THE FLIGHT OF BIRDS.—II.*

THE MECHANICS OF A BIRD'S WAY IN THE AIR.

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SO FAR as the author is aware, it was Pettigrew who first pointed out the analogy between the action of a bird's wing and that of the blade of a screw propeller, but he apparently made but little real use of the idea. It appears to the author that a very great deal of that which is essential in the active mode of flight may be learned by the study and development of the screw propeller analogy.

When one watches a moor hen swimming by means of its wings under water, the wings are seen to behave as elastic flaps attached to rigid pillars by their anterior margins, so that as the said pillars move up and down about their articulations as pivots, the elastic flaps act alternately as right and left-handed screw blades, and so propel the bird in a forward direction. It is evident that the wings act equally on both up and down strokes, for the moor hen is of approximately the same specific gravity as water, so that the

FIG. 20.

wings have no weight to sustain, and their action is thus strictly that of propeller blades.

When the bird is employing its wings for flight the conditions are different, for they then serve to sustain as well as to propel. Now, when a screw propeller is mounted on a shaft inclined to the direction of motion, as frequently is the case (Fig. 20) it is easy to show that it also gives a sustaining as well as a propelling reaction, so that the analogy may still hold.

Thus, in Fig. 21, we may suppose in the various diagrams *a*, *b*, *c*, etc., two positions of the propeller blade are given, corresponding to the beginning and end of a short interval of time. In the upper diagram the blade is supposed to be ascending, and in the lower figures descending. Then, the distance *o p* being the motion of translation during the said interval of time, it is evident that in diagram 21*b* the whole of the propulsion will be done by the descending blade, which will experience an upward reaction, while the upward-moving blade will be idle. In diagram 21*a* both ascending and descending blades experience an upward reaction. In diagram 21*c* both blades are assisting in the propulsion, but most work is done by the descending blade, and although the reaction on the ascending blade is downward, it is less than the upward reaction on the descending blade. These three diagrams represent three points, chosen at different distances radially along the blade of a propeller.

If the incline of the shaft be correctly adjusted for the purpose of our analogy, some point along the blade of the propeller will, as in diagram *b*, do the whole of its work on the down stroke. At points nearer the blade extremities there will be a propulsive component on both up and down strokes; at points farther from the blade extremities there will be a continuous but fluctuating sustaining reaction. In all probability the bird's wing is far from being an exact

FIG. 21a.

helical form, as assumed in the propeller analogy. Nevertheless, the main facts, without doubt, apply, i. e., the wings behave as blades of a screw propeller, mounted on an inclined axis.

When one of the smaller birds rises from the ground, and until it has reached its normal velocity of flight, the axis of the equivalent screw must be

* Read before the Birmingham Natural History and Philosophical Society.

regarded as inclined at a greater angle than is ordinarily the case, in fact for the first instant the axis is approximately vertical (Fig. 22). In the case of a pigeon it is often noticed that the wings each swing through a full 180 deg. so that they may sometimes be heard to smite each other with considerable noise. Under these conditions we may closely imitate the motion by means of two single-bladed propellers of opposite hand and rotation (Fig. 23); the blades changing places at the points where the direction of motion and pitch change in the real bird.

We may similarly represent the wings of a bird in full flight by two propellers of say three blades (Fig. 24) in which the blades are supposed to vanish and come into existence again as they pass into and out of the shaded areas.

In reality wing motion is far more complex than might be gathered from these diagrams, and it is difficult even with the beautiful chronographic records of Prof. Marey to make out the complete details. The main observable departure from the simple screw-like motion appears to be that the wing is partially folded or flexed on each up stroke. This action is in all probability one of purely dynamic import; the upward motion of the wing being roughly as represented in Fig. 26, it is evident that the reversal of the wing motion when it reaches the top causes a certain stress on the pectoral muscle, and this is diminished owing to the fact that the inertia is taken up in giving a final flick to the terminal portion of the wing, which expends the energy so received in propulsion, for we

FIG. 21b.

have seen that the terminal portion of the wing is propelling on both up and down strokes. On the up stroke of the wing the part close to the fulcrum is still acting to sustain the load, so that it is actually receiving energy from the aerodynamic reaction. This during the early part of the up stroke is advantageous, as it supplies the necessary upward acceleration, and so relieves the second pectoral muscle.* By the delay in the return of the terminal part of the wing the resistance is, as it were, saved to the last, and so is used to arrest the wing motion as above described.

The reality of the screw-propeller theory of wing motion receives very substantial support in the fact that the general run of the motion, relatively to the bird, Fig. 25, is in a direction that corresponds with the plane of rotation of the hypothetical propeller by which the action of the wing is represented.

The question of the efficiency of wing propulsion is one that has never been adequately dealt with. There is an idea lurking in the minds of many workers that wing propulsion is far more efficient than the best result obtainable with the screw propeller; it is a question whether this view can be substantiated. On the face of it wing action is not liable to the loss of kinetic energy imparted to the fluid by a screw propeller at right angles to the line of flight, since this motion can be imparted in a downward direction, and so serves the purpose of sustentation. We will examine this question more closely.

Let us suppose, Fig. 27, that the mass of the bird or aerodone is suspended from an aerofoil by means of a rope, and as the aerofoil descends in its gliding path, let us suppose that the bird climbs up the rope to maintain its level constant by mechanism of perfect effi-

* This is the muscle by which the wing is elevated.

ciency; we may take it also that the rope and aerofoil are without weight. Then so long as the process can continue the expenditure of energy will be just that done by gravity in ordinary gliding descent; the efficiency is, therefore, 100 per cent. In order to suppose the process continuous we will take it that when

FIG. 21c.

the rope is all absorbed we abandon the aerofoil and create a new one at a convenient altitude with a new rope to climb; it is evident that since neither aerofoil nor rope possesses weight no energy will have been expended in the transformation, and the efficiency will be as before—100 per cent. Now, since we cannot really create a new aerofoil at intervals it is necessary that we should lift the old one up to its initial position after each climb, and the system with a little modification of mechanical detail becomes a system of flying with an aerofoil worked with a parallel motion instead of an angular movement, as in the flight of birds. We will assume, in order to simulate bird flight as closely as possible, that the lifting and descent of the aerofoil occupy two equal periods, and that during its lift the aerofoil slides through the air edgewise with no resistance other than skin friction. Then this skin friction on the aerofoil represents the energy lost.

In Fig. 28 the weight is shown sustained during the up-stroke of one aerofoil by the simultaneous down-stroke of another, the supposition being that the mechanism is duplicated so as to give uniform sustentation. This arrangement would be analogous to that of a bird fitted with two pairs of wings after the manner of a dragon-fly, the motion of the two pairs being presumed to be in opposite phase. The action is not materially affected if only one aerofoil be employed, but in this case the flight path (Fig. 28) will be an undu-

FIG. 22.

lating curve instead of a straight line; during the periods of sustentation the mass center will be in the hollow of an undulation, with intervals of projectile flight, between the said periods as in the leaping or bounding variety of flight.*

It is evident, therefore, that the necessity for returning the aerofoil to its initial position after each working stroke involves a loss of energy equivalent

* "Aerial Flight," vol. i, Aerodynamics, appendix iv.

to doubling the coefficient of skin friction. If the aerofoil were in the first instance designed for least resistance, the author has shown that the skin-frictional resistance will be just half the total resistance; hence unless we readjust the design to suit the new conditions the return stroke uses half as much energy as the working stroke, and the efficiency will be 66.6 per cent. It is evident, however, that for best efficiency the wing area must be altered to continue to comply with the conditions of least resistance, and the new design will be given by employing a coefficient of skin friction double of its actual value. Theory shows that this will give a resistance $\sqrt{2}$ times greater than previously, approximately in the relation 10:7; thus the efficiency will be about 70 per cent.

Now, in the case of wing motion the angular character of the movement renders the problem more complicated, but the author will venture the suggestion that whatever in actual wing motion does not partake of the action of a screw propeller is accounted for as above, and that which does partake of the screw propeller is subject to the loss of efficiency inherent to the screw propeller in its simplicity; hence the efficiency of wing propulsion will lie between the value above obtained and that proper to a well-formed screw propeller.

Now, it is a fact that serves our present purpose exceedingly well that, so far as we have knowledge, the best efficiency obtainable with the screw propeller is approximately the same as obtained above for the reciprocating aerofoil; hence there is every reason to believe that wing propulsion has an efficiency of approximately 70 per cent, and thus possesses no advantage on the score of efficiency over a well-designed screw.

The possibility or otherwise from a physiological point of view of a bird being able to generate suffi-

FIG. 23.

cient power for flight is a ground on which estimates of power expenditure have sometimes been challenged. It must be remembered that birds of over about 1 pound weight have, generally speaking, a very limited capacity for active flight; they principally employ the soaring mode. It must also be remembered that the power varies as L^2 law applies very closely to animal life as well as to machines, and that a direct consequence of this law is that the rate at which an animal can increase its altitude is—other things being equal—inversely proportional to the cube root of its weight.

Let us take the homing pigeon and the horse for purposes of comparison; although the two, considered as machines, are of widely different type, both have been bred carefully as power producers, and the comparison should yield results of the right order.

Assume, as indicated in the present paper, a gliding angle = 1 in 6 and a flight velocity of 54 feet per second; that is to say, the rate of gliding descent will be $54/6 = 9$ feet per second, or, taking the efficiency of wing propulsion as estimated at 70 per cent, this corresponds to an increase of 13 feet per second altitude as representing the work done in flight. Taking the horse as weighing equal to 1,300 pigeons, say (11^3) pigeons, we have the rate at which a horse should be able to increase its altitude $13/11$, or 1.18 feet.

There seems nothing improbable in the above result, for a horse of 1,200 pounds weight it is equivalent to slightly over $2\frac{1}{4}$ horse-power, an output of which such a horse should be capable for quite a considerable time daily. It would thus appear that the limiting size of birds of active habit may be approximately predicted by modern flight theory from the known working capacity of a horse.

There is a variety of active flight practised more particularly by some of the smaller species which the

author has termed "leaping" or "bounding" flight. In this mode the bird may be seen to progress through the air by a series of bounds; close observation shows that the "take-off" consists of a period of active flight, and the leap is a simple parabolic trajectory performed

FIG. 24.

like a projectile with the wings closed. The author has discussed this mode of flight in his "Aerodynamics";* it may be accounted for on the grounds that the bird when exceeding its normal velocity of flight—that for which it is designed—endeavors to approximate to the conditions of least resistance by closing its wings intermittently to obviate skin friction. The faster the bird flies the shorter relatively becomes the active period; this is as theory requires. It is worthy of note that apart from body resistance the energy expended for a given distance will be approximately the same, whether the bird is flying steadily at its normal velocity, or whether it be flying at an accelerated velocity by the leaping method.

It is only the smaller birds that indulge in the leaping mode of flight; it is a very common mode of progression among the wagtail group; the largest exponent of the leaping mode observed by the author is the green woodpecker. The reason for this limitation is the question of size as affecting power development, with which we are already familiar. Thus let us suppose that a given bird be correctly proportioned for flight at, say, 40 miles per hour, and that its maximum sustained power output is just sufficient for flight at this velocity; then in the case of a geometrically similar bird, the law of corresponding speed will give the velocity for which it is correctly proportioned, and this velocity for a bird of half the linear size will be 40 divided by $\sqrt{2}$, or approximately 29 miles per hour. But such a bird will, at this speed, have an enormous surplus of power at command, for it should be capable of lifting itself at twice the rate of the larger bird, and thus of flying at a far greater velocity; hence, although adapted by design for a velocity of only 29 miles per hour, it can, by adopting the leaping mode, attain a much higher speed; in fact, on elementary theoretical grounds at least, it should be thus capable of a speed higher than that of the larger bird. The body resistance probably becomes formidable when the smaller bird flies as fast as the larger, and puts a limit on this conclusion.

Another field in which the horse-power weight factor is of moment is in the capacity of a bird for stationary

FIG. 25.

FIG. 26.

flight, and hand in hand with this the capacity to rise from the ground without a preliminary run; again the advantage obviously rests with the smaller bird, a conclusion that is fully borne out by observation.

There is one kind of flight that must be admitted to be a vexed question. According to observers having a reputation for accuracy, the migrations of birds are carried out at almost incredible velocities, running sometimes into hundreds of miles per hour. It is

quite possible that flights of this kind sometimes occur; but it would be absurd to suppose that the said velocity is that of flight; it rather represents the velocity of some great aerial current on which the bird is borne, and of which the flight velocity of the bird constitutes but a small and unimportant part. If this conclusion is at fault, the phenomenon of migratory flight must be something quite apart from that of flight under normal conditions. The rarefaction of the air at high altitudes may account for some increase in the flight velocity under the conditions of migration, but theory gives the increase on this score as inversely proportional to the square root of the density, an amount which is quite inadequate as an explanation.

THE THEORY OF DYEING.

By S. H. HIGGINS, M.Sc.

PERHAPS there is no part of chemistry concerning which so many speculations have been made, and so few really quantitative experiments carried out, as that portion dealing with the actions taking place during dyeing operations. Many observations have been made and deductions drawn, but yet there is a surprising lack, in this branch of applied chemistry, of the large amount of accurate work which is so characteristic of practically all other branches of chemical science. The art of dyeing is very old, for Pliny observed polygenetic color dyeing and the application of different mordants; nevertheless, we have not progressed very far toward a true explanation of the phenomena observed during the dyeing of textile fibers.

The different theories which have been advanced may be divided into (1) the chemical theory; (2) the solution theory; (3) the mechanical theory. It is true that other theories also exist of the nature of chemico-

FIG. 27.

mechanical, but the above are the definite classes of opinion. The chemist with pardonable pride attempts to explain the process by saying that chemical combination takes place during dyeing, and that the product is mainly the result of chemical action between the fiber and the dye-stuff. He is imbued with the all-embracing nature of his science, and resembles the apostle of electrolytic dissociation who is busy attributing all chemical actions to the whims of those mysteries—the ions.

It is evident from the literature which is issued from time to time that most investigators of the dyeing process support the chemical theory; but it is also noticeable that most of their conclusions are based

FIG. 28.

upon investigations of animal fibers, as silk and wool, whereas the actions taking place during the dyeing of vegetable fibers, as cotton and linen, have been left almost entirely without elucidation. It is maintained that silk and wool are capable of entering into definite chemical reactions with dye-stuffs, but whereas it is realized that cellulose, which is the chief constituent of vegetable fibers, cannot exhibit strong acidic or basic properties, yet the vegetable kingdom is left alone, and broad generalizations are made from experiments on the other fibers mentioned. At the outset it must be recognized that any theory of dyeing must include all classes of dyeing operations.

The solution theory was advanced in 1890 by Witt, and was the attempted application of the solid solution theory of physical chemistry to explain the phenomena observed during dyeing operations. This theory displayed the genius of its author, and afforded plausible explanations of many experiments, but in other respects it was found lacking. Witt drew attention to the fact that wool dyed with magenta was of the same color as a water solution of magenta, and not the dark green color of the magenta crystals. He said that this observation supported his contention that the magenta was dissolved in the wool. It was shown by Von Georgevics, however, that if magenta crystals are only made fine enough they also exhibit the red color of the solution in water. Further, Walker and Appleyard, working with picric acid, made observations which were incomparable with Witt's conclusions, and thus the new theory of dyeing was shaken at its foundation.

The formation of theories is usually left to the greatest minds, to those of a philosophical turn, and it is possible that in this selection long experience

* Appendix iv.