Some Modes of Mechanical and Animal Locomotion.

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SUCH questions as how do birds fly, how do fish swim, how do ships steer, or snakes crawl, have been subjects of interest from very early times.¹ The present note is concerned with these and some other forms of locomotion, all of which may be placed under the heading of motion in fluids and motion on solids. Motion in fluids includes ships, airships, flying machines, birds, winged insects, fish, whales, and various swimming insects and Crustacea. Motion on solids refers to various legless creatures such as snakes, molluscs, and microscopic organisms.

MOTION IN FLUIDS.

A very general proposition applicable to all cases may be stated with regard to motion through a fluid; namely, if a body moves with a velocity v and experiences a resistance R , momentum is generated (either by pushing, pulling, or rubbing) in the direction of the motion such that $d(MV)/dt = R$. Here MV is an abbreviation for the integral of the mass of each element of fluid $\times$ velocity imposed on it by the progress of the body. If the source of power is contained in the moving body, an equal variation of momentum in the opposite direction must be generated in the fluid to overcome the resistance.

For the present purpose the source of power, whether screw, wing, paddle, or jet, may be called the accelerator, since its purpose is merely to accelerate the fluid in a direction opposed to R . The ideal accelerator may be taken as an area placed broadside to the stream, supplied with means of increasing the potential of the fluid passing through it, and experiencing therefore a reaction equal to the accelerating force. To determine what total flow and what velocity is required to produce a given reaction, let A be the area of the accelerator, v the velocity of the fluid, and ρ its density. The flow of mass is ρAv . If R is the given reaction and F the accelerative force acting on the fluid, and if $R = Mg$, then M is the mass of fluid which weighs R and occupies a volume Av . Thus $\rho AvF = Mg$. M is a constant, so that $F/g = 1$ and $A = \text{volume} \div v$. Take, for example, the case where the fluid is air and let $R = 1000$ lb. and $A = 1000$ ft.². A thousand lb. of air has a volume of about 12,800 cubic feet, and this volume per second will, starting from rest, acquire a velocity of 32 ft./sec. in passing through the accelerator when acted on by a force equal to its own weight. If the area is halved the velocity must be doubled and $F = 2g$, and so on.

The power required to produce the velocity is vR . In the diagram (Fig. 1), curves are given showing, in term of the area of the accelerator, the velocity of the air current necessary to cause a reaction of 1000 lb., and also the horse-power required to maintain it. A curve is added showing the

diameter of the stream if the cross-section is a circle.

In this diagram it is assumed that the accelerator itself is stationary and that therefore all the work goes in creating currents in the air. If, however, the pressure drives the accelerator forward at a velocity v_2 , then, in the absence of any acceleration, the flow of mass through the accelerator will be ρAv_2 per sec., and if v_1 is the velocity which must be added to this flow to maintain the reaction R , the power required will be $R(v_1 + v_2)$, and the requisite accelerating force will be less than that indicated in Fig. 1 in the ratio $v_1/(v_1 + v_2)$, i.e. a

FIG. 1.—Curve A. Ordinates show the velocity in ft./sec. which must be given per sec. to a volume of air weighing 1000 lb. (in terms of the area over which the volume extends) in order that the reaction against acceleration should be 1000 lb. Curve B. Horse-power required to maintain the stream. Curve C. Radius of a cylinder of the same section area as that of the stream.

smaller force acting at a higher speed on a greater mass.

A somewhat similar case is that of a barge being poled along at a speed v_1 against a resistance R . If the bottom of the canal is hard and the pole does not slip, the bargee walks aft at the speed v_1 and does useful work at the rate v_1R . If, however, the pole slips at the speed v_2 , he has to walk at the rate of $v_1 + v_2$, expending power $R(v_1 + v_2)$, of which Rv_2 is wasted.

For bodies the weight of which is borne by the fluid (such as airships, fish, etc.), the stream emitted by the accelerator is in the direction of the fluid resistance, but for flying machines, birds, and

¹ See Proverbs xxx. 18, and Epistle of James iii. 4.

winged creatures in general, whose weight has to be supported dynamically, the stream must have a downward momentum component Mv_y , giving $d(Mv_y)/dt = W$, while the horizontal component Mv_x makes $d(Mv_x)/dt = R$.

In flying machines, the horizontal component, corresponding to R , is supplied by a screw, and the weight is supported by the inclined surface of the wing. With flying animals, however, the wings have to propel and also to support the body.

Fig. 2 shows diagrammatically the attitude of the wing during one complete beat. The propulsion effect is dependent on the change of wing angle during the up-and-down stroke, and is similar to the

FIG. 2.—Diagram showing the attitude of the wings of a bird during one complete beat.

propulsion in sculling with a single oar. The weight is supported by the downward current induced by the curved wing section.

When a plane surface moves in a fluid, making an angle α with x (the direction of motion), it experiences a resistance R and a lateral force L in a direction y . L/R varies with α and has a maximum value of about 10 when the fluid is air or water. If the wing, instead of being a plane, is suitably curved and convex on the upper surface, the ratio L/R may approach 20. The reason for the approximate doubling of the lift is indicated in Fig. 3. The flow of the stream past the plane surface is as in (a), and past the curved surface as in (b), from which it may be seen that the downward component of momentum is nearly doubled in the latter. I need not here refer to the dynamics of these two forms of flow, on which there has been much discussion.

Birds which soar with their wings stationary make use in general of ascending air currents, though it is possible, as was shown by the late Lord Rayleigh, that when the velocity of the wind is different at different levels, they may soar by passing alternately into strata of quicker and slower wind speeds, provided that the speed gradient is sufficiently steep. I do not know, however, of any observations proving that this method is actually used. Ascending currents are formed in many ways, such as by the ascent of heated air, or by the configuration of the ground or waves on a water surface. With their long experience, birds have probably learnt to make use of any conditions which give the desired result.

Dr. Hankin, in India, made many observations on the soaring of birds, and found that none of the birds on the plains began to soar until the sun had risen for some time, and I myself have noticed that, on a hilly tropical island, soaring does not begin until the sea breeze has been established.

From this it seems probable that ascending currents are the chief agents in soaring flight.

Hovering, that is, keeping the body stationary in still air by the working of the wings, is only found in Nature in small birds and insects. The heaviest bird which I have known to hover is our English kingfisher, but humming-birds are the typical vertebrate hoverers. More striking examples are to be found amongst insects, such as hawk-moths and hover-flies, but the best of all is a dipterous fly (*Bombus*), like a small humble-bee, which when feeding on a flower will insert and withdraw its proboscis as steadily as if it were controlled by a fine adjustment screw.

The kestrel hawk has the power of keeping its position for short intervals with wonderful exactness. This, however, is not true hovering, but merely flying against the

wind at the speed of the wind. In all true hovering the attitude of the body is nearly vertical, and the mean plane of motion of the wings approaches the horizontal.

The limitation of the size of hovering animals is, as may be gathered from Fig. 1, the small power to weight ratio in muscular action. From the diagram also it may be seen how futile it is to attempt to construct hovering machines, using as accelerators screws of size common in aeroplanes.

If inventors or designers could develop a machine which, with 1000 lb. total weight, could carry a 100 h.p. engine with an accelerator of any kind of an effective area of 600 ft. to 1200 ft. (which in the form

FIG. 3.—Flow of fluid (a) past a plane surface placed obliquely in a stream; (b) past a surface plane on the upstream surface but with a convex back.

of a screw would imply a diameter of 40 ft. to 60 ft.), a hovering machine would become a possibility.

There are many examples in Nature of the use of oars and paddles. The chief paddlers are the swimming and diving birds with webbed or partially webbed feet. The general action of paddling is indicated in Fig. 4, which shows the position of the foot and the opening and closing of the toes during one complete stroke. When referred to a fixed point in the body, the foot describes a nearly circular path, and the successive positions of the web are not unlike those of floats in a feathering paddle-wheel.

The contrast between acceleration by paddles and wings may be well observed at the Zoological

Gardens when the diving birds are fed, for the penguin uses its short wings to fly under water, and I think that anyone would give the prize for speed and manœuvring power to the wings.

It is worth noting that these under-water wings, not having to support the weight of the bird (and therefore not having to give a downward component to the fluid on which they act), are nearly plane surfaces, and not, as in the case of air wings, convex on top.

The most familiar examples of the use of natural oars are found in the Dytiscus family and in the water-boatmen (Notonecta). Here one pair of legs greatly exceeds the other in length, and the last joints are bordered by a row of stiff bristles which stand vertically up and down during the backward or propelling stroke, but collapse in a horizontal plane as the leg is moved forward, thus in effect forming an oar which feathers under water.

Another and very curious example is found in the Gyrinidæ beetles. Here the tarsi are expanded into long paddle-shaped blades capable, when not in use, of folding within an enlarged upper joint. See illustrations *a*, *b*, *c* in Fig. 5. I do not know whether these blades are used as oars or as wings, but it would be possible, and certainly interesting, to

Flat fish (soles, etc.) have two modes of progression: one for moving slowly in contact with the ground, the other being kept for quicker travel. In these fish the dorsal and anal fins are greatly developed, extending from head to tail. For slow movement these fins are bent into a waved surface (Fig. 7), the waves, with the water between the fins and the ground, travelling in a backward direction.

When higher speeds are desired the body is raised from the ground and the main series of

FIG. 4.—Diagram showing the action and position of the webbed feet of a swimming bird: (*a*) with reference to a fixed point, (*b*) with reference to the body of the bird.

muscles, which are connected with the spine and ribs, act in the same way as in the upright-swimming fish, but the flexure of the spine is now up and down, instead of from side to side.

Among the rays the ribs are almost wanting, and the whole width of the body is occupied by the greatly developed pectoral fins. The fin-rays are very numerous, and each of these is connected with a muscle rather similar in form to the muscles which in other fish are attached to the ribs.

FIG. 5.—Swimming legs of *Gyrinus*, showing paddle-shaped tarsi (*a*) fully extended, (*b*), (*c*) partly closed.

take moving photographs of their action with the lens focused on the underside of the water surface.

In upright-swimming fish and whales the accelerator is the tail fin or flukes, and to some extent the tail end of the body, the action being that of sculling with a single oar. The greater part bulk and weight of both these classes consists of the muscles working the accelerators. The outstanding difference in the mechanism in Pisces and Cetaceæ is that in the first the muscular action bends the spine into a curve alternating to the right and left, while in the latter similar motions are caused up and down (Fig. 6).

I have had no opportunity to observe the way in which the rays use their pectorals, but it seems likely that it is similar to the action of the dorsal and ventral fins in flat-fish.

Flying-fish when submerged swim as the other upright-swimming fish, and must for a short time at least be able to travel very fast, for I have seen them rise close to the side of a ship going 15 knots and pass ahead at perhaps 4 or 5 knots faster. While in the air the pectoral fins act as glides only, as may be shown by the small size of their muscular attachments, but where the water is smooth they can prolong their flight by sculling with the tail fin,

keeping its lower half in the water, so that the weight is supported by the air and the propulsion given by the sea. It is interesting to notice the increase in the speed of the fish after the tail is immersed.

The steering of ships, especially those with small

FIG. 6.—Showing the position of tail fin of an upright-swimming fish during one complete cycle.

rudders, is not completely explained by the action of the stream on an oblique rudder surface.

The course of an even perfectly symmetrical ship is unstable if not steered, since the centre of fluid pressure is in advance of the centre of inertia. In consequence of this instability, the wake tends to make an angle with the line of the keel, and thus to exert a turning movement on the ship. Even a small rudder, however, is sufficient to determine the direction of the instability, that is, whether the wake shall deviate to port or starboard, and a large part of the efficiency of the helm is dependent on this cause.

The unstable wake gave a great deal of trouble in some of our earlier warships, and there was a class of small gunboats (meant originally, I believe, for service in the Chinese rivers) which were notorious for their erratic steering. There was a story of a captain of the *Excellent* entering Portsmouth Harbour on one of them being hailed by the master of a sailing barge beating out with: "Now, sir, if you will tell me what part of the harbour you want to get to, I'll try to squeeze into the rest."

FIG. 7.—Showing wave-like form given to the dorsal and anal fins of flat-fish when moving slowly.

The manner of the progress of snakes has been much misrepresented. In Prof. Owen's "Anatomy of Vertebrates" there is a figure of a snake in the attitude of a looper caterpillar, like a Greek Ω . It has been said also that a snake 'walks' on the ends of its ribs; also it has been stated that it can, without any curvature of the body, move in a straight course by the ratchet-like action of the large ventral scales.

So far as my own observation goes, a snake on a flat smooth surface is in a very helpless condition, and can only progress by slightly raising the curved body on the right and left sides of the course alternately and straightening the raised portions. The track left by a snake in crossing a dusty road looks like a succession of horse-shoe marks such as are represented in Fig. 8. If there are any projections on the surface—grass, sticks, stones, branches, or in fact anything against which the body can get a 'purchase'—the snake bends itself into a curve to fit one or more of the projections and causes the curve to travel backward along the body,

so that, with reference to the projections, the curve remains stationary and the body passes through the shape (Fig. 9).

The coefficient of friction between the body and the projection is involved in this, and here no doubt the edges of the scales on the under surface are of use in preventing backward slip.

The crawling of molluscs has not, I think, ever been satisfactorily explained, and I can

only contribute two observations which bear on the subject.

(1) Having harnessed a large *Helix aperta* by a silk thread to a spiral spring, I found that it could pull about two and a half times its own weight

FIG. 8.—Track of a snake on a flat dusty surface.

before the foot began to slip on the surface on which it was crawling.

(2) Taking young specimens of the same snail, which are translucent, and examining the foot by transmitted light, it was seen that, so long as the animal was in motion, dark waves were passing in a forward direction through the substance of the extended foot. There were two or three of these waves visible at the same time. Whether they indicate muscular contraction or regulate the secretion of mucus remains to be determined.

That there is some periodicity in the secretion of mucus is proved by the intermittent tracks with which snails mark garden walks, leaving patches of mucus separated by clear ground. The intervals between the marks are very constant so long as the character of the ground does not change.

On dry ground more mucus has to be expended, and where there is dust it is not uncommon to find a snail has died from exhaustion. On a

FIG. 9.—Showing mode of progression of a snake.

dusty road having on one side a drying ditch and on the other a wet one, I once saw the tracks of a number of young *Limax* which had tried to cross. Not one had succeeded. The tracks, in parallel lines a few inches apart, extended from 6 inches to 2 feet over the dust,—a dead snail at the end of each.

Many microscopic forms of life are capable of

moving slowly by the action of cilia. The action of cilia seems to be that each individual hair is capable of extension and retraction as well as of lateral bending, and that in the extended state the extremities are all moving in the same direction, thus causing a flow of fluid over, or giving motion

to, the ciliated surface when in contact with a fixed body, an action which is not unlike that of the fire-bars in an automatic grate.

I know of no explanation of the mechanism by which the cilia are actuated or of the conditions which determine their periodicity.

Nova Pictoris as a Double Star.

A RECENT note in our astronomical column stated that observations in January at La Plata and Johannesburg showed that Nova Pictoris was surrounded by a nebulous ring. About Mar. 26 the La Plata observers noted that the appearance of this ring had altered; they telegraphed to Johannesburg, asking for an examination to be made with the 26-inch refractor; this was done, and revealed the fact that the star appeared double.

A Reuter telegram on Mar. 28 added that the position angle was 70° , the components were about equal in magnitude, that each was nebulous, and that the distance between their centres was half a second. It was added that separation of two stellar points at this distance would have been easy, and that under the actual conditions a darker band could be detected between the nebulous discs. On the other hand, Dr. Spencer Jones, His Majesty's Astronomer at the Cape, in a statement quoted in the *Times* for Mar. 29, gives the distance between the stars as one-fifth of a second. The Johannesburg estimate is probably to be preferred, the telescope there being larger, and the observers having much practice in measuring difficult binaries.

Dr. Spencer Jones adopts the view that the outburst was due to an actual collision of two stars, which have now drawn apart sufficiently to enable them to be seen separately; this is the theory that Mr. Bickerton has advocated for the last forty years, but most astronomers have decided that there are far too many Novæ for this explanation to be tenable in general. It would be expected to happen only once in many million years. Nova Pictoris, however, differed in several respects from the average Nova, so the possibility of a collision need not be immediately dismissed; an opportunity will be afforded to test the suggestion when measures of the pair have been taken for some

months. The rate of angular separation would not be uniform; it would slow down owing to the mutual gravitation of the stars, which would pass each other on hyperbolic paths.

There is, in any case, one important difference from Bickerton's theory; he postulated the formation of a third body between the stars, which would be for some time more luminous than them; but the Johannesburg telegram mentions a darker region in the middle.

Harvard College Bulletin 852, published in November last, quotes Mr. Davidovich's spectroscopic parallax $0.006''$ (giving a distance of 540 light-years) and derives a proper motion of $-0.042''$ in R.A. (great circle) and $-0.018''$ in declination. This is from comparison of old plates with recent ones, both taken with the 24-inch Bruce refractor, the time-interval being 24.2 years. The original magnitude of the star was 13 (absolute magnitude 7); if there were two stars on the old plates, their images would probably be blended. The above motions give position angle 247° , which is very nearly in line with the angle 70° now reported.

The outburst occurred on May 25, 1925, so that the interval up to the detection of duplicity is 2 years 10 months; assuming that the stars were then together, this gives $0.18''$ as the average annual rate of separation; but it would have been much more rapid at first, and would now have sunk to perhaps a third of this, so that a trustworthy measure of the rate cannot be expected for several months.

The occurrence is unprecedented in the history of Novæ, and is of great interest; the similarity of the two stars in magnitude and appearance leaves little doubt that they are at the same distance from us, and that the phenomenon is not to be explained by the motion of the Nova revealing an independent star that previously was hidden in its rays.

Obituary.

MR. E. W. MAUNDER.

THE death of Mr. Edward Walter Maunder on Mar. 21, at seventy-six years of age, will be regretted by astronomers in many parts of the world. Mr. Maunder was for many years a member of the staff of the Royal Observatory, Greenwich, and his appointment indicated the beginning of the change in the character of that establishment that has occurred in the last half-century. In his report, read on June 1, 1872, the Astronomer Royal, Airy, put to the Board of Visitors the proposition that a continued series of observations of the solar

spots, and perhaps some solar spectroscopic work, of which he spoke with less certainty, might fitly be undertaken at Greenwich, though the Observatory would then become *pro tanto* a physical observatory, and hinted that its operations might be extended in that direction in the future. This resulted in the appointment of Maunder as photographic and spectroscopic assistant on Nov. 6, 1873, and in the first half of the following year a spectroscope by Browning was attached to the $12\frac{1}{4}$ -inch equatorially mounted telescope, then known as the Great Equatorial, and a photo-