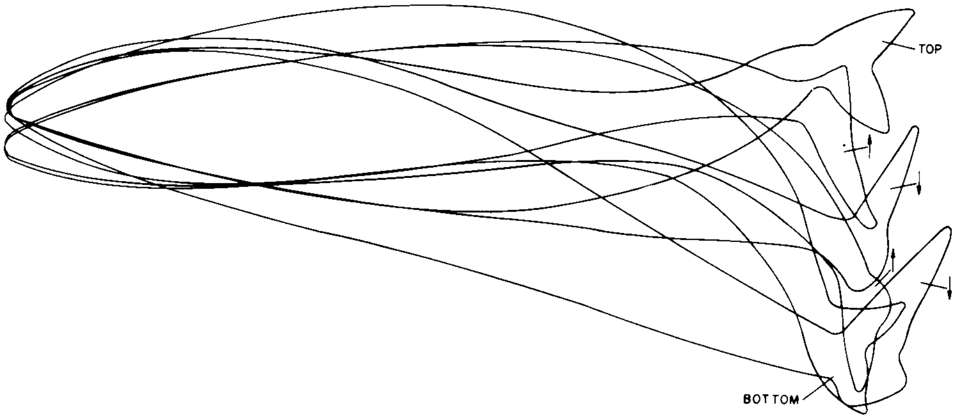

FIG. 11. Dolphin movements during acceleration.

MECHANISM OF THRUST PRODUCTION

Motion pictures of body movement were taken during the various runs. One such series (taken during acceleration when the animal was wearing a collar) is shown in superimposed form in figure 11. Considerable body movement and tail movement are seen, indicating that thrust is developed by both means. Some body movement is required, of course, to keep the net forces and movements in balance. An undulating rigid hydrofoil, such as the tail fluke, is a well-known thrust producer. The thrust produced by an undulating flexible body is not so well understood.

Recent theoretical work by Wu (1961) and experimental work by Kelly (1961) have proved that an undulating flexible plate simulating fishlike motion can be a very efficient thrust producer. These men are shown in figure 12 beside a mechanism (in the water channel) developed for the experiments by G. Bowlus. Their research has answered many questions about the development of thrust with fishlike movements. For example, Wu (1961) shows that swimming is most efficient when wave amplitude increases toward the tail. Although this theory was

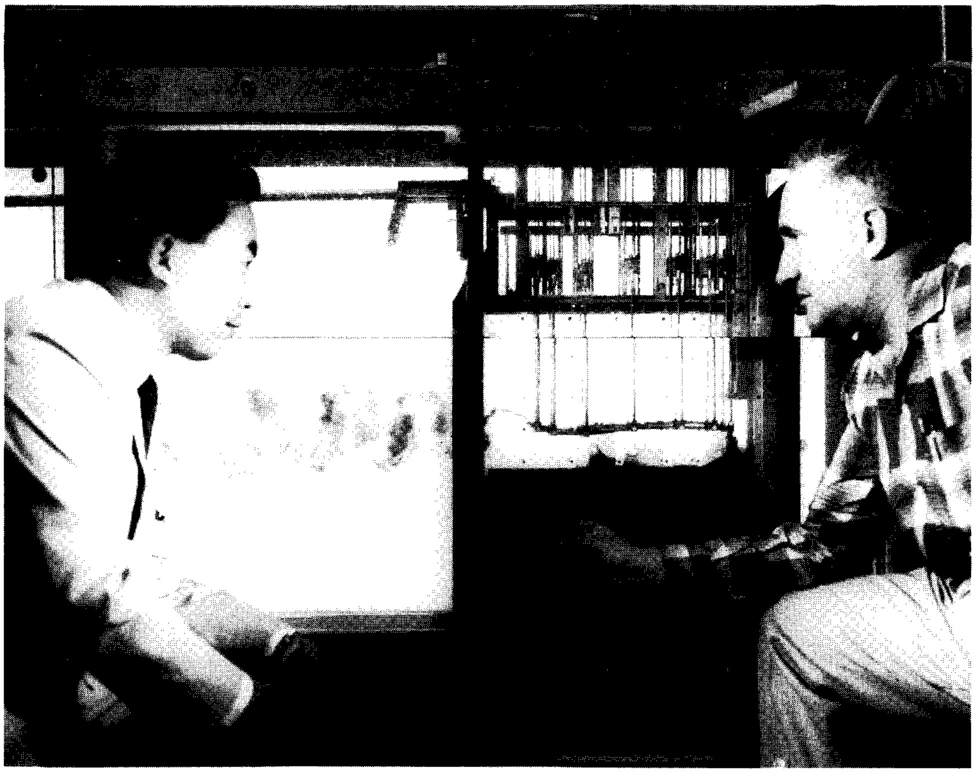

FIG. 12. Flexible plate experiment.

developed for two-dimensional motion, it is also partly valid for three-dimensional bodies. A different hypothesis for swimming, developed by Rosen (1959), is called the Vortex Peg Hypothesis. Rosen postulates that alternating vortices are generated at the nose, around which the body undulates; thrust is produced by the action of the vortices on the body. This hypothesis has not been tested so thoroughly as the work by Wu, although evidence of vortex motion was observed in a flow-visualization study of Notty by Rosen (1963).

POWER REQUIRED FOR SCULLING

Additional information on power may be obtained by observing an animal sculling with its weight partly above water, as shown in figure 13. In the sculling state, the power output is the product of the thrust times the water velocity induced at the tail. Considering the tail as a propeller, the thrust, T, is the change in momentum of the water mass, m_w, passing through the cross-sectional area, A_t, traversed by the tail. As in propeller theory, the velocity induced at the tail is half the total velocity change, v_t. Consequently, with units expressed in the foot-pound-second system, the horsepower and thrust are, respectively,

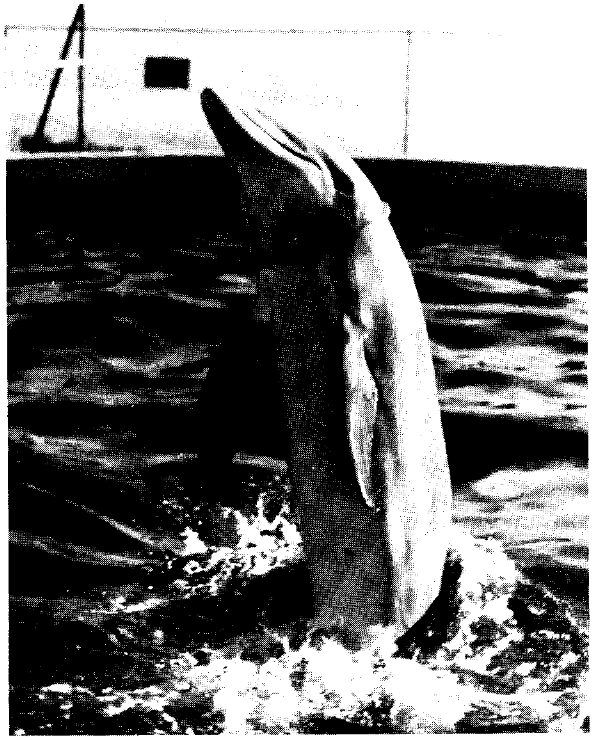

FIG. 13. Dolphin sculling. (Courtesy Marineland of the Pacific, California.)

$$HP = \frac{Tv_t/2}{550} \text{ and } T = m_w v_t = \rho A_t v^2{}_t/2 \approx W_a,$$

where W_a is the weight supported above water and ρ is the density of seawater in slugs/ft^3. Assuming the area traversed by the tail is approximately a square whose sides are the fluke span, b_t, the expression for HP, after manipulation of the two equations, becomes

$$HP \approx \frac{W_a{}^{3/2}}{1100\, b_t} \sqrt{\frac{2}{\rho}}$$

For a dolphin with Notty's dimensions, the power required to scull with three-quarters of the body weight above water is

$$HP = \frac{(150)^{3/2}}{(1100)(1.68)} = 1.0$$

This is consistent with the power output of a trained athlete in a 1-minute period.

CETACEAN JUMPS

The jump height (i.e., the distance of the center of gravity above water) provides a reasonably good approximation of the animal's speed at water emergence; however, it tells nothing about power output, which can be determined only by measuring the acceleration developed as the animal prepares the jump. Unfortunately, many forces are interacting as the animal leaves the surface, so that the simple conversion of kinetic into potential energy is not an exact expression. As an example, assume that the animal is underwater and is traveling upward at top speed. Just before reaching the surface, its weight is approximately counteracted by its buoyancy, and its drag is counteracted by its thrust. When the animal is halfway out of the water, its buoyancy and drag are reduced to half, its weight is constant, and its thrust is still probably close to full value. Although the center of gravity is at the surface, there has already been a partial conversion from kinetic to potential energy owing to the part of the weight above water. The loss in buoyancy will therefore be correctly accounted for by equating kinetic to potential energy. Not included, however, is the part of the energy which arises from the excess of thrust over drag as the animal emerges from the water.

Assume that the average excess thrust is about a third of the drag, and that the action distance is the animal's length. The increase in energy is therefore ⅓ Dl, which is equivalent to an increase in jump height of about 1 per cent if laminar flow exists, or of about 5 per cent if turbulent flow exists, assuming that the jump height (center of gravity) is about 15 ft. Letting h represent the corrected (reduced) jump height, the maximum underwater speed, V, may be expressed as

$$V = \sqrt{2\,gh}$$

Therefore, $V = 30$ fps (17.8 knots) when $h = 14$ ft; $V = 32$ fps (19 knots) when $h = 16$ ft; and $V = 34$ fps (20.1 knots) when $h = 18$ ft.

The power generated by a dolphin before a jump may be calculated from a typical example reported by Gero (1952), using the acceleration equation discussed earlier. An acceleration-thrust–versus–time graph in Gero (1952, p. 18) shows the performance of a 400-lb dolphin that jumped 6 feet above the surface from a motionless underwater position. The acceleration was accomplished in 0.6 to 0.7 sec. The horsepower output was about 0.021 hp/lb of total weight. This value of power output, making further allowance for propulsive efficiency, is comparable to the 0.035 hp/lb of humans for a 0.5-second period. In this example, drag was not of great significance because the top speed was relatively low. This result further indicates that the power output of cetaceans is not unusual.

TYPES OF FREE-RIDING BEHAVIOR

Cetaceans sometimes get "free rides" from other cetaceans. One of the most basic types results when one animal takes advantage of the thrust produced by another by swimming in the hydrodynamically favorable area arising from the interaction of their pressure fields (fig. 14). Norris and Prescott (1961) describe this behavior and report that a smaller animal often gets a free ride from a larger

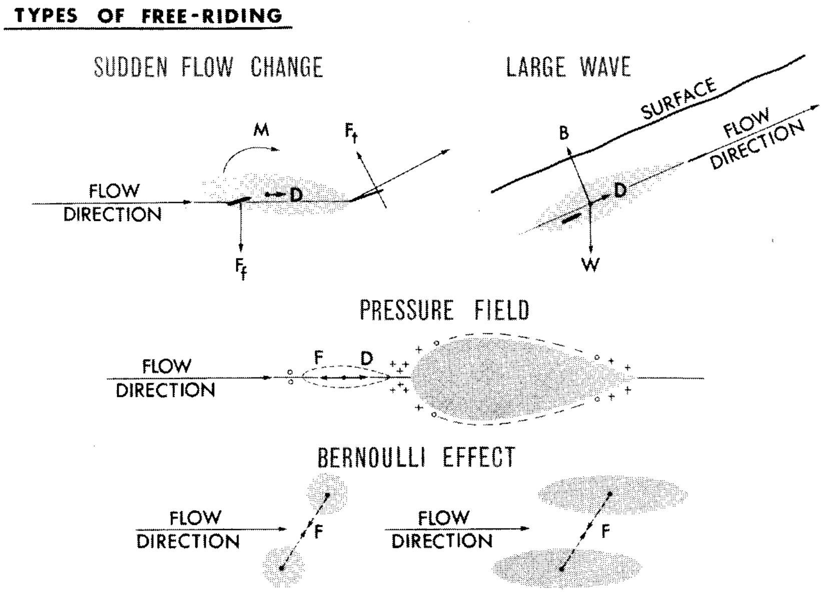

FIG. 14. Types of free riding.

one by positioning itself beside, and slightly behind, the maximum diameter of the lead animal. Conversely, they cite one example of an adult that obtained a similar free ride from a half-grown animal, causing an obvious increase in exertion to the smaller cetacean.

In theory, an equal and opposite force is exerted on each animal; if one benefits from increased thrust, the other is handicapped by added drag. H. R. Kelly, in a 1959 NOTS internal report, calculated the attractive force between two spheres traveling in echelon formation. The force, generated by the Bernoulli effect of reduced pressure owing to increased water velocity between the spheres, was directed through their centers, producing a thrust component on the trailing sphere. The maximum thrust coefficient calculated was about one-fourth the drag of a sphere with a turbulent boundary layer. Applying this coefficient to a streamlined body by extrapolation is difficult, but the theoretical results on spheres indicate significant thrust and agree qualitatively with cetacean free-riding phenomena.

Other types of free riding have been observed, such as planing within large storm waves and waves near the surf, planing within the bow or side waves of ships, and gliding within the bow pressure fields of submarines (fig. 14). Several explanations of the bow-riding phenomena were suggested after Woodcock's (1948) report appeared. Of these, Hayes's (1953) force diagram appears valid for large bow waves, as shown in figure 14. Such a free bow ride has been demonstrated in water-tunnel model experiments by Perry, Acosta, and Kiceniuk (1961).

For ships with a sharp keel and a small bow wave, the "sudden flow change" diagram in figure 14 is probably valid, despite numerous objections to it. This general model, first proposed by Scholander (1959), was extended by M. W. Rosen, as reported by Norris and Prescott (1961). The main objection cited in the literature is that the moment M shown in figure 14 does not exist to counteract the moment produced by the combined tail force F_t and the fin force F_f. Munk in Durand (1934), however, shows that a large overturning moment can be produced by a bare body placed at an angle of attack (see fig. 14). A rough calculation shows that a body angle of attack of about 0.1 radian (6°) is needed if the flow change at the tail is 30 degrees and the boundary layer on the body is turbulent. The body angle diminishes if the boundary layer is laminar, or if the change in flow angle is larger.

Another apparently valid explanation of bow riding was put forth by Fejer and Backus (1960). If the bow of a ship is blunt, they said, a rather large pressure field is induced in the water ahead of the ship. If the animal's body is small in relation to the bow size, the static-pressure gradient ahead of the bow will produce thrust on the animal. This explanation is also valid in instances of submarine bow riding by smaller cetaceans.

In summary, the most correct explanation of bow riding is probably a combination of the various idealized models presented in figure 14.

ANALYSIS OF PREDICTED AND OBSERVED SPEEDS OF DOLPHINS, WHALES, AND FISH

An interesting analysis of the documented top speeds of cetaceans and fish in the open ocean may be made by comparing them with predicted values, using the experimental drag coefficients of rigid streamlined bodies and the power-output ratios of humans.

In calculating the drag and speed of cetaceans and fish of various sizes, it is assumed that their general shape is approximated by a 6:1 ellipsoid with an added tail region that extends the ellipsoid length 20 per cent. The weight of each body is assumed to be that of the basic 6:1 ellipsoid of neutral buoyancy. The surface area of each body, however, is assumed to be 20 per cent larger than that of the basic ellipsoid, to compensate for the fins and the tail.

The drag coefficients are those resulting from experimental tests reported by Hoerner (1957) on rigid, smooth, streamlined bodies as a function of the Reynolds number. These coefficients include some of the effects of laminar flow (Hoerner, 1957, pp. 6–16), if the Reynolds number is below 2×10^7.

As the muscles of porpoises are in daily use, it is probable that their power output per pound of total body weight is about equal to that of trained human athletes. Because of their highly specialized muscles and skeletal structure, however, the power output of swimming dolphins may be somewhat greater than the output of any human being. On the other hand, physiological evidence indicates that the power output of whales is significantly lower, on a weight basis, than that of the smaller cetaceans (Hill, 1950). To simplify calculation, however, the power-to-weight ratio is held constant.

In view of the possibility that sea animals maintain full laminar flow, calculations were also made using the experimental laminar-flow drag coefficients of Hoerner (1957) extrapolated to higher Reynolds numbers. The results are shown in figure 15. Body weights ranged from 2 pounds for smaller fish to 200,000 pounds for blue whales. The solid lines in figure 15 are the estimated top speeds, using experimental human power ratios and rigid-body drag data. The broken lines refer to the same conditions with the additional factor of full laminar flow. The two sets of lines converge in the weight range of 2 to 5 pounds, indicating that full laminar flow would normally be expected for fish of this size. It is interesting that, despite increased turbulent flow, the expected top speed continuously increases as body size increases. Note also that because of the crossover from laminar to turbulent flow, the top speed is fairly constant for body weights between 20 and 200 pounds. It must be remembered, however, that these calculations are simplified, resulting in some sacrifice of accuracy.

It is interesting to compare the sightings reported by Johannessen and Harder (1960) with the predicted values. The sightings established maximum dolphin

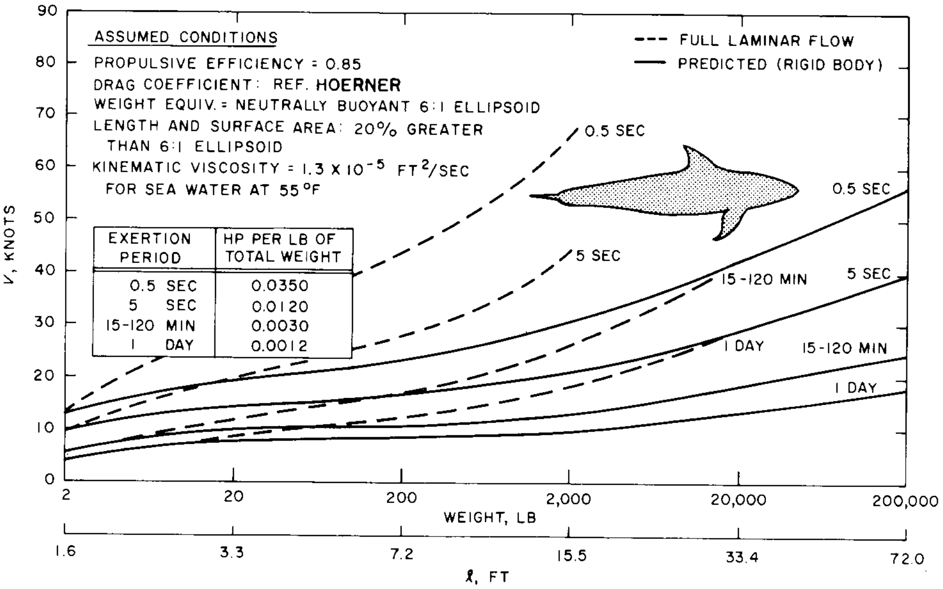

FIG. 15. Predicted top speed of cetaceans.

speeds of 17 to 18 knots for periods of 8 to 25 minutes. These animals, Pacific striped dolphins, have typical weights of 200 pounds. Figure 15 shows that the expected nonlaminar top speed is only 11 knots, while the laminar speed is 17 to 18 knots. It may therefore be concluded either that the dolphins' power is high by a factor of 4 or that their boundary layer is fully laminar and not chiefly turbulent, as would be expected for a value of $R_l = 1.5 \times 10^7$.

Johannessen and Harder (1960) also note that dolphin speeds of 19.6 to 21 knots were observed only for 1- to 2-minute periods, suggesting that sustained travel at this speed was beyond the dolphins' ability. Assuming that human power ratios are applicable, this result again agrees with the estimates of figure 15 if the boundary layer is fully laminar at $R_l = 2 \times 10^7$, unless porpoises are five times as powerful as humans.

These same authors also reported on a killer whale between 15 and 24 feet long. It approached a ship at about 30 knots and then swam around it for 20 minutes at a speed in excess of the ship's speed of 20.6 knots. Figure 15 shows that the expected nonlaminar speed for periods between 15 minutes and 2 hours is about 16 knots, and the laminar speed is about 32 knots. The longer-period results indicate either about 70 per cent laminar flow or about three times the expected power. The laminar-flow prediction would indicate a Reynolds number of about 4×10^7, which is possible with some type of boundary-layer control.

The performance, reported by Gray (1936), of a 200-pound porpoise swimming at 20 knots for at least 7 seconds is seen in figure 15 to lie between the expected nonlaminar value of 15 knots and the laminar value of 26 knots. The 15-

minute expected nonlaminar value is 11 knots, and the 15-minute laminar value is 17 knots. This sighting is therefore explainable by laminar flow of about $R_l = 2 \times 10^7$.

An interesting observation of a blue whale that traveled at 20 knots for 10 minutes and at 14.5 knots for 2 hours is reported by Gawn (1948). As a blue whale may weigh as much as 200,000 pounds, this performance must have required about 40 per cent less power than would be predicted by the turbulent-flow values for 24 knots for 15 minutes and 50 per cent less than would be predicted for 18 knots for an all-day period. This sighting is fully explainable on the basis of turbulent-flow and human power ratios; however, in view of Hill's (1950) belief that human power ratios do not apply, it would appear that even blue whales require some type of drag-reduction mechanism.

Norris and Prescott (1961, p. 343) report that a 13-foot pilot whale chased a Pacific striped dolphin three times around an 80-foot tank in about 15 seconds. They state that it is reasonable to believe that the animals swam in a tight circle at a speed of at least 20 knots. This would indicate significant laminar flow for the dolphin and somewhat less laminar flow for the whale. If the swimming diameter had been 70 feet, the authors state that the animals' speed would have been 26.4 knots, and the extent of unusual performance would have been much greater.

The largest power output of a fish measured and recorded by Gero (1952) was 0.040 hp/lb, produced by a 20-pound barracuda whose top speed was 23.5 knots. The expected nonlaminar speed for this power is 20 knots, and the laminar speed is 30 knots. Unfortunately, the exertion period is not mentioned. Given the reported thrust measurements, however, about 1 second would be required to accelerate 20 pounds to this top speed, with due allowance for frictional drag. Although this power output is slightly greater than would be expected for the period, it may be explained by the extreme exertion that occurred in this single instance during a period of unusual stress. Similar exertion phenomena have been observed in humans during unusual stress. The hydrodynamic results indicate more than 50 per cent, but not complete, laminar flow. It is possible that full laminar flow would have existed, had not the fishline that Gero used in his piscatometer (a device used for the determination of thrust, velocity, and horsepower of large saltwater fish) contacted one side of the barracuda's body. This contact could have caused at least one-third of the boundary layer to become turbulent, even if the other two-thirds remained entirely laminar. The incident demonstrates one possible shortcoming of the piscatometer, even though it is an excellent device for measuring power.

LOW-DRAG HYPOTHESES

A number of hypotheses have been proposed in an effort to obtain low drag. One of the most natural possibilities is shape modification, as described by

Schlichting (1960). By maintaining a favorable (reducing) pressure gradient to the 50-to-65 per cent point of a streamlined body, the boundary layer might be kept laminar up to that point.

A recent theoretical study by van Driest and Blumer (1963) indicates that laminar flow can be obtained up to $R_l \approx 10^8$ in a strong pressure gradient. The normal laminar-flow R_l on a flat plate is 3×10^6. Experimental studies on a gravity-propelled body in the ocean have recently been performed by the Marine Ordnance Group of the Space and Information System Division of North American Aviation, Inc. A personal communication from that group indicates that the experimental laminar R_l was 14.5×10^6 at 45 knots, as deduced from the drag results. This result indicates that the boundary layer was laminar back to 55 per cent of the body's length. Assuming a favorable pressure gradient and the extension of laminar flow as far as 66 per cent rearward, drag could be reduced by a factor of about 3.

Greater drag reduction would require a powerful means of boundary-layer control which would maintain laminar flow in spite of an adverse pressure gradient. The hypothesis presented by Kramer (1960) may be such a means. Kramer obtained 1.6 feet of laminar flow on a 4-foot model at a model Reynolds number of 1.5×10^7. This indicates a laminar-flow Reynolds number of 6×10^6, even with a slight adverse pressure gradient at the nose. The model was covered with a special fluid-backed resilient rubber coating. The hypothesis is that tiny disturbances in laminar flow, which normally build up to cause turbulence, are damped out by the resilient coating, thereby maintaining laminar flow. The coated model had only 40 per cent of the drag of an uncoated rigid model. Further development is needed to make this coating more practical for bodies traveling at Reynolds numbers of 4×10^7 and higher.

Kramer's experimental results are supplemented by a number of theoretical reports, such as those of Betchov (1959), Benjamin (1960), Boggs and Tokita (1960), and, most recently, Landahl (1961). Landahl writes: "The limited number of numerical calculations presented seems to indicate that the increases in critical Reynolds number obtainable with flexible surfaces of rather large flexibility are quite modest. It seems therefore unlikely that the reported success of Kramer's experiments could be explained on the basis of simple stability theory alone." Landahl concludes that the most likely alternate explanations are either that the flexible surface modifies some later stages in the process of transition, or that it has an effect on the fully developed turbulent boundary layer.

An alternate explanation for low drag with regard to cetaceans is that they actively adjust the flexibility and movement of their skin to damp out the microscopic disturbances in the laminar boundary layer. Betchov showed that the laminar flow might be extended indefinitely by this means. The structural complexity of the skin required for this purpose, however, may be a biological impossibility. These theoretical types of flexible skins should not be confused with the skin folds photographed on dolphins by Essapian (1955). The folds are undoubtedly drag-producing phenomena, and may occur only during acceleration, deceleration, or turning, as a by-product of loosely attached skin needed for other hydrodynamic or physiological reasons.

Another interesting method of extending the laminar region, discussed by Schlichting (1960, chap. 17), is to change the temperature in the boundary layer. The object is to reduce the viscosity of the inner region of the boundary layer in such a way as to modify the boundary-layer profile into a shape that makes it more stable, thereby keeping it laminar. The effect of temperature change on viscosity alone is small, compared with the overall stabilizing effect. In air, the desired result is accomplished by reducing viscosity by cooling, whereas in water it is done by heating. The effectiveness of this method, however, is probably limited, as a temperature change of 30°F produces only a 32 per cent reduction in kinematic viscosity.

A possible explanation for low drag on fish, and one that is of some interest here, is the boundary-layer change produced by the addition of long-chain molecules, as reported by Fabula, Hoyt, and Crawford (1963). These investigators report reductions in the pressure drop of water flowing through tubes when certain chemicals are added which tend to make the water slimy. The mucus exuded by fish is composed of a similar type of long-chain molecules.

Other possible methods of reducing drag are based on the effects of body undulations. One method suggests the extension of laminar flow by means of an unsteady velocity, or pressure gradient. This method is discussed by Schlichting (1960, chap. 11). The second method, presented by Rosen (1959), involves the formation of a vortex near the nose of a body and its effect on the body as a whole.

A related explanation is presented by Purves (1963), who reports the presence of dermal ridges underlying the skin and indicates that their orientation follows the flow pattern. As the dermal ridges of the common dolphin are angled relative to the body, he suggests that the true Reynolds number of flow is somewhat less than the animal's length. This possibility certainly exists, but it is difficult to believe that the flow could be so oblique as that shown in figure 2 of his paper. As shown in figure 11 of this paper, however, movements exist during acceleration when the tail is angled considerably downward, giving rise to significant cross flow. Showing that an animal has laminar flow is a difficult task. One possible means of obtaining boundary-layer photographs is the Schlieren system discussed by Allan (1961).

CONCLUSIONS

1. Results of performance tests with the dolphin Notty show no unusual physiological or hydrodynamic performance. The test conditions suggest, however, that hydrodynamic performance was adversely affected by one or more environmental factors.

2. Analysis of cetacean sightings and performance tests reported in the available references indicates that the drag of these animals is significantly lower than expected. Several low-drag hypotheses offer possible explanations. Additional, and more accurate, top-speed measurements are needed, preferably taken under natural oceanic conditions.

3. A brief analysis and summary of the available literature show that several types of free-riding behavior are exhibited by cetaceans. Different explanations for the bow-riding ability of dolphins exist, and the true explanation may be a combination of various explanations.

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