

LOCOMOTION IN DOLPHINS Part I: Hydrodynamic experiments on a model
of the bottle-nosed dolphin, *Tursiops truncatus*, (Mont.)

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Summary

By measuring the rate of deceleration of a Pacific striped dolphin *Lagenorhynchus obliquidens* in a „glide” situation after attaining a top speed of 15 knots, LANG (1966) **calculated** that the resistance afforded by the drag of the water on the body was 1.4 to 2 horse power.

In order to evaluate the performance of a bottle-nosed dolphin *Tursiops truncatus* in a glide situation by **direct measurement**, a series of resistance experiments were carried out on a wooden model of a fully grown female specimen which was comparable with those for *Lagenorhynchus obliquidens*.

In 1936 GRAY suggested that the action of the tail whilst actively swimming would have an effect in reducing the drag, and PURVES (1963), suggested that the orientation of the „dermal ridges” which are known to occur under the skin of cetaceans would indicate the direction of the water-flow over the body.

A „paint test” on the rigid model showed that the water follows the orientation of the dermal ridges over the anterior half of the body but that there is evidence of boundary-layer separation after the point of maximum cross section, when the animal is in a glide situation.

As the dermal ridges occur over the entire body in the living animal it would appear that the tail action operates to prevent separation of the boundary layer from the posterior half of the body, thus reducing the drag.

This being so, the mathematics relating to dolphins in a glide and to rigid, streamlined bodies cannot be applied to actively swimming animals.

The resistance measurements of the wooden model are also compared with those of a comparable „body of revolution”.

Introduction.

Using the standard mathematical equations relating to rigid, streamlined bodies, GRAY (1936) postulated that the power available in the locomotory muscles of a six foot common dolphin, if comparable with a rigid model, would be insufficient to overcome the drag of the body at 15 knots (the best authenticated sustained maximum speed of this species). He based his conclusion on the assumption that the boundary layer would be turbulent, which indeed must be expected on account of the Reynold's number related to the length and speed of the model. He also assumed that the power output of the muscle per unit weight would be equivalent to that of a trained oarsman.

From this he inferred that in the living animal the flow past the body must be almost completely laminar, and suggested that this might be due to the acceleration by the action of the caudal flukes on the water particles in the boundary layer. Quoting EWALD GRAY et al. (1930) stated „in the case of a rigid body anchored in a stream, the resistance due to turbulent flow is caused by frictional retardation of the flow in the vicinity of the boundary of the body. If any accelerating or retarding pressure differences exist in the layers of water which adjoin the boundary layer, these differences of pressure affect the flow in the boundary layer also. If the external flow is accelerated by a fall of pressure in the direction of motion of the water, the fluid particles which are travelling more slowly in the boundary layer also receive an impulse in the direction of motion, hence all particles continue on their way past the surfaces of the body.”

GRAY (1936) stated: „the evidence suggests that the water in the vicinity of the hind end of the body of a dolphin is being influenced by a fall of pressure in the external flow and to this extent it seems conceivable that the flow past the surface of an actively moving dolphin is much less turbulent than is the case when the inert organism is towed through the water.”

GRAY's premises have been criticised for a number of reasons. The available power of muscle, expressed as a function of the oxygen consumption, is dependent on the time over which work is done and it is therefore not possible to express the power which must be delivered as a simple factor of muscle weight. According to TAGGART (1968) it is invalid to take muscle power of a trained oarsman as a criterion, for an oarsman needs more secondary muscle power to keep his body in the correct attitude. He proposes that it is more correct to take the muscle power of a trained racing cyclist as a basis for calculation. PURVES (1963) stated that since the flow past the body of *Delphinus delphis* as indicated by the orientation of the dermal ridges is obliquely posterodorsal it would be incorrect to use the total length of the animal in the calculation of Reynold's number. In an exhaustive series of experiments with a Pacific striped dolphin *Lagenorhynchus obliquidens* LANG (1966) came to the conclusion that the power available in the muscles of this species was no greater than that of trained athletes within similar parameters, although he later calculated, when working with the pelagic dolphin *Stenella attenuata*, that the latter species could develop 2½ times the power per unit body weight than a trained athlete over a similar period of time. It seemed that throughout the experiments this author was unwilling to concede anything to a „low drag” hypothesis of which a number had meanwhile been propounded.

Van DRIEST and BLUMER (1963) proved by theoretical methods that with a favourable streamlined shape a laminar boundary layer was possible up to $R_n - 10^8$.

Experiments by KRAMER (1960) purported to show that a flexible surface could operate in stabilizing the laminar boundary layer and PALMER and WEDDELL (1964) suggested that turbulence could be damped out where and when it occurred on the body surface autonomic control of the skin through the operation of an elaborate distribution of nerve endings in the dermis. The theoretical views of LANDAHL (1961) and others concur with this idea but recent experiments by TANEDA and HONJI (1967) have not confirmed the general hypothesis. Another theory has been advanced by FABULA et al. (1963) that presence of polymers along the body could substantially raise the value of the Reynold's number at which the transition from a laminar to a turbulent boundary layer occurs — such a phenomenon having been demonstrated in laboratory experiments with polymers.

The present authors reviewed the experimental and theoretical data contained in the aforementioned publications and found that there were a number of important omissions without which it would be impossible to approach an accurate assessment of the problem. For instance in GRAY's paper there are no technical details of towing experiments with an actual model of a dolphin so that the distinction between „skinfriction” and residuary resistance cannot be made. It was also required to be proved that the orientation of the dermal ridges followed the flow of water as proposed in PURVES' hypothesis. The rest of the contributions

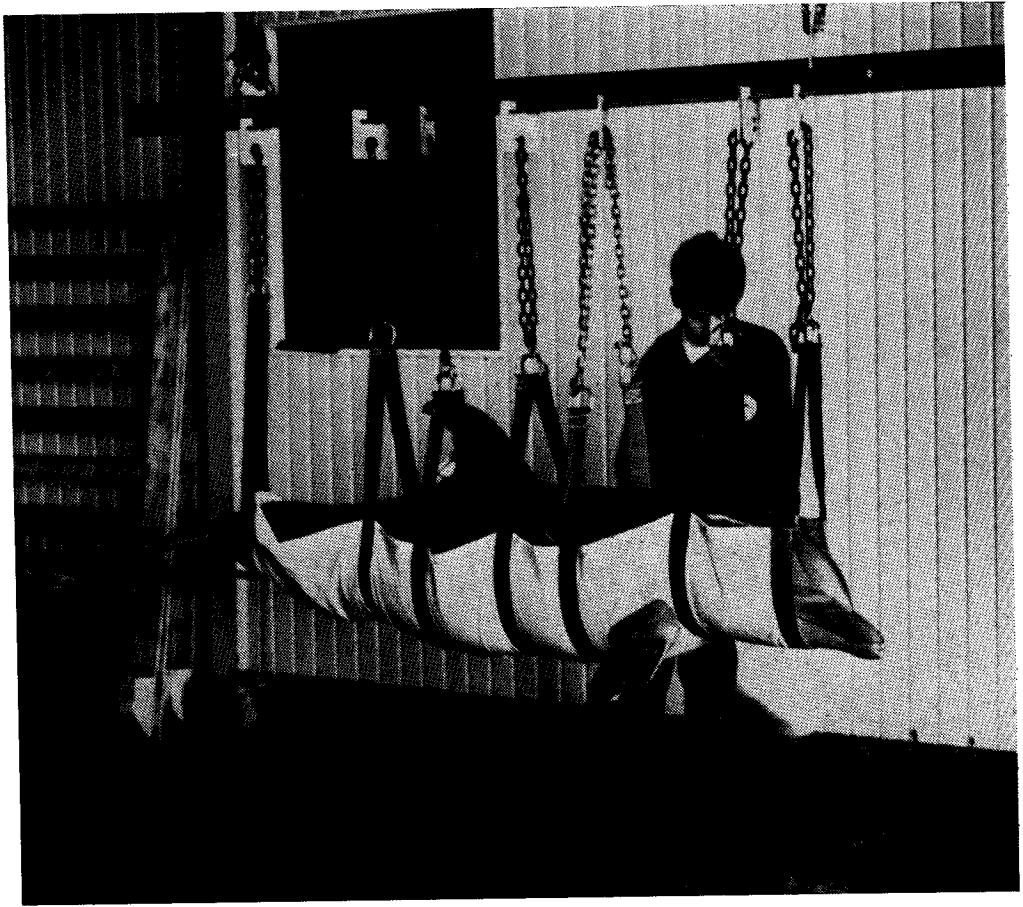
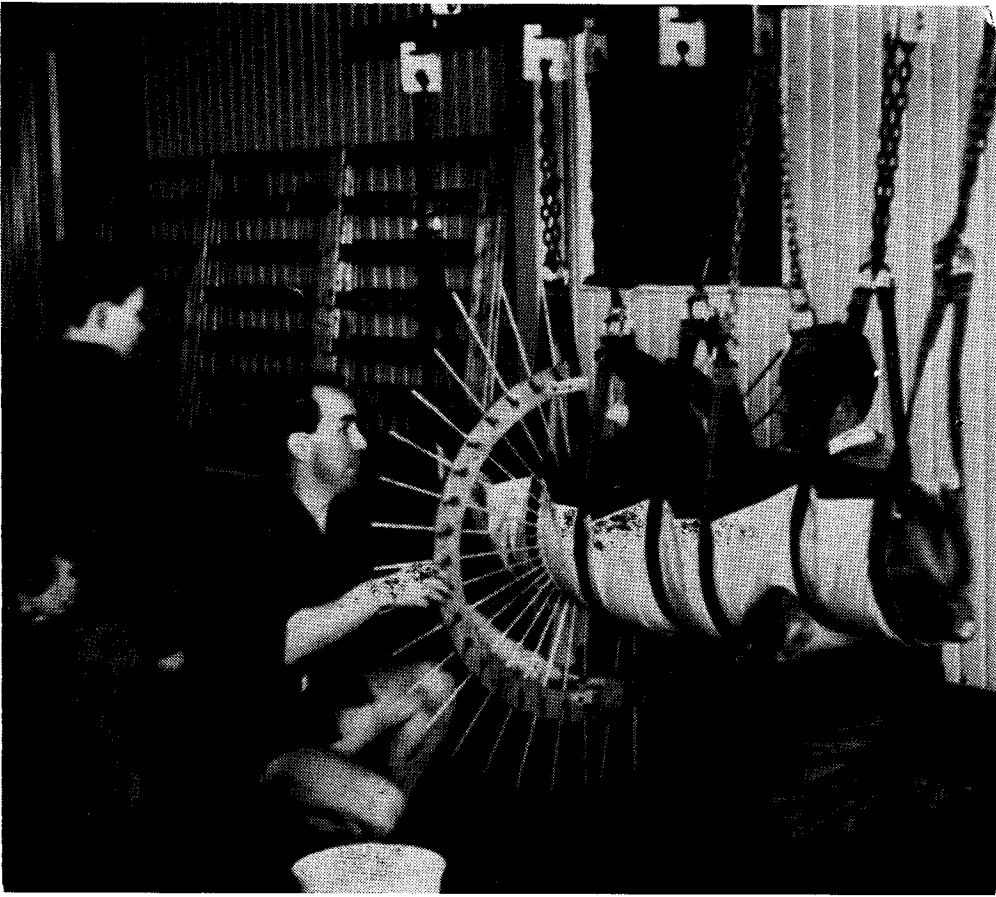


Plate 1: A. Photograph showing method of suspending live animal;

showed at best a somewhat rudimentary knowledge of cetacean anatomy and physiology.

LANG's measurements of resistance depended throughout upon evaluating the animals rate of deceleration from top speed whilst in a „gliding” movement. This top speed in the case of „Notty”, the Pacific striped dolphin, was 15 knots and in the *Stenella* 21 knots — a result which is hardly surprising in view of the experimental conditions. A study of Fig. 11 of LANG's paper shows that „Notty” was suffering under a severe handicap as the entire propulsive effort of the tail is shown to have taken place below the anteroposterior axis of the body. This implies that the main, epaxial locomotor muscles were never thrown into more than half contraction and were consequently in their most inefficient phase of contraction. It is conceivable in view of the mode of locomotion and the depth of water (not more than 2 meters and frequently less) that the animal would have



B. Apparatus for measuring body contours of *Tursiops Truncatus*.

had to concentrate throughout on avoiding impact with the bottom of the tank. It is significant that the smaller animal *Stenella* in 3 meters of water produced a much greater *calculated* output of power per unit body weight notwithstanding the greater surface to volume ratio. LANG also inferred that the resistance whilst swimming was about equal to that whilst gliding. This also implies that the flow pattern over the body whilst swimming would be identical with that whilst gliding. Owing to the fact that the skin of dolphins is totally devoid of arrector pili muscles and that the panniculus is only developed on the belly and part of the flanks it seemed to us that there was no provision for voluntary or autonomic control of the skin contours nor hence for the spontaneous correction of turbulence. Amongst those unacquainted with cetacean anatomy it is frequently imagined that whales and dolphins have acquired „de novo” structures which have been specially evolved to equip them for the aquatic life.

In fact, nothing that has hitherto been discovered about cetacean anatomy is without its counterpart in the terrestrial mammal and more specifically in Man. It more frequently happens that structures are lost rather than gained, as with the external ears and pelvic limbs, but rudiments of these can be found in the early foetal life. Recently, HARRISON and THURLEY (1974) have demonstrated that the outer layers of epithelium in cetaceans is never fully keratinized and that the quantity of mucopolysaccharides (long chain molecules) in these outer layers is approximately 10% greater than that in human epidermis. Therefore the hypothesis of FEBULA et al (loc. cit.) may have some significance in the reduction of turbulence in the boundary layer.

The muscle fibres of cetaceans are essentially similar in structure to those of terrestrial mammals but their metabolism has been altered in a way not yet fully understood. Thus the oxygen consuming, restitution phase can be delayed for relatively long periods during which the muscle works anaerobically. It is not possible therefore, to estimate the energy output in terms of simultaneous oxygen consumption as has been done with terrestrial mammals. In this respect the muscles may be less efficient than those of trained athletes. It has become increasingly apparent to us that propulsion in cetaceans is a vertically asymmetrical movement consistent with their evolution from terrestrial mammals and is therefore quite unlike that of teleost fishes, with which it has often been compared.

It seemed to us that a first requirement would be to study the flow pattern over a typical cetacean body in order to judge whether the classic hydrodynamic formulae could legitimately be applied. This has not yet been achieved in respect of the living animal and it is doubtful whether the technology required to make such observations is at present available. We therefore decided to establish first of all the basic hydrodynamic properties of a rigid model and to find out how these varied with small alterations in the direction of the flow relative to the long axis of the body. Thereafter, we would study the water flow of the model in normal towing conditions to see how this differed from the inferred flow on a living animal as indicated by the orientation of the dermal ridges. If this showed any significant degree of similarity it would seem possible to reproduce the exact flow, using relatively simple techniques and to correlate the result with observations of the method of locomotion in living animals. A final phase would be to analyse in detail the anatomy of propulsion to find out how the mechanics of such locomotion was achieved.

Since this manuscript was prepared, comments on the differential linearity of the flukes whilst swimming have been made by PURVES (1969) and DUDOK VAN HEEL (1968).

Description of the model

In order to make the model, accurate measurements were taken of a full-grown female specimen of a Florida bottle-nosed dolphin, *Tursiops truncatus* (Mont.), which had been caught in the Gulf of Mexico off Florida Keys. For this purpose the animal was suspended in a form of sling and the contours of the body and fins determined in the manner shown in Plate 1. A number of drawings based on

these values were made upon which the shape of the dolphin was recorded. Fig 1 shows the contours of the body and the cross-sections of the body, the tail, the pectoral fins and the dorsal fin. Table I gives the general dimensions of the dolphin. A full-sized wooden model was made on the basis of the drawings, but as the research was in the first instance aimed at the shape of the body the model was not fitted with pectoral flippers. Plate 2 shows various stages in the construction of the model.

In order to prevent the tail from producing lift forces at different angles of attack, it was attached to the body with hinges, and its specific gravity was adjusted to that of the water. Recesses were made in the body to allow for the inclusion of measuring instruments and the former were finally closed with brass plates carefully moulded to the contours of the body to prevent discontinuities. The model was finally given several coatings of waterproof lacquer to give it a fine finish.

A complete set of full-scale drawings can be obtained at cost price from the Dolphinarium, Harderwijk, Netherlands.

TABLE I. *Dimensions of the dolphin - Model 3723 - Scale of Model 1 : 1.*

Surface area of dolphin with tail and flippers	1.891 m ²
Surface area of tail flukes	0.171 m ²
Surface area of one flipper	0.068 m ²
Surface area of dorsal fin	0.090 m ²
Displacement of dolphin with tail and fins	100.629 dm ³
Displacement of tail flukes	1.830 dm ³
Displacement of one flipper	0.528 dm ³
Displacement of dorsal fin	1.002 dm ³
Position of centre of gravity of volume of dolphin with tail and flippers posterior to snout	0.909 m
Position of centre of gravity of volume of tail flukes posterior to snout	2.151 m
Position of centre of gravity of volume of flipper posterior to snout	0.670 m
Position of centre of gravity of volume of dorsal fin posterior to snout	1.142 m
Length of dolphin as measured along the nose-tail line	2.250 m
Length of dolphin as measured from tip of snout to posterior extremity of flukes	2.322 m
Maximum thickness of dolphin	0.372 m
Tip of snout to point of maximum thickness	0.808 m

Description of the measuring apparatus.

For the experiments, the model was suspended from two streamlined struts the upper ends of which were attached to the towing carriage. Each strut consisted of an inner tube (which took up the forces) and an outer nacelle, which at its proximal end was just free of the model. The inner tubes were connected to the

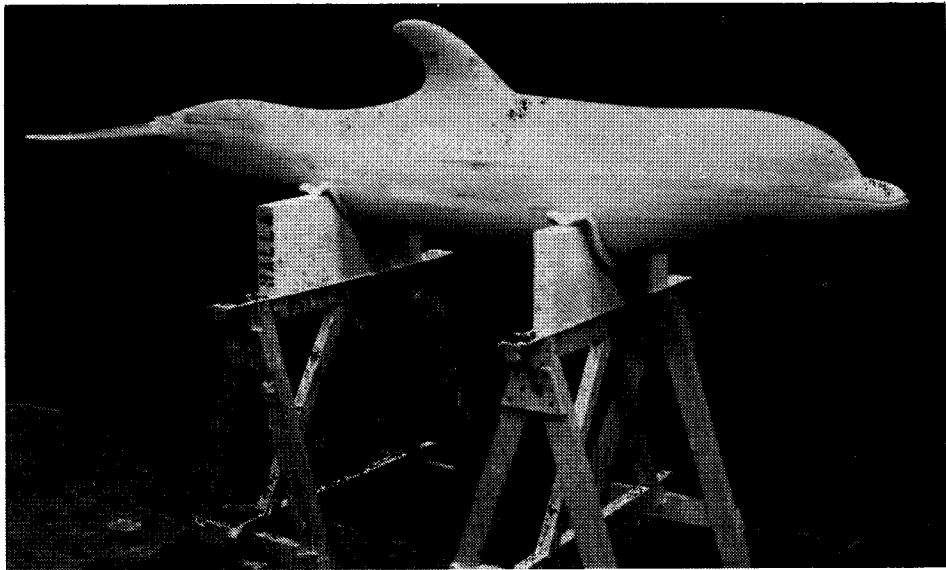
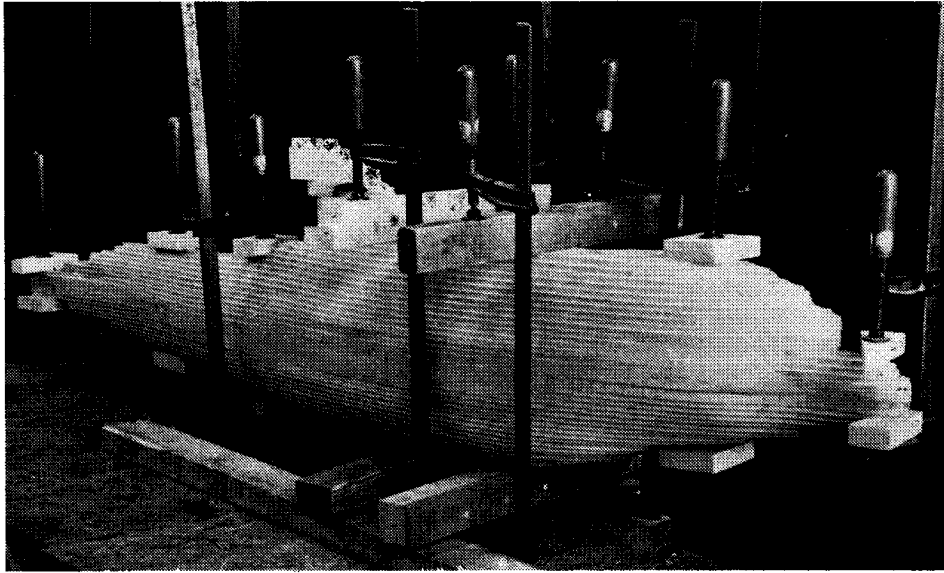


Plate 2: Photographs showing various stages in the construction of a model of *Tursiops truncatus*.

measuring units in the manner shown in Fig. 2. During the tests the struts were maintained in a vertical position. To alter the angle of incidence of the model with reference to the nose-tail line, the rear strut was moved downward (positive angle of incidence) or upward (negative angle of incidence) and at the same time shifted over a certain distance in the direction of translation. Measuring-unit A registered the vertical component of the force acting on the model at the location of the front strut whilst measuring-unit B registered the component acting in the

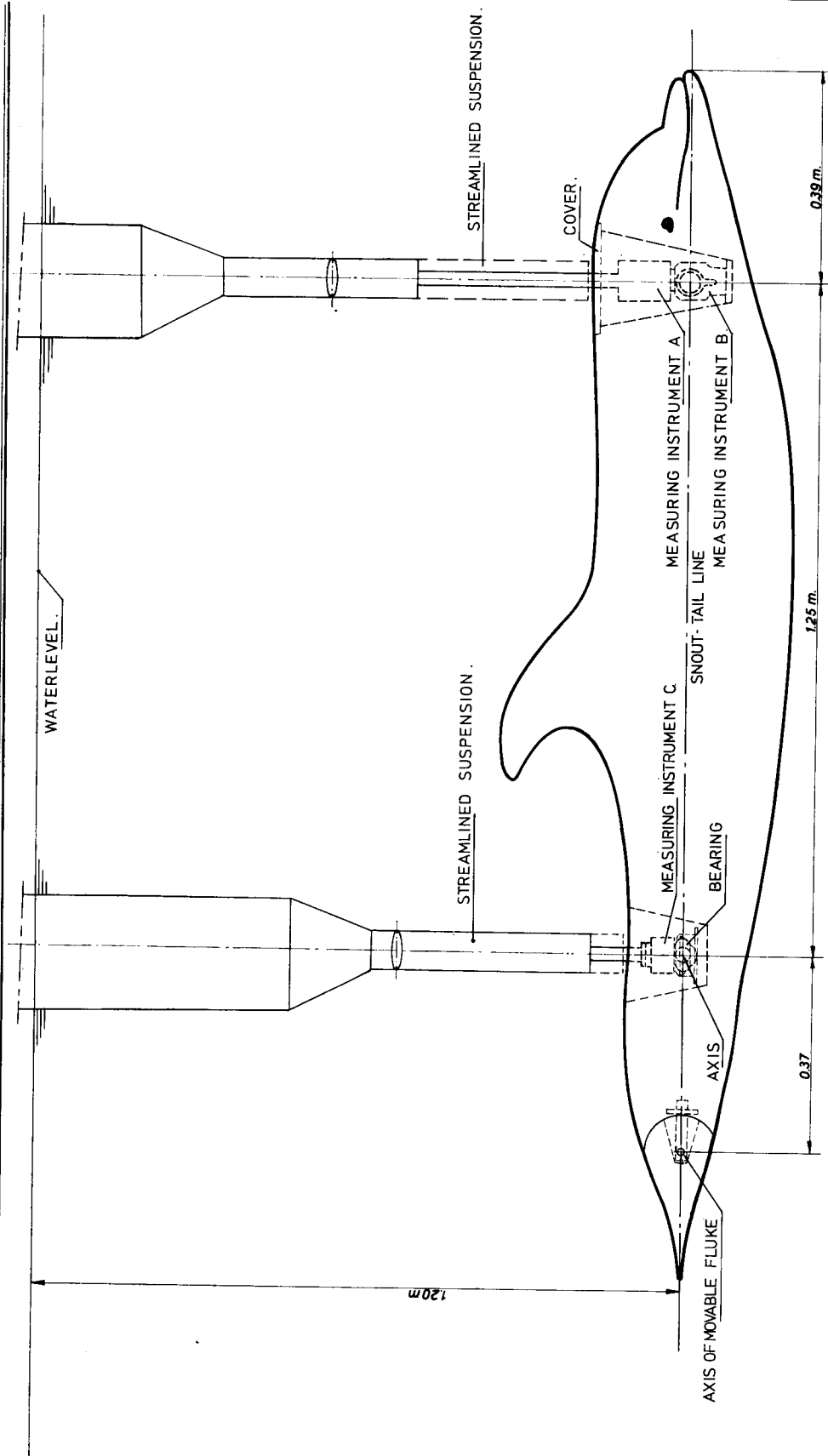


Fig. 2: Test arrangement.

direction of the nose-tail line. There was a hinge between measuring-units A and B. At the location of the rear strut, there was insufficient room to install a measuring-unit similar to that at the front strut, therefore a statically fixed situation was created by installing a universal bearing in such a way that the model itself could also rotate around this bearing. Measuring-unit C registered the vertical component of the force applied at this point and working perpendicular to the nose-tail line. To keep the line of action of this force continuously perpendicular to the nose-tail line during the tests, it was arranged, by visual monitoring of two contact points at each side of the shaft, that the shaft was constantly in the middle of the bearing.

The test procedure

The hypothesis of PURVES (1963) and DUDOK VAN HEEL (1968) is based on the assumption that under the influence of the swimming movement in which the upstroke is the power stroke the water does not flow horizontally along the animal but is orientated obliquely upwards.

This would be the equivalent of the dolphin moving horizontally at a certain positive angle of incidence, at which the drag should be minimum. To check the above mentioned hypothesis drag measurements were carried out at one set speed and at different angles of incidence (Fig. 3 en 4). At the optimum angle of incidence the drag was measured over a speed range of 1 to 8.5 m/sec so that a correct comparison with data known from the literature would be possible. The shape of the camber of the wooden model, although not a time-average shape, was fairly similar to that of a dolphin in a glide. Since most of the observations on swimming performance of dolphins have been made whilst the animals were at or near the surface, the wooden model was submerged to a depth of 1.20 meters measured on the nose-tail line. It was assumed that at this depth no noticeable wave drag would be produced but on the basis of the results this assumption turned out to be incorrect. The flow pattern was recorded at an angle of incidence of 0° and a speed of 16.4 m/sec by means of a „paint test”, whereby paint is applied to the model at a number of points. The direction in which the paint was spread out along the body under the influence of the water velocity indicated the flow pattern, i.e. the trace of the streamlines.

Results of towing experiments

In Fig. 8 the results of the drag measurements at different angles of incidence and a speed of 6.14 m/sec are shown in the form of a drag coefficient:

$$C_D = \frac{D}{\frac{1}{2} \rho V^2 A}$$

$$\text{a lift coefficient: } C_L = \frac{L}{\frac{1}{2} \rho V^2 A}$$

$$\text{and a moment coefficient: } C_M = \frac{M}{\frac{1}{2} \rho V^2 A \cdot c} \text{ as a function of the angle of incidence } \alpha.$$

It will be noted that when the model was in motion at zero angle of incidence there was an appreciable lift and upward turning moment about the centre of

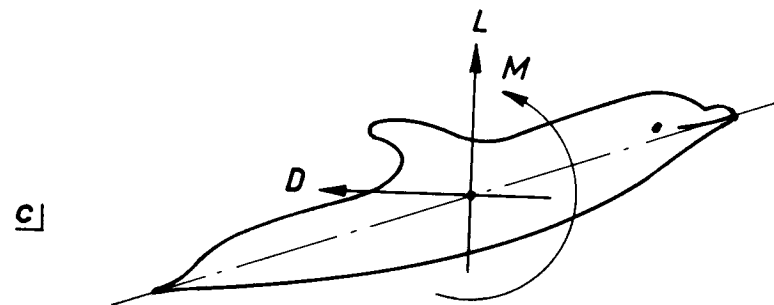
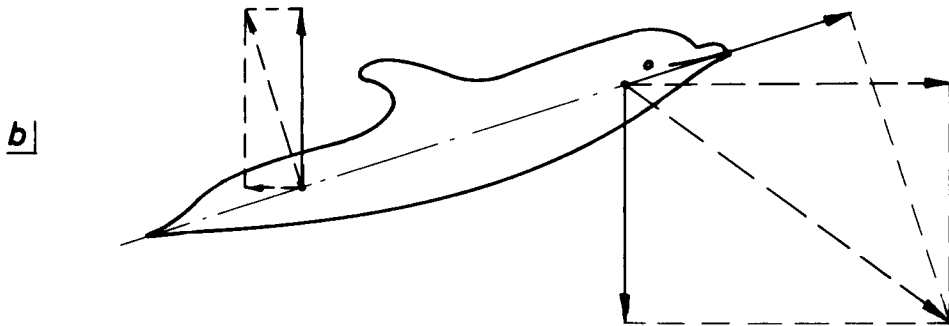
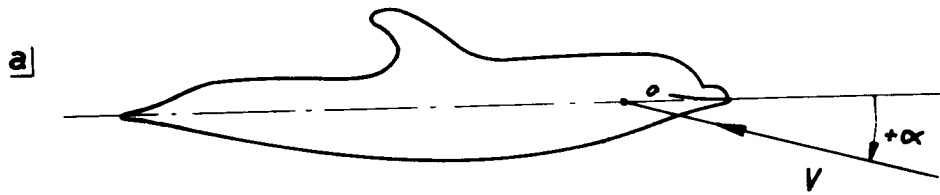


Fig. 3: Definition of forces, moments and angles.

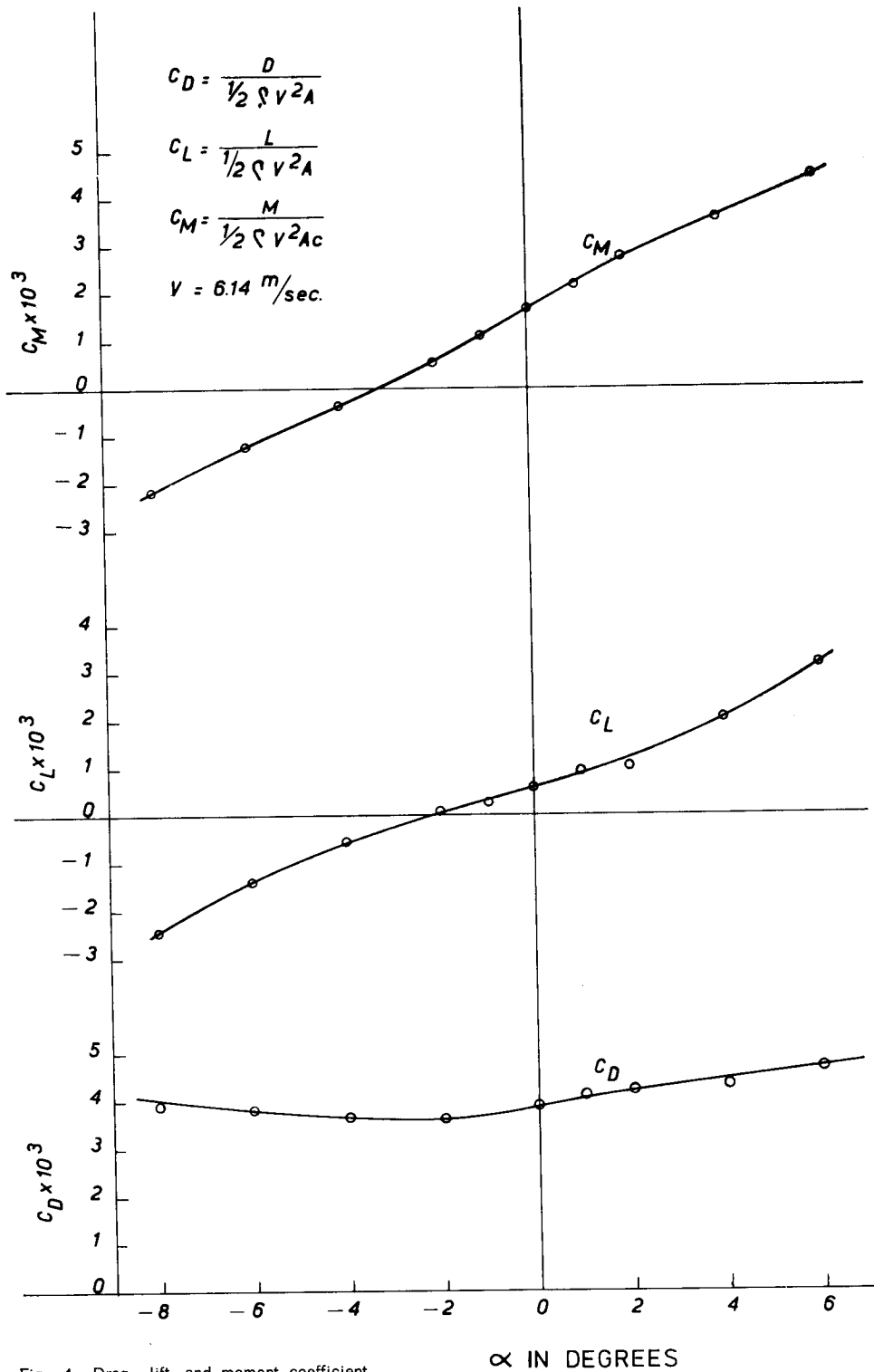


Fig. 4: Drag, lift- and moment coefficient as functions of angle of incidence.

gravity due to the shape of the body. See Fig. 6 in PURVES (1969). It is apparent that the minimum bedrag is reached at an angle of incidence $\alpha = -2^\circ$. On the basis of this it is, however, not possible to ascertain whether the upstroke is the power stroke. The fact that in the experiments the model did not have a time-average shape is perhaps a contingency which cannot be neglected. To determine such a shape would require a protracted research. The fact that at large negative angles of incidence the increase in drag is smaller than at large positive angles of incidence is probably due to the interference between the struts and the model on one hand and between the rear strut and the discontinuity in the body caused by the hinged tail part on the other hand. The results of the experiments carried out at an angle of incidence $\alpha = -2^\circ$ and over a speed range of 1 to 8.5 m/sec are shown in Fig. 5. Of that, the C_D curve gives the most salient picture.

The relatively high C_D values at $R_n \cong 2$ to 3×10^6 are probably due to the separation of the laminar boundary layer over the dorsal fin and the tail. At $R_n > 5 \times 10^6$ a noticeable wave drag occurs, which increases to approximately $D_n \cong 6 \times 10^6$, the moment on which a transverse pressure wave has developed. The dimension of this pressure wave is dependent on the submergence h . To avoid the wave-drag the ratio h/t would have to be around 9 to 10 which would require a submergence of 3.30 to 3.70 meters. For practical reasons it was not possible to arrange this.

Interference between the struts and the model had some influence on the test results. Because resistance was the most important component, only those values

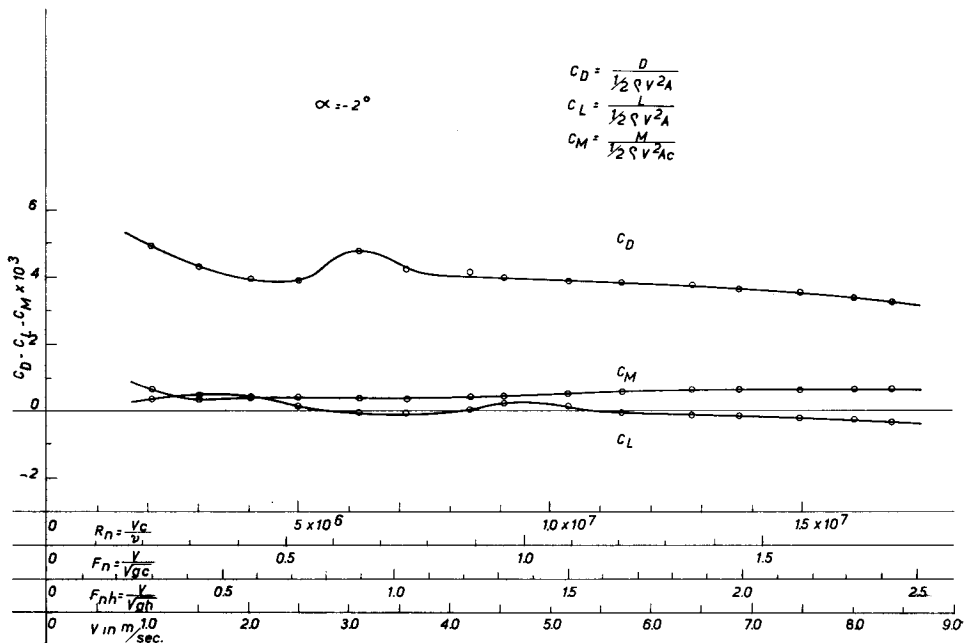


Fig. 5: Drag-, lift and moment coefficient as functions of Reynolds number, Froude number and velocity at an angle of incidence of -2° .

TABLE 11. Dimensions of body of revolution.

Surface area of body of revolution	3.060 m ²
Displacement of body of revolution	292.798 dm ³
Position of centre of gravity of volume of body of revolution posterior to nose	1.274 m
Length of body of revolution	2.743 m
Maximum diameter of body of revolution	0.457 m
Distance from tip of nose to position of maximum diameter	1.097 m

were corrected for. The correction applied was based on experiments carried out by GERTLER (1950) on a systematic series of bodies of revolution. The value of this correction was determined by means of resistance experiments on models with and without dummy struts. The dummy struts were rigged in such a way that there was no interference with the permanent struts. GERTLER proved that the correction was constant throughout the whole speed range. The interference resistance is, amongst other factors, dependent on the dimensions of the model. The determination of the interference resistance coefficient was therefore based on an equivalent body of revolution, the dimensions of which are given in Table II. With the help of the data from GERTLER for this specific body of revolution the correction for the model of the dolphin was worked out to be $\Delta C_D = 0.450 \times 10^3$. In this figure is also incorporated the resistance of the small discontinuity in the

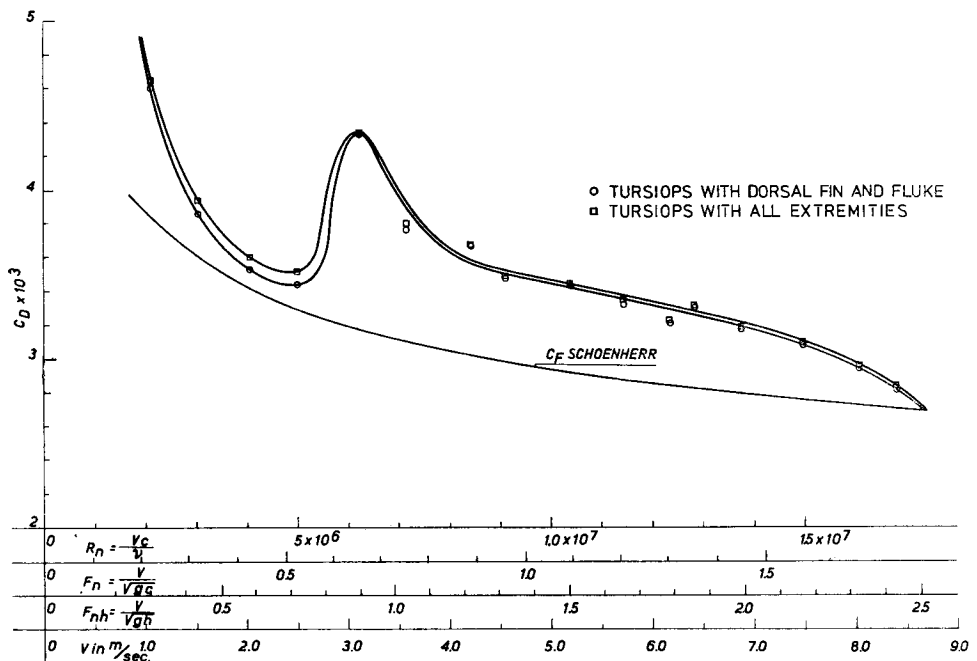


Fig. 6: Drag- and friction resistance coefficient as functions of Reynolds number, Froude number and velocity at an angle of incidence of -2° .

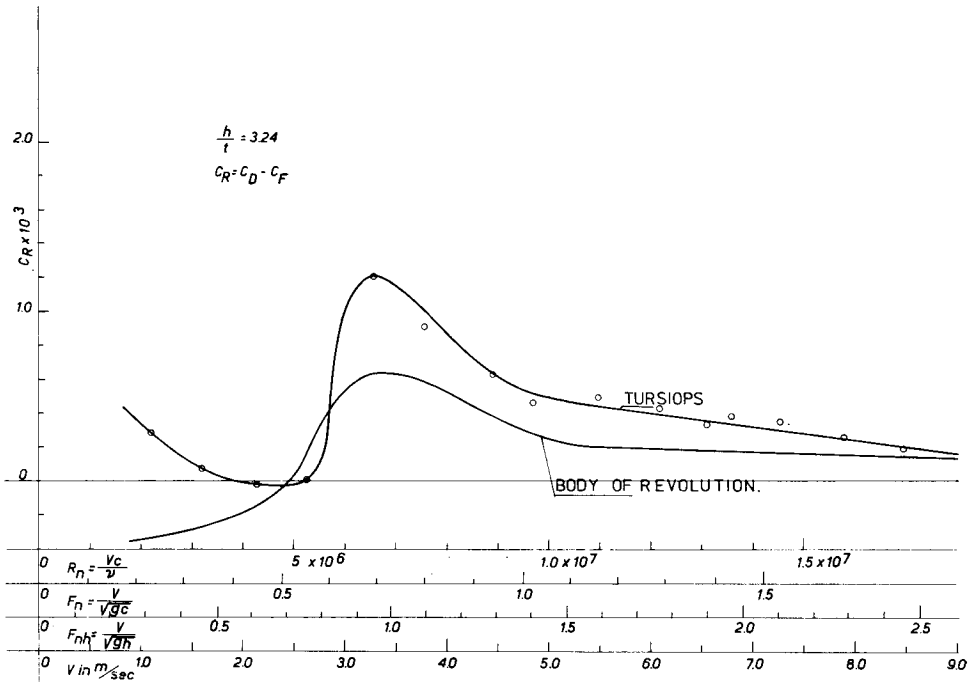


Fig. 7: Residuary resistance coefficient as a function of Reynolds number, Froude number and velocity at an angle of incidence of -2° .

shape of the model due to the hinged tail part. The corrected C_D values are given in Fig. 6. In this graph are also shown the friction resistance coefficients for a turbulent boundary layer according to the Schoenherr Formula: $\frac{0.242}{\sqrt{C_F}} = \log_{10} R_n \times C_F$

Due to the fact that the model on which the experiments were performed did not have pectoral fins, the influence of these was calculated and a correction applied to the measured values. For the calculation, the boundary layer was supposed to be partly laminar and partly turbulent.

In locating the transition point, use was made of the research on fin profiles carried out by LANG (1968). The maximum thickness was located approximately 35% of the chord length posterior to the leading edge. Analysis of the pressure gradient over the profile shows that the profile is very favourable for $R_n \cong 10^6$ and that it is reasonable to assume that the transition point is located at the maximum profile thickness. It is noteworthy that the profiles of the pectoral fin, the dorsal fin and the tail show approximately the same characteristics. The large radius of curvature of the leading edge and the relatively large thickness ratio of the profile point to a certain variation in angle of incidence without immediate risk of cavitation. It is evident from the experiments of LANG (loc.cit.) that the shape of the profile is a compromise between the profile FX 05-191 from Wortman and the profile EA6(-1)-018 from Eppler. The resistance of the tail and dorsal fin were calculated in the same way, after which it was possible to derive the C_D values of the body. For purpose of comparison with the body of revolution, the friction resistance coefficients according to Schoenherr were subtracted from those C_D values to obtain the residuary resistance coefficients C_D . These are shown in Fig. 7. Hence it appears that R_n being approximately 3 to 4 x 10⁶ the

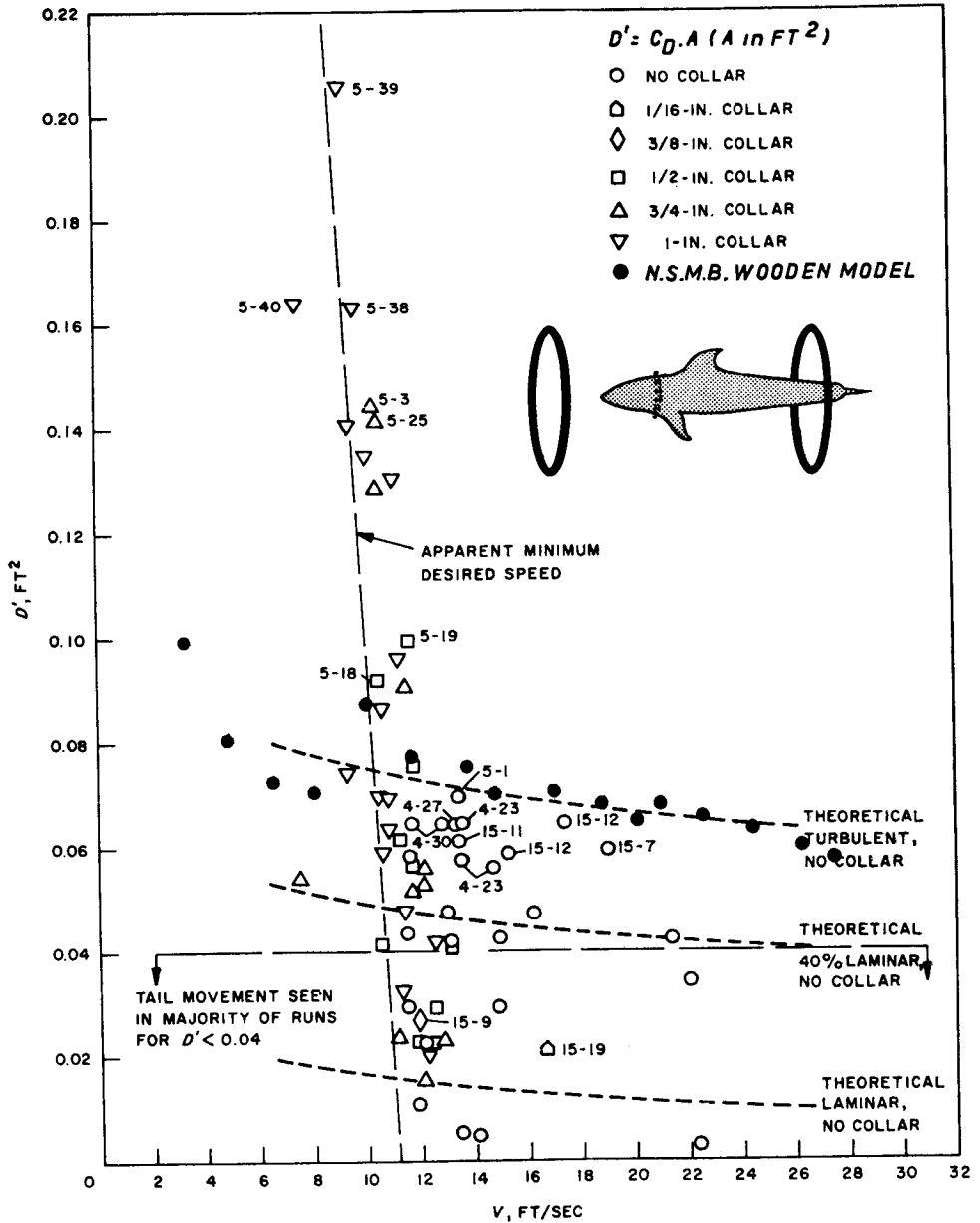


Fig. 8: Drag coefficient as a function of velocity for comparison with a live specimen (after Lang).

boundary layer is laminar over about 12% of the length. In the B_n range investigated, the body of the dolphin model does not seem to be more efficient than the body of revolution. From aerodynamic researches on bodies of revolution by HERTEL (1967) it appears, however, that the parabolic form of the anterior part

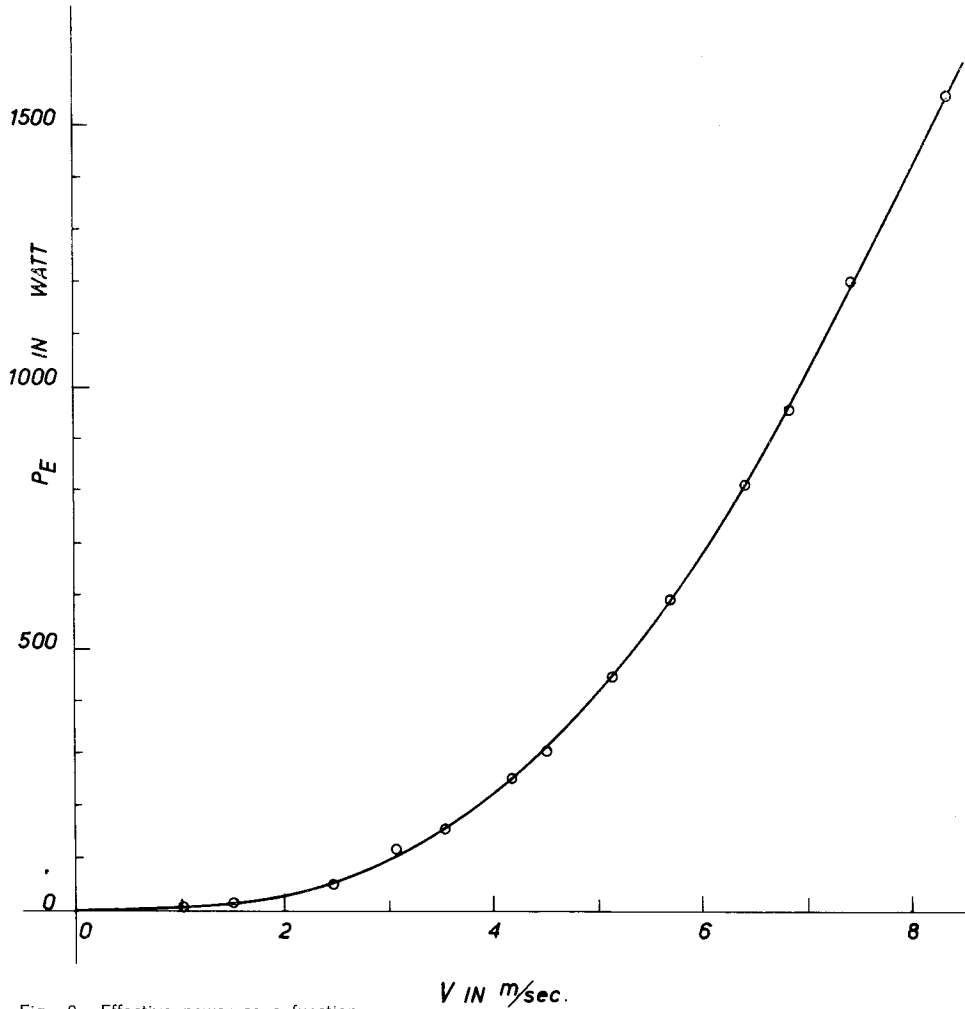


Fig. 9: Effective power as a function of velocity.

of the body gives a more favourable pressure gradient for $R_n = 10^7$ to 2×10^8 .

The shape of the body does not show much resemblance to the laminar profiles known from aerodynamics and is relatively thick i.e. $t/c =$ approximately 0.17. For parabolic bodies of revolution the optimum thickness is around 0.20 (least resistance, greatest volume). In general it can be stated that shape of the body and fins is efficient for the specific R_n range. When comparing with bodies of revolution it should be borne in mind that, where the dolphin swims near the surface of the water, an asymmetrical form in relation to the plane through the nose-tail line and perpendicular to the vertical plane of symmetry would be a more favourable one.

In Fig. 8, taken from LANG (1966), the results of model experiments are compared with those of a live animal, *Lagenorhynchus obliquidens*, in a glide. In both cases

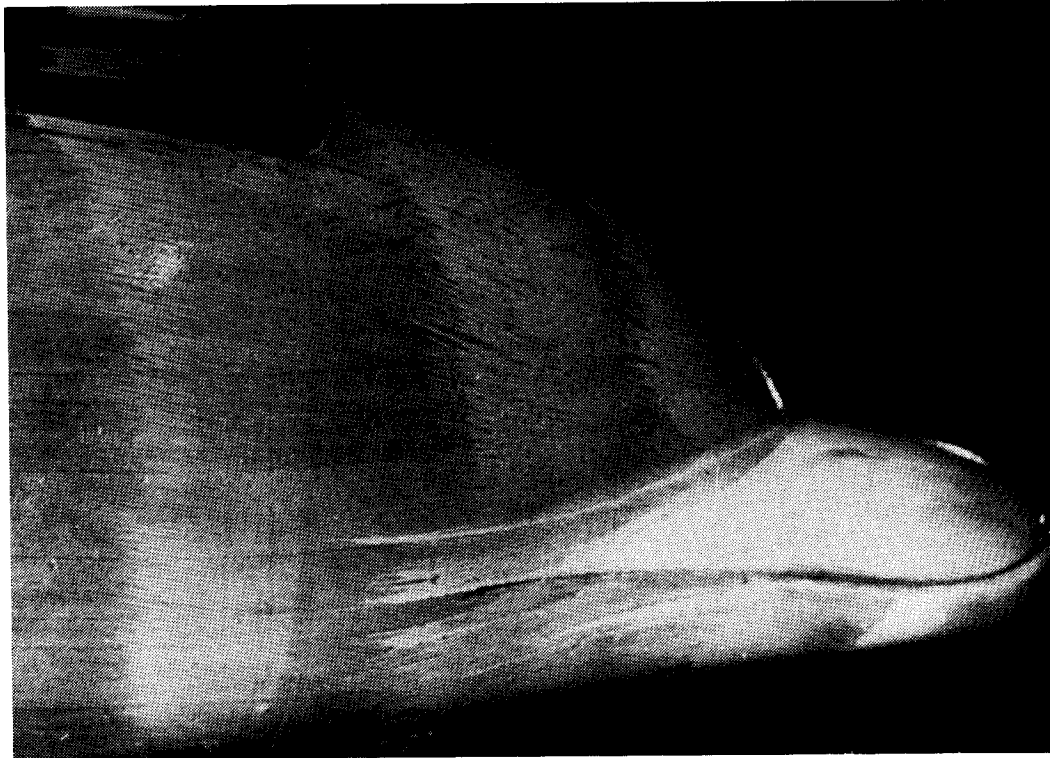
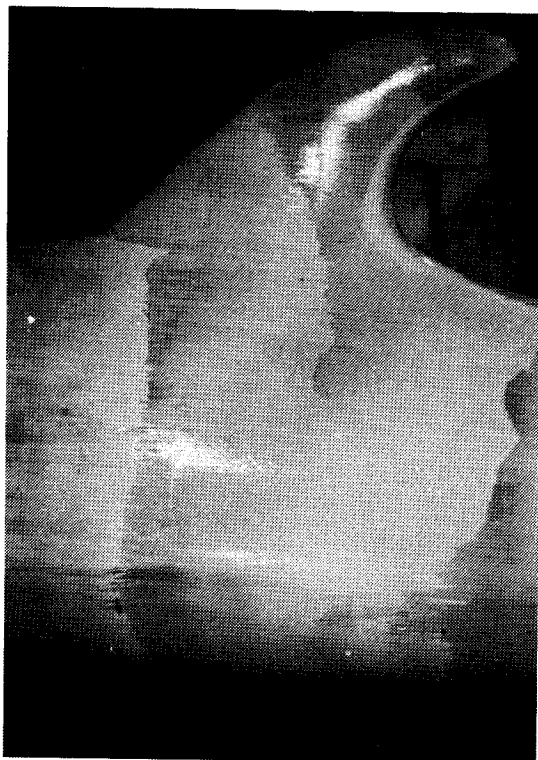


Plate 3: Photographs showing the direction of streamlines on A. head, B. dorsal surface, C. region of dorsal fin in model of *Tursiops truncatus*.

the h/t ratio has about the same value. It turns out that the characteristics of the model are somewhat inferior to those of the live animal, which has a laminar boundary layer for over an average of 20-25% of its length. These results were confirmed by observation of flow on the same specimen. Transition takes place at a local $Re =$ approximately 2×10^6 at a speed of 4.6 m/sec. In some instances, however, with the live specimen a laminar flow over an even greater length was reached.

The resistance of a rigid body is probably somewhat greater since the influence of the locomotion upon the boundary layer has not been taken into account. The power required to tow the wooden model with tail, pectoral fins and dorsal fin as calculated from the resistance measurements is given in Fig. 9 and it will be seen that at 15 knots or 8 meters/sec. the resistance is a little over 1500 watts or approximately 2 horsepower. The weight of propulsive muscle (of the hypaxial muscle mass and rectus abdominus are included) in a living specimen of *Tursiops* of the same dimensions as the model would be expected to be 36 kgms, and therefore if the drag characteristics of the model are equivalent to those of the live animal the muscle per kgm must be capable of a sustained output of at least 4.2 kgm meters/sec. This matter is re-examined in the Discussion.



The paint test

The foregoing description of the hydrodynamic characteristics of body-shape of *Tursiops* gives no indication of the direction of the water-flow over the body, a factor which would appear to be of considerable importance in determining the actual mode of locomotion in the living animal.

It has long been known that the epidermis of cetaceans is keyed on to the dermis in a series of parallel ridges similar to those on the palmer surfaces of the hands and feet in Man and primates but these are not visible on the surface in cetaceans the external skin being perfectly smooth and undifferentiated. They can therefore play no part in the reduction of turbulence as has been postulated by KRAMER (loc. cit.).

It has generally been stated, from the examination of isolated pieces of skin, that the dermal ridges lie parallel with the long axis of the body but it was demonstrated by PURVES (1963) loc. cit. that this was incorrect and that the ridges were orientated in various directions which, he postulated, lay along the streamlines of water flow over the body. In an attempt to ascertain the truth or otherwise of this hypothesis, a low-viscosity paint was applied at various points on the model of *Tursiops* which was then towed at 0° angle of incidence at a velocity of 6.14 m/sec.

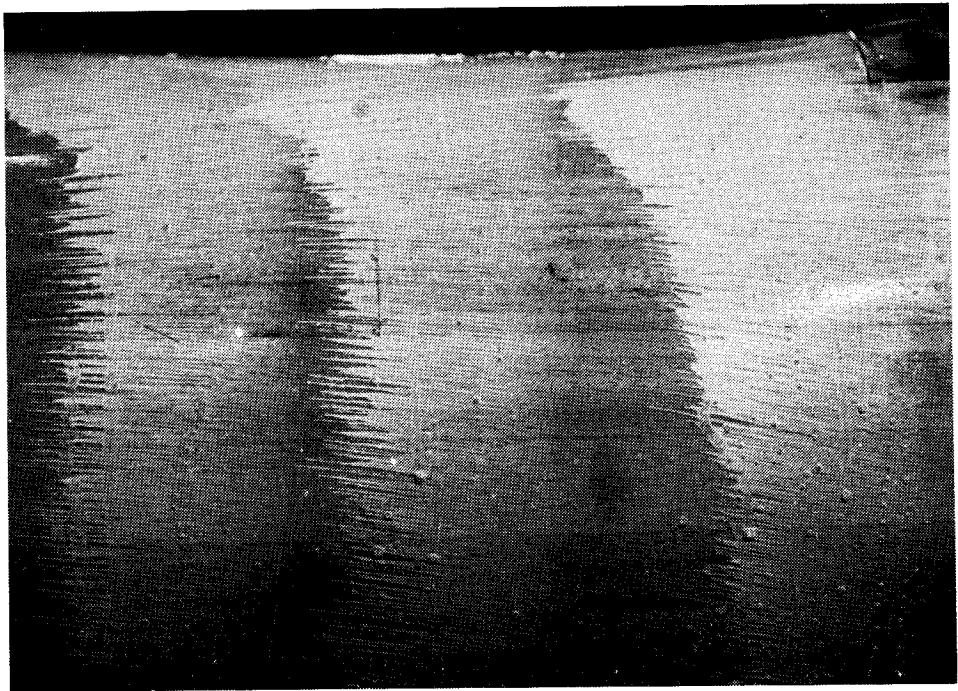


Plate 4: Photograph showing streamlines on side of thorax pointing obliquely upwards in model of *Tursiops truncatus*.

Results of paint test

It may be stated that, whatever the supposed acoustic properties of the „melon” in odontocetes are, there is no doubt that it is of considerable hydrodynamic significance, a fact which is borne out by the paint test now to be described. From Plate 3A it will be seen that paint applied on the head and snout of the model (towed at 6.4 m/sec, 12 knots) demonstrates streamlines divided into two separate components. From the insertion of the snout one component spreads over the head with those on the lateral surfaces of the face making an angle of approximately 20° to the horizontal. Another component spreads downwards towards the angle of the gape and thereafter sweeps upwards in the general direction of the upper component. Those on the dorsal surface (Plate 3C) continue straight backwards towards the insertion of the dorsal fin. Plate 4 shows that on the lower two thirds of the side of the thorax the streamlines continue obliquely upwards though at a somewhat smaller angle, approximately 10° . This diminution in the angle of flow is caused by convergence with the dorsal streamlines which are diverted round the dorsal fin. The foregoing description of the orientation of the streamlines on the dorsal and lateral aspects of the head and thorax of the model of *Tursiops truncatus* is also an exact description of the orientation of the dermal ridges under the same area of the skin of the living animal and differs from that of *Delphinus delphis* (Fig. 10) only in the narrower width of the dorsal

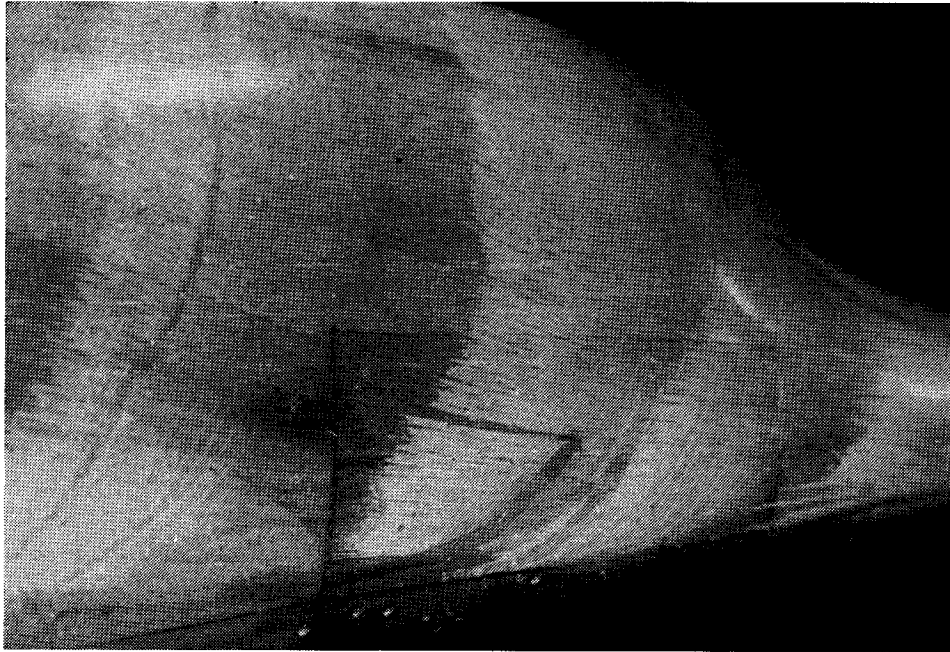


Plate 5: Photograph showing streamlines on chin and thorax in model of *Tursiops truncatus* without pectoral fins.

component in the latter species. On the ventral aspect of the chin and thorax (Plate 5) the streamlines diverge from the mid ventral line and in this respect they differ from the living animal in which the ridges converge towards it. This difference can be attributed to the absence of pectoral flippers in the model which in the living animal produce a ventrally deflected water flow over both their upper and lower surfaces. There is evidence of separation of the boundary layer at the trailing edge of the dorsal fin and from the body behind the dorsal fin. The streamlines on the dorsal fin and tail run more or less parallel with the nose-tail line and in this respect differ from the orientation of the dermal ridges on the dorsal fin, flippers and flukes in the living animal, in which they are directed towards a point on the nose-tail line posterior to the caudal notch. Plate 6 shows the streamlines flowing predominantly over the upper surfaces of the flukes from the caudal peduncle as do (much more pronouncedly) the dermal ridges in *Tursiops* and *Delphinus* (Fig. 10). All these paint experiments were carried out with the model at zero angle of incidence to the water and from the evidence it seems doubtful whether the small adjustments to the angle of incidence made during the resistance trials as demonstrated in Figures 3 and 4 would have made any gross difference to the direction of water flow. At the point of least drag coefficient, the posterodorsal obliquity of the flow over the head and thorax at least, would be reduced by only 2° . The paint experiments show that on the anterior part of the body, the streamlines follow the orientation of the dermal ridges without any induction by a tail action. It is well known, however, that dermal ridges occur over the entire body of cetaceans and it will be the object of future experiments to determine the influence of the locomotion on the separation of the boundary layer.

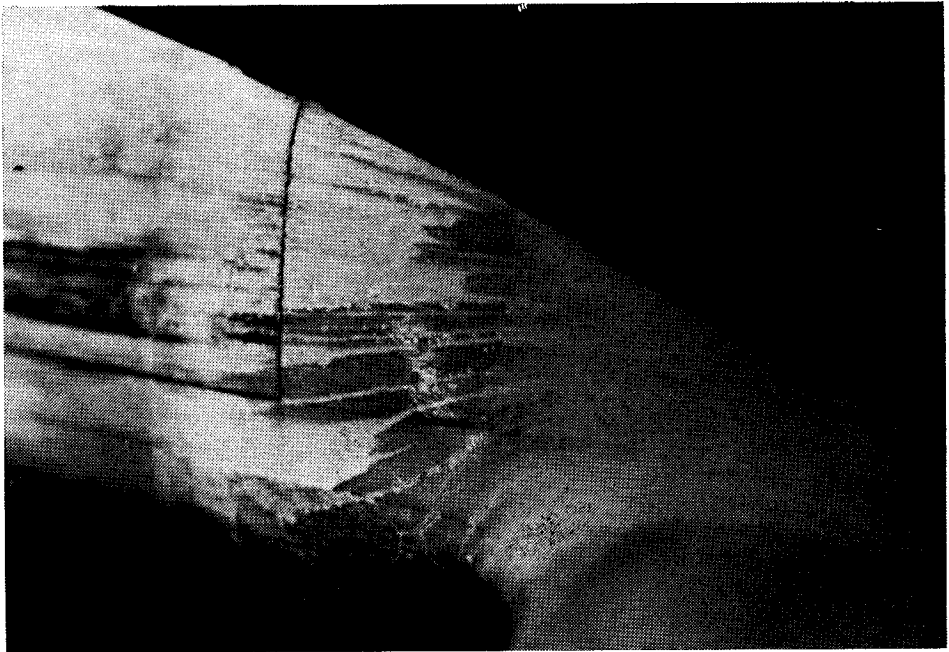
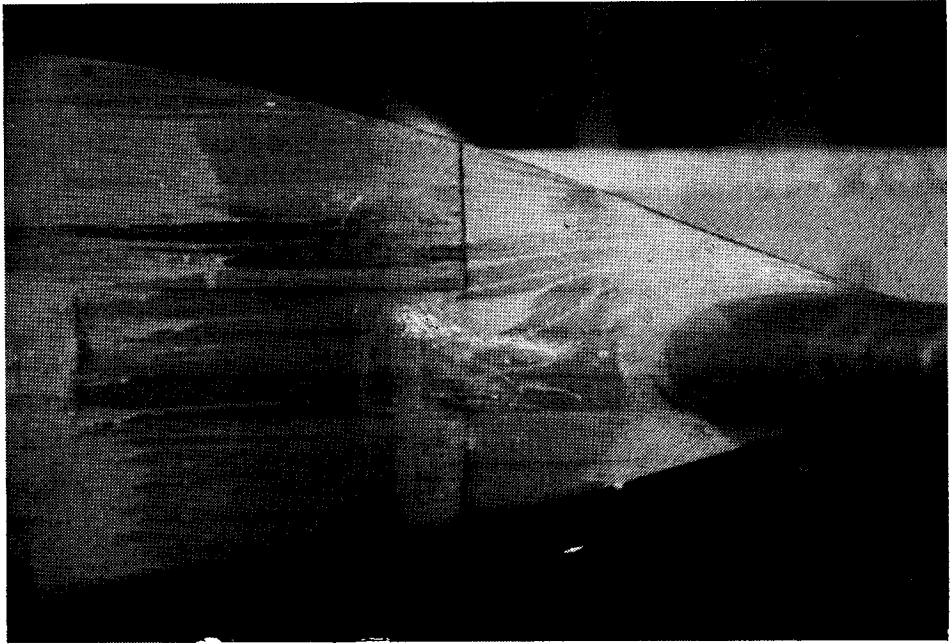


Plate 6. Photographs showing direction of streamlines in region of caudal peduncle in model of *Tursiops truncatus*.

Conclusions

The experiments and calculations described above show that at relatively low Reynold's numbers the basic shape of the bottle-nosed dolphin is hydrodynamically less efficient than that of an equivalent body of revolution, the greater resistance being largely attributable to the presence of appendages such as the tail flukes, flippers and dorsal fin. However, at speeds in excess of 15 knots where the effect of these appendages is less significant, the coefficient of total resistance rapidly diminishes so that the resistance curve intersects the Schoenherr line at about 17 knots $R_n \cong 1.7 \times 10^7$ (Fig. 6). The curve of residuary resistance coefficient of the dolphin similarly reduces and intersects that of the body of revolution at 18 knots $R_n \cong 2 \times 10^7$ (Fig. 7). This general trend towards a lower resistance coefficient at higher Reynolds' number is also shown in LANG's experiments with the living specimen of *Lagenorhynchus obliquidens* (Fig. 8), although a resistance coefficient equivalent to 50% laminar flow was achieved at speeds as low as 6.5 knots. The lowest resistance coefficients in the living animal with no visible tail movement were achieved between 8 and 13 knots these being equivalent to at least 40% laminar flow. It is significant that no speed above 8 knots was achieved when the animal was fitted with a turbulence inducing collar. From these results it may be inferred that the live animal is hydrodynamically more efficient than the wooden model but that both are superior to an equivalent body of revolution at speeds above 18 knots. From the work of HERTEL (loc. cit.) it seems that the parabolic form of the anterior part of the body provides a favourable hydrodynamic shape for $R_n = 10^7$ to 2.10^8 .

The majority of the toothed cetaceans, the Odontocete, swim in this R_n -range.

The lowest calculated drag horsepower of the specimen of *Lagenorhynchus obliquidens* used by LANG (loc. cit) was 1.4. This figure was arrived at when the animal was in a „glide” from a top speed of 15 knots. There are reliable reports (JOHANNSEN and HARDER, 1960) of this species being able to maintain a sustained swimming speed of 15 knots for 20 minutes and therefore if the drag whilst gliding is equal to that whilst swimming as LANG postulated, this species is capable of a sustained output of at least 1.4 horsepower. The animal weighed 90.7 kgm and as a maximum of 20% of this consists of propulsive muscle the output per kgm of muscle would be 5.8 kgm meters/sec. This compares with 4.2 kgm meters/sec for *Tursiops*. According to WILKIE (1960) a trained cyclist using a cranking machine which employed both arms and legs, could only generate approximately 0.5 horsepower for a period of 20 minutes. Taking the minimum weight of muscle employed, say 20 kgm, the output per kgm of muscle would be 1.9 kgm meters/sec. Thus the *calculated* power output of the dolphin muscle is approximately two to three times that of the trained athlete. Although the comparison is rather more favourable than GRAY's when he assumed fully turbulent flow it is untenable from the physiological standpoint and seems to indicate that the drag whilst actively swimming is considerably less than that whilst gliding. The paint test showed that the waterflow does indeed follow the orientation of

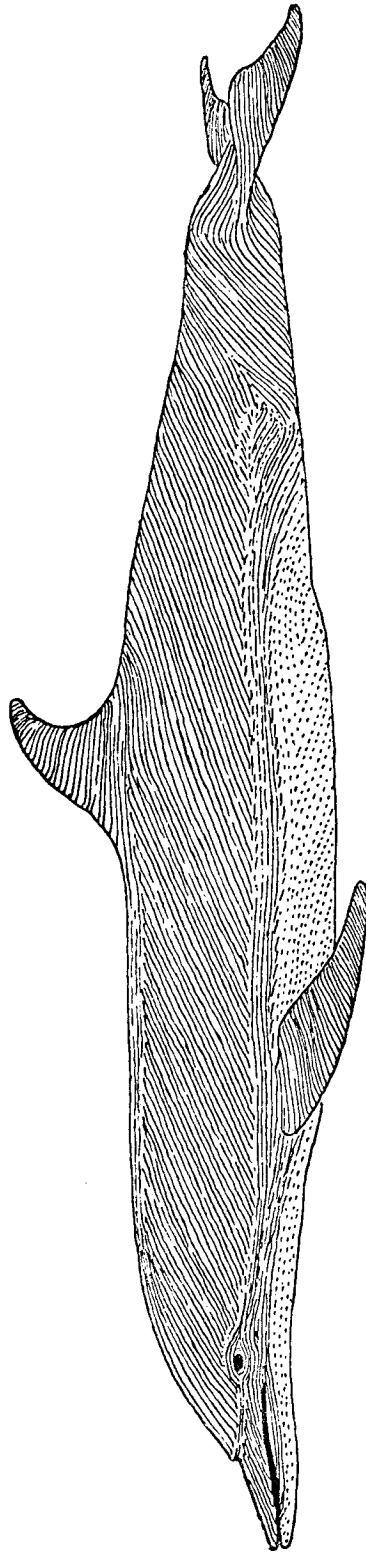


Fig. 10: Diagram showing the orientation of dermal ridges under the epidermis of the common dolphin, *Delphinus delphis*.

the dermal ridges which as stated, occur over the entire body. If the flow, as indicated by the orientation represents the condition whilst swimming at high speed then the mathematics of towing or gliding in particular, a Reynolds number which employs the total length of the animal in its evaluation, cannot be applied to the swimming. The anatomy and mechanics of swimming will be the subject of a later paper.

Symbols and Definitions.

Symbols:

Units:

A	= Plan area of dolphin	m^2
C	= Length of dolphin — the chord of the profile	m
C_D	= $\frac{D}{\frac{1}{2} \rho V^2 A}$ = drag coefficient	—
C_F	= Skin friction coefficient according to Schoenherr	—
C^L	= $\frac{L}{\frac{1}{2} \rho V^2 A}$ = lift coefficient	—
C_M	= $\frac{M}{\frac{1}{2} \rho V^2 A c}$ = moment coefficient	—
C_R	= $C_D - C_F$ = Residuary resistance coefficient	—
D	= Drag force applied at centre of gravity of volume	Kgf
D'	= $C_D A$ = drag coefficient according to LANG	—
F_n	= $\frac{V}{\sqrt{gc}}$ = Froude number related to length	—
F_{nh}	= $\frac{V}{\sqrt{gh}}$ = Froude number related to submergence	—
g	= Acceleration due to gravity	$m.s^{-2}$
h	= Submergence of model as measured on the nose-tail line	m
L	= Lift applied at the centre of gravity of volume	Kgf
M	= Moment about the centre of gravity of volume	$Kgfm$
P_E	= Effective power (the power required to tow a body at a certain speed)	$Watt$
R_n	= $\frac{V.c}{\nu}$ = Reynold's number	
t	= Maximum thickness of body or profile	m
V	= Velocity	$m.s^{-1}$
α	= Angle of incidence	degrees
ρ	= Density of water	$Kgfm^{-3}$
ν	= Kinematic viscosity coefficient	$m^2.s^{-1}$

Definitions

The definitions of the angle of incidence is given in Fig. 7a, the forces measured in Fig. 7b, whilst the positive notation of the forces and the moments acting in the centre of gravity of volume are given in Fig. 7c.

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