THE THEORY OF THE DUNNE AEROPLANE.*

THIS small addition to the evening's programme has been made possible by the courtesy of Mr. Mervyn O'Gorman, who has cut out a portion of his lecture in order to make room for me. You, as scientific people, will realise that this is just about as generous a thing as a man can do, and I can assure Mr. O'Gorman that I am proportionately grateful.

The title of Mr. O'Gorman's lecture has suggested to me that perhaps after all the simplest and most readily comprehensible way of describing this machine is to present it in its aspect of a combination of a number of stability devices. This lecture will, therefore, be more qualitative than quantitative.

The first person to try the effect of negative wing tips was

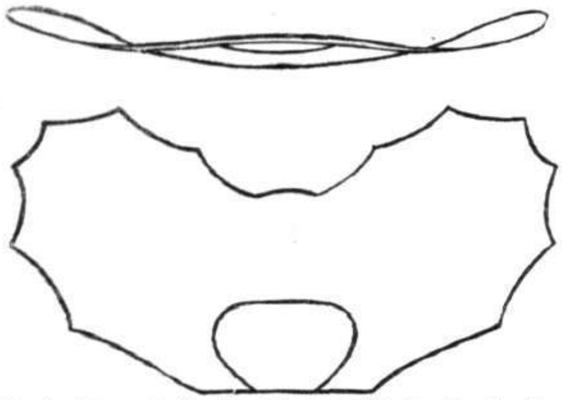


Fig. 1.—Zanonia Leaf. (From *Kritik der Drachenflieger*).

Professor Marey—he tried it on a double sheet of note-paper, weighted as a glider.

The first person to propose the use of backward-sloping wings was Mouillard. In advocating this plan-form he does not appear to have had stability in his mind at all, nor did he propose a permanent slope-back. His object seems to have been simply to provide a means for varying the speed. His apparatus was a man-carrying, motorless affair; the wings, pivotted at the shoulder, being kept pointing forward at slow speeds, and sloped-back at high speeds.

More modern machines which combine the sloped-back wings with the negatively disposed tip differentiate themselves naturally into two distinct classes. In one of these is contained all machines of

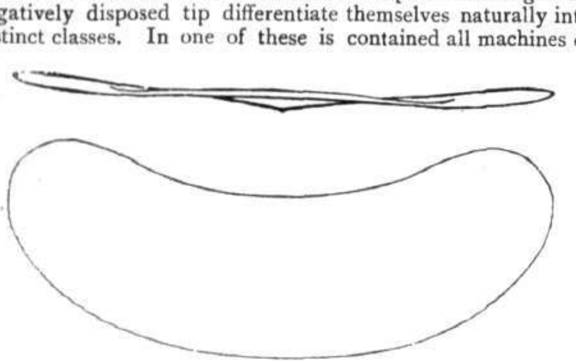


Fig. 2.—Etrich. (From 1905 Patent).

that type which in Austria and Germany is styled "Zanoniaform," the other comprises those types with which I prefer to experiment.

So far as I know, the Zanonia leaf represents Nature's solitary attempt in the Botanical Kingdom at the production of a gliding aerofoil.

Fig. 1 shows a front elevation and plan view of this extraordinary leaf. You will see that the heavy seed-pod is placed right in front of what constitutes the leading edge of this little aeroplane, so as to bring the centre of gravity into the proper position. The wings curve back on either side. As the leaf withers and dries, the tips, which are the rearmost part of the wings, curl up behind so as to present a very marked negative angle of incidence.

Ahlborn of Berlin was the first to draw attention to the gliding qualities of the Zanonia leaf. Various persons have attempted to embody its characteristics in full-size aero-surfaces, Blériot among the number. Herr Etrich has, however, given the greatest amount of time and attention to the study of this division of the retreating-wing machine. Fig. 2 shows a plan and front elevation of the early Etrich glider, taken from the 1905 patent. You will see that he has followed the leaf pretty closely. The cross-sections shown in the patent drawing are nearly identical with those embodied in the Weiss machine; but the Weiss form was more elongated fore and aft, and was, I understand, evolved independently.

Later Etrich added a tail (Fig. 3), and modified his main wings considerably.

Etrich has had many followers, particularly in Germany, and doubtless the names of many machines built on these lines will

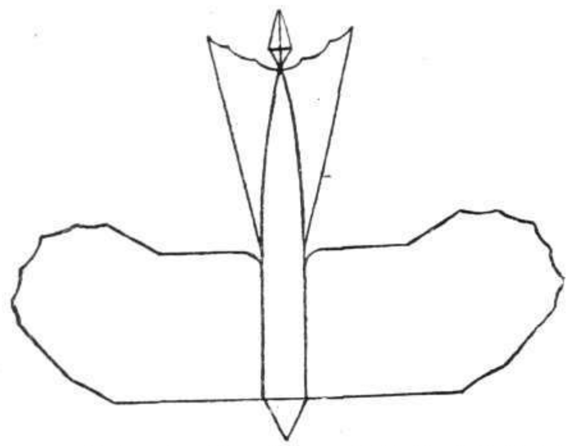
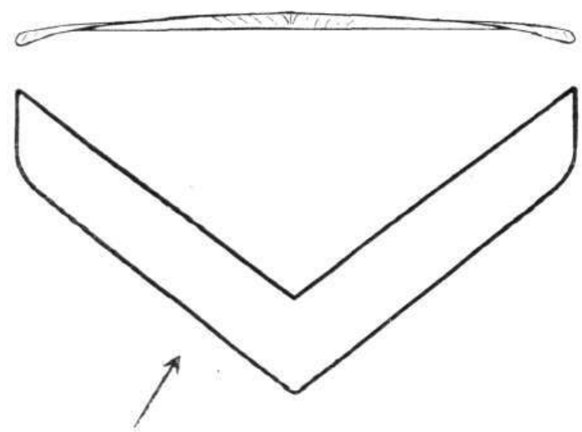


Fig. 3.—Modern Etrich. (From *Kritik der Drachenflieger*).

occur to you, but it is with the general characteristics of sloped-back wings that we have to deal, and this division is best described, as in Germany, as the Zanonia division.

Violently opposed to the Zanonia type in most characteristics are the wing forms in the other division of the retreating-wing, negative-tip group: the division to which I have given most of my attention since 1904.†

It is, perhaps, hardly worth while devoting any of the limited time at our disposal to an elaborate description of the shape and contour of these wings. As you know, I give the wings a much more definite arrow form (*see* Fig. 4) than that of the Zanonia type; the tips are rolled down in front instead of rolled up behind, so that we have a concave under surface instead of a concave upper surface in this region; while the outstanding feature of the type is the fact that the whole wing forms the roof-part of a tunnel running backwards and outwards across the wing, the crown of the tunnel being sloped back at a greater angle than are the wings themselves, and the sides of the tunnel preferably converging towards the rear end. The improvement in efficiency gained by this method of construction is quite extraordinary; but as I wish to confine myself to-night to the safety devices embodied in the wings, I must for the present ask you to take my word for it that this converging tunnel tends to produce a positive pressure under the negative wing-tip, so that for the same amount of negative *pressure* on the tip we are able to use a greater negative *angle* than in the Zanonia type. And it is the geometrical difference between the angle at the tip and the angle at the front of the machine which counts for most, though not for all, in natural stability.



Figs. 4*a* and 4*b*.

* A Communication to the Aeronautical Society of Great Britain, by J. W. Dunne, A.F.Ae.S. (Read at Meeting on January 29th, 1913.)

† My attention having been accidentally directed to fluid flow in diverging, converging, and vena-contracta pipes, it occurred to me that wings built in such forms would give pressure distributions quite different from the ordinary, and also quite different travels of the centre of pressure, and were therefore worthy of investigation. But the stability actually obtained with the first model came as an astounding surprise.

(*To be continued.*)

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(*Continued from page* 914.)

Now the first device with which we have to deal I call the "Vanishing Wing" device.

When a machine, travelling straight ahead, is struck by a side gust, the effect of compounding the air velocity relative to the machine, due to the latter's advance, with that of the side gust, is to produce as an actual resultant a single relative current which arrives from the port or the starboard bow as the case may be. Such a relative current is shown by the arrow in Fig. 4. Imagine yourself looking along that arrow. Obviously you will be looking down the tunnel under the leeward wing and across the tunnel on the windward wing. Fig. 5 is a projection showing the view of

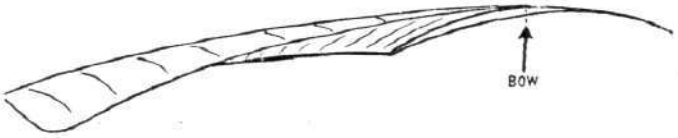

Fig. 5.—Dunne type.

the machine you would obtain. The current is supposed to be blowing straight from your eye towards the picture. Because you are looking down the tunnel at the leeward wing, the outer part of that wing presents in this projection merely a thin line—it practically vanishes.

On the windward wing the situation is reversed. Here you are looking straight across the tunnel, and consequently not only is the amount of wing-surface that is exposed to your view considerable, but also the cambers of the sections along which you are looking are very much deeper than those along which you would look if you viewed the machine from straight ahead.

Obviously the resistance which the windward wing offers to this relative current blowing from your eye to the picture is enormously greater than that offered by the leeward wing. The machine evidently cannot for a moment maintain such an attitude. The windward wing will swing back, and the vanished leeward wing will swing forward, until the machine is facing you, and pointing straight along the air-current. Thus the entire surface forms a great vane, far more powerful, and far quicker acting than anything that could be obtained by the use of a fin at the back of an ordinary

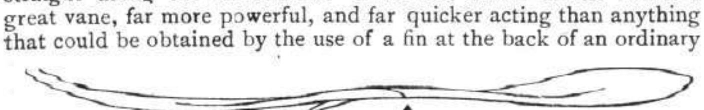

Fig. 6.—Zanonia type.

machine. Obviously sideways motion of more than a moment's duration is impossible; the machine will immediately nose into the new direction of motion. It would take a very violent and very sudden gust indeed to produce even a momentary condition of affairs such as we have pictured. For the instant, the relative wind begins to veer so as to arrive from the port or starboard bow, the machine heads towards it, and brings it back again to the normal straight-ahead condition.

Now turn to Fig. 6. This is a projection of the Zanoniaform showing the same condition of affairs, as regards relative wind, as does Fig. 5. The air-current is blowing straight from your eye to the picture, and striking on the starboard bow of the machine. You will notice that the condition of things in all other respects is completely reversed. Here the upturned windward tip is now in an edge-on position to your eye—that is, to the wind. The upturned leeward tip, which when viewed from the normal front is fore-shortened, now presents its fullest and broadest aspect to your eye—that is, to the current. Evidently the windward wing will advance and the leeward wing will retreat. As a consequence the machine points even more away from the relative wind than before. There is nothing to stop sideways motion; on the contrary, it is encouraged. So we see that with the slightest deviation of the relative current from the exactly-straight-ahead direction, the apparatus will yaw away from it so as to turn broadside-on to it, and if you care to work out the resultants of the normal flight velocity and an accelerating side-component, you will see that the yawing will persist until the apparatus has turned completely round and is heading in the opposite direction.

Now, Nature never persists in the use of a peculiar design unless it pays. Why then does she stick to this obviously erratic-flying Zanoniaform? She should just as easily construct a leaf which would curl after the manner shown in Fig. 4a. The reason is this. Nature's object is to carry the seed as far from the parent tree as possible. The withered leaves are blown off by the first wind that comes along. If they glide down nicely and steadily keeping head to wind, they will evidently land close together somewhere among the roots of the tree. Therefore Nature so designs them that, the instant they commence to glide, they swerve away from the wind, and then glide away down-wind in an erratic, rolling flight which distributes them all over the place and far away from the parent tree.

But now look at one of Nature's designs in a case where effortless balance in high, turbulent winds is her object. Fig. 7 shows the aspect presented by any one of the great sea-birds when viewed slightly from the side as in the other two figures. You will see that the leeward tip vanishes in precisely the same manner as it does in Fig. 5. Once you have noticed this aspect of a sea-bird's wing, it continually forces itself upon your attention.

Fig. 7.—Sea-bird.

So much for the "Vanishing-Wing" device. Its effect, be it remembered, is to increase the drift of the more advanced wing and reduce that of the other. Its object is purely directional.

Now let us look into the longitudinal stability. Here we have, to commence with, the ordinary longitudinal "Vee," with negative pressure on the rearmost part. Beyond that we have three other devices. The principle of the longitudinal "Vee" is well known to all of you, and it is not worth while spending much time on it. Briefly, the arrangement of the centre of gravity, and centre of pressure, is as shown in Fig. 8.

M is the mass, N is the negative pressure, by which I mean down-pressure, L is the lift, and P is the resultant of L and N. Of course in normal conditions L, multiplied by its distance from M, equals N, multiplied by its distance from M. Neglecting for the moment what happens to L, it is evident that if the angle of incidence widens, the down-pressure N decreases to nothing, or even changes to an up-pressure, in either case allowing the back of the system to rise and reduce the angle of incidence to normal. While if the angle of incidence narrows, then the back of the system will get increased negative pressure, pressing it down and increasing the angle of incidence until it is again normal. With flat planes the travel of L is such as to assist this action; with curved surfaces its travel is such as to hinder it. So with curved surfaces the negative tail portion of the system has to be made more powerful in its action in order to compensate for the dangerous movements of L, and, in addition, allow a sufficient margin of righting effect.

A constant-angle-of-incidence-machine such as this is, *ipso facto*, a constant speed machine. For if the speed is accidentally reduced, the machine begins to sink: this increases the angle of incidence; P consequently goes back, which makes the machine dive slightly and thus recover its proper speed. While, if the speed is accidentally increased, the machine rises: this reduces the angle of incidence; P consequently goes forward, which makes the machine elevate and slow down to its proper speed.

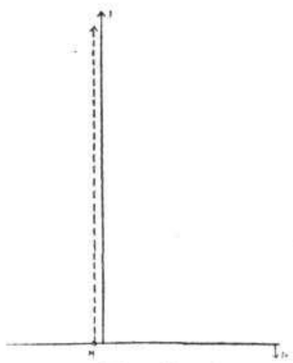

Fig. 8.

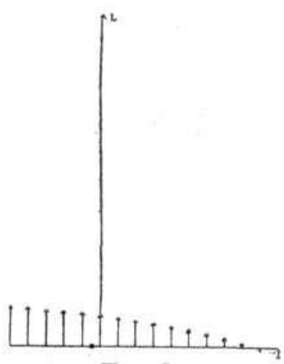

Fig. 9.

Of course all this is ancient history.*

(*To be continued.*)

* My late friend, Captain Ferber, told me that Penaud was the first to explain the stabilising effect of the longitudinal "Vee." But I understand that Penaud acknowledged considerable indebtedness to Sir George Cayley.

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(*Continued from page* 939.)

Now, in the ordinary type of machine the lift pressures are distributed comparatively close to a line running transversely across the machine from tip to tip; hence in such a side-view diagram as Fig. 8 we can take them as all concentrated in the neighbourhood of L, and moving as L moves.

In fact, L may be considered as their resultant.

Now I want you to notice two points.

First: That if we were to increase some, and decrease others, of these forces distributed along this transverse line, we might thereby make L smaller or larger, but we would not necessarily alter its position.

Second: That the stabilising back part of the system is the comparatively very small tail plane. Being of a *fixed area*, its automatic stabilising effect for a given change of angle cannot exceed that of the change in the pressure on that small fixed area.

Now in the machine shown in Figs. 4a and 4b, the lift pressures are not distributed along any transverse line, but along lines sloping back from in front of the centre of gravity to a considerable distance behind it. So that if we draw for this machine a similar diagram to Fig. 8 (see Fig. 9), L becomes the resultant of a number of little L's ranging from in front of M all the way back to N. Again the

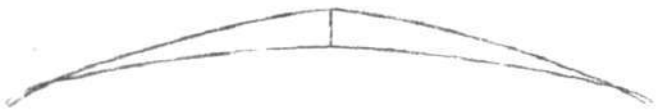

Fig. 10.—Front view, with "nose up."

angle of incidence of the wing decreases gradually towards the negative tips, which tips actually form the negative tail, double in this case. These two points will be made clearer if you look at Fig. 4a, which shows the machine travelling straight towards you. So in Fig. 9 the distributed lifts that go to make up the resultant, L, must be shown smaller and smaller as they go aft, until they change their sign and become negative at N. The forward pressures are, of course, greater than those of an ordinary machine, the rearward pressures less, the average being the same. Now, leaving out

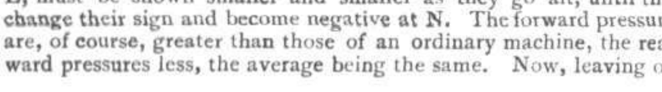

Fig. 11.—Front view, with "nose down."

of consideration for the moment what happens to our negative double tail, it is evident that if the angle of incidence of the whole system increases, those lift pressures which are farther from the bow will increase more rapidly than those which are more forward. This is because the farther back they are the nearer is their angle of incidence to the zero angle. Since the rear pressures grow faster than the forward pressures, the resultant of them all, L, goes back, which is the required direction for righting. If, on the other hand, the angle of incidence decreases, it is evident that the rear pressures die out faster than the forward pressures, and the resultant goes forward. Thus, quite apart from what the negative tail-tips may be doing, *the whole of the lifting part of the surface* is utilised to assist in this manner the righting travel of L.

But besides this, look what happens to the negative tail-tips. Figs. 4a, 10, and 11 show the machine flying straight towards you. The negative part is that part where the upper surface is exposed to the flight line towards your eye. In Fig. 4a the mean angle of incidence is normal. In Fig. 10 it is greater than normal. Notice that not only is the negative part at a less negative angle, as happens with any ordinary negative tail, but also that its area is greatly reduced. In Fig. 11 the mean angle of incidence is less than normal. Note that not only is the angle of the original part of the tail-tips more negative than before, but also that the area of the negative tail is now enormously greater.

Here for a moment we may pause and sum up the advantages we have gained over the ordinary tailed machine with its tail disposed so as to give longitudinal stability. In both cases we have the tendency of the final centre of pressure to travel wrongly owing to the centre of lift on each curved *section* travelling wrongly. Opposing this we have in both cases the changes in the amount of the pressures on the normal tail portion. But in our case we have in addition, assisting the correct travel of the centre of pressure, the change in the proportions of the entire distributed lifts on the backwardly-extending main surfaces, and also the change in the *area* of the negative tail-tips.

This latter effect may become enormous. In the case of a dive at an angle of incidence which in an ordinary machine would be less than zero, and put the whole of the main wings under top-pressure, the front part of our machine would still be lifting, while three-fourths of the entire area would have become negative-pressure tail.

A nose dive is therefore impossible. Moreover, the righting couple is so powerful, even for minute changes of the angle of incidence, that you can safely build the machine with any longitudinal moment of inertia that it is possible for you to obtain under practical conditions of construction.

All this is obtained without the necessity of introducing anything out of the way in the shape of non-lifting tail-tip surfaces in *ordinary normal* flight. For the tail-tips remain a convenient size until they are required to compete with exceptional disturbances. And, being placed at the side of the forward surfaces instead of trailing in the disturbed air behind them, they are more efficient, and so do not detract so much from the general efficiency of the whole system. Note that every single rib of the machine is in the position of a stabilising tail to those diagonally in front of it.

We have considered three separate longitudinal stability devices. These are:—

(1) Change in unit tail pressure. (The ordinary "Vee.")
(2) Change in *diagonal* distribution of lift.
(3) Change in tail area.

There remains yet a fourth, perhaps the most important of all. This is a veritable safety device, quite supererogatory to stability, and perhaps the best name for it is the "reserve tangential" device.

If you look back to Fig. 9, you will notice that I have drawn all the vectors parallel to one another and normal to the supposed plane of the wings. This was for the sake of simplicity in dealing with the device we were investigating at the time. But as a matter of fact

Fig. 12.

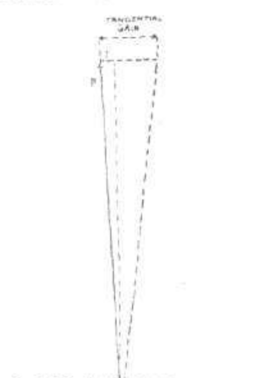

Fig. 14.

every rib of the machine has a different angle of incidence, and the vectors should properly be drawn as in Fig. 12, that is to say, as we work back from the bow the vectors not only become smaller and smaller, but also change gradually from backwardly-inclined attitudes to upright and finally to marked forwardly-inclined attitudes. Since the more forward and more backwardly-inclined

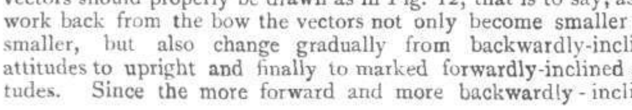

Fig. 13.

vectors are the longer, the resultant of the whole lot, including those which are negative, will be also backwardly-inclined. We may show it as P, and it is obvious that it has a backward component, D.

Now, supposing the machine to be climbing steeply or planing at too flat an angle, so that it begins to lose speed and so lose lift. It then begins to sink, and *ipso facto* increases the angle of incidence. This, as we have seen, is sufficient in any machine with a good longitudinal "Vee" (and especially in this machine) to cause the centre of pressure to move back, tilting the nose downwards so that the machine recovers speed. The flight path due to this action alone would be somewhat as shown by the full line in Fig. 13. The sharp descent (first pancake, and then dive) to recover lost speed might evidently have dangerous results if the ground happened to get in the way. But in our machine the increased angle of incidence produces a secondary effect. We have seen that the vectors towards the rear part of the wing increase at a greater rate than those more forward, thus moving the resultant back. But since these increasing vectors are inclined more forward than those in the more advanced portion of the wing, the resultant, besides travelling back, also takes a decidedly more forward inclination, and becomes somewhat as shown in Fig. 14. Instead of the retarding component, D, of Fig. 12, we now have the propelling component, T, and this is just enough to carry the machine over the crest of the phugoid, and save the steep plunge down the other side. As a result such descent to recover speed as may be necessary is done at a decent easy angle, somewhat as shown by the dotted line in Fig. 13, instead of in a highly dangerous combined pancake and plunge. In brief, this reserve tangential affords an ever-available and entirely automatic means of temporarily increasing the speed in emergencies without the immediate necessity of diving. The effect this has on the smoothness of the flight-path in high winds is quite amazing when first experienced.

One curious result of this reserve tangential—curious, that is, to the spectator—is the ability of the machine to maintain itself under full control at apparently impossibly large angles of incidence.

These four longitudinal devices, utilising as they do the entire aeroplane surface, probably confer the maximum longitudinal stability obtainable, and *prima facie* considerably greater than that which can be obtained by the manipulation of small subsidiary surfaces attached to a main unstable surface. The directional stability also we have seen to be very considerable. Let us now examine the effect of these two properties in a state of affairs where the machine is tilted sideways.*

Since the days when Wilbur Wright first showed us what banking really meant, every student of aeronautics knows the old diagram shown in Fig. 15. Here AB is a front or back view of the tilted plane, P is the air-pressure, G is gravity, and R the resultant of P and G. The force f is the centrifugal force necessary to balance

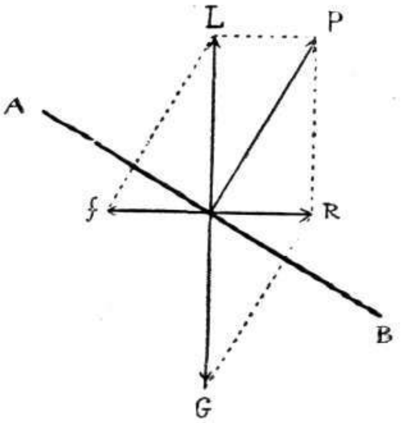

Fig. 15.

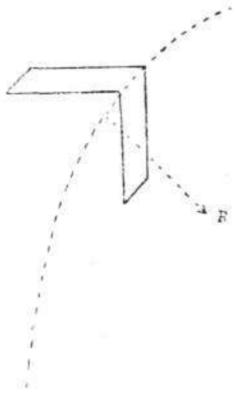
Fig. 17.

R; or, looking at it another way, f and P together have the resultant L which balances gravity. If that force f can be obtained, the system is in equilibrium, and the necessary support against gravity is maintained. Lacking that force, there is neither equilibrium nor a continuity of support, and the machine must fall, *no matter what the reserve of power*. Recovery there may be, due to a magnificent sideslip bringing some fin- or dihedral-angle effect into operation, but our object is to maintain steady equilibrium throughout the flight and adequate support at all times, and we particularly want to avoid these falling, slipping, rolling evolutions. Therefore, the equilibrating centrifugal force f must be obtained at all costs, which is equivalent to saying that the machine must be made to revolve about some such axis as N. (See Fig. 16.)

Now the revolution about the axis N, with radius r, and angular velocity ω, and centrifugal force f, can be resolved into two simultaneous revolutions, one about the axis X with radius r_1, and angular velocity ω_1, and the other about the axis Y, with radius r_{11}, and angular velocity ω_{11}. The centrifugal forces due to these simultaneous revolutions are respectively f_1 and f_{11}, which combined have the resultant f. The revolution about the axis Y is in this case evidently a purely directional manœuvre, due to tail or fin or some equivalent. The revolution about the axis X is a movement of elevation involving a longitudinal manœuvre.

In order, therefore, that the aeroplane shall revolve round N following the path a, a_1, a_{11}, and so produce the requisite force f, it *is necessary that it shall have sufficient directional stability to follow* with its bow the lateral deviation in the trajectory of its mass induced by the lateral component of R (Fig. 15), and sufficient longitudinal stability to follow with its bow the upward deviation in the trajectory of its mass induced by the upward component of R.† The machine under discussion fulfils, as we have seen, both these requirements.

This resolution of the turn into two components is not necessary unless we want to understand in detail exactly what is happening. For a general comprehension of the idea, Mr. Berriman's lucid statement that, granted "weathercock" stability, a machine will follow with its nose any deviation in its trajectory induced by R, is less complicated. But I have shown the full analysis, in order to introduce to aeronautical students this method of resolving banked turns into components in the planes controlled respectively by rudder and elevator. It enables you to see what is actually happening, without the usual necessity of assuming some complicated interchange of the relative functions of these organs.

We have it then established that if the machine be in a tilted position with one wing lower than the other and all controls normal, it will commence to circle towards the depressed side. Fig. 17 shows the aeroplane circling thus, seen from above. I have shown the machine as heading straight into its curved path, and it will presently be obvious that such a position cannot be maintained.

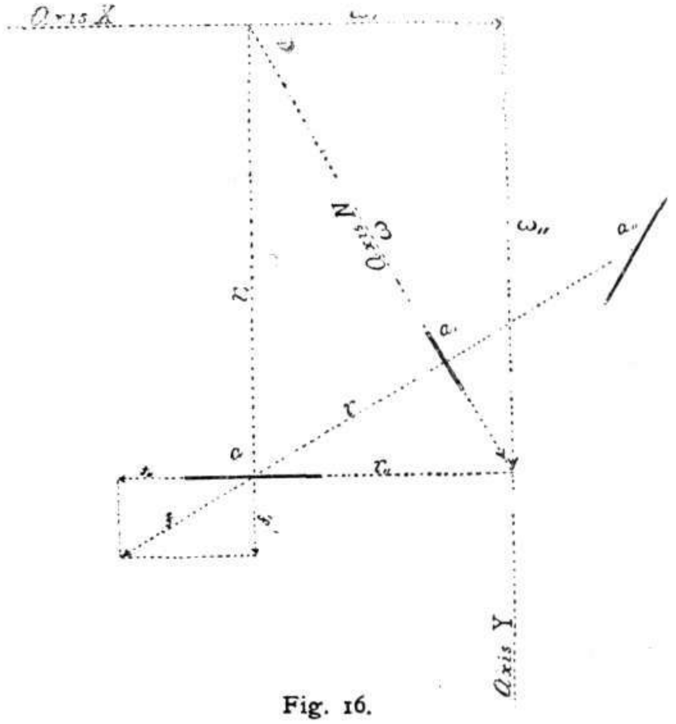

Fig. 16.

In the first place the outer wing in order to keep up would have to travel through a greater arc than the inner wing in the same time, and so overcome greater resistance. Obviously this outer wing will tend to lag behind.

In the second place the outer wing would tend to be depressed, and this for two reasons. First, the pressure increases gradually towards the outer tip, because the arc described by each portion of *the wing increases in length as you travel out towards that tip.* And, as the pressures increase, so are they applied to less and less positively inclined portions of the wing, till at the outer part, where the pressures are greatest, the tip is actually negatively inclined.

Now, in the early days of my experiments, I used to think that this negative inclination of the outer and faster-moving tip was sufficient to account for the fact that the machine—if turned by an ordinary rudder—depressed the outer wing. In this I was wrong. Later quantitative analysis of the positive and negative couples showed at once that, with the small amount of negative surface we use, the counterbanking couples were utterly insufficient to balance the banking couples due to the increased pressures on the lifting parts of the outer wing and the shortage of pressure *on the inner* negative tip. In this I believe I have the support of Mr. Hume Rothery, who calculates that in order to obtain a counterbanking result one would require to have a quarter of the negative surface inclined so as to come under negative pressure. I think it would be impracticable to do this with the class of machine and motor we have at our disposal at present.

But if a practicable negative tip does not produce sufficient counterbanking, we must look for something else in the construction which supplies the deficiency.

* As if, for example, it were deliberately banked over by the use of the ailerons, which were immediately afterwards returned to their normal position.

† *i.e.* It must elevate as the angle of incidence is reduced by this upward deviation.

(*To be concluded.*)

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(*Continued from page 969.*)

Now from long experience with earlier arrangements of surface—as far back as 1904—I had managed to acquire a fairly complete empirical knowledge of the constructional device necessary to complete the turning stability. But this knowledge remained empirical until Professor Bryan supplied me with the proper explanation. He pointed out that an aeroplane travelling round a circle is not only describing a circular path, but is at the same time spinning round its own vertical axis.

The idea is a little complex at first, and one is apt to confuse, as I did, the resultant motion of the tips with the conception we have already taken into account, viz., that the outer tip is merely describing a bigger arc than the inner. But the two phenomena are really totally distinct. This will be evident if we look at Fig. 18. Here the aeroplane is travelling round the centre of the several concentric circles. These concentric circles show, where they meet the leading edges of the wings, the actual relative paths of the air-currents at those places. Because these wing edges slope back across the line joining the centre of gravity to the centre of the circles, and for no other reason, the air-currents impinge on the inner tip from a direction which runs more from inside to outside than does the direction of the air-current in normal straight-ahead flight. That is to say, they are able to strike on the underside of the inclined tip by getting at it from the inside—down the tunnel—and so lift this tip although it is geometrically negatively inclined to the straight-ahead direction. While on the outer tip the currents impinge from a direction which runs more from outside to inside than does the direction of the air-current in straight-ahead flight, if you will look again at Fig. 5 you will see that this means that the surface is more negatively disposed to these currents than it is to those coming from straight-ahead in normal flight, and so is more pressed down than in normal flight. While, with regard to the surfaces ahead of the line joining the centre of gravity to the centre of the circles, the currents on the inner wing impinge in a direction which runs more from outside to inside that the normal, and another glance at Fig. 5 shows us that the positive surface we find here opposes to them a deeper camber than it does to normal straight-ahead currents. The reverse obtains where the outer forward surfaces are concerned. Thus, again, the inner wing gets more lift and the outer wing less than in normal flight.

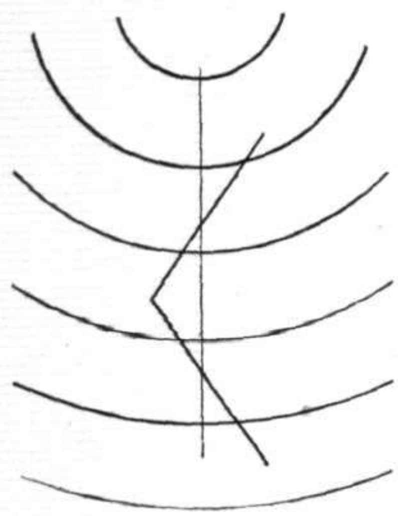

Fig. 18.

With a wing edge set parallel to the line joining the centre of gravity to the centre of the circles, this phenomenon would obviously not occur. With a "Zanonia" leaf form the lifting and depressing effects would be reversed, tending to increase banking instead of checking it, which, I imagine, is why the "Zanonia" form seems to do better in practice when the slope back of the wings is comparatively slight.

Now add to the effect we have just examined the fact that the outer tip is travelling faster than any other part of the machine, and we have ample explanation of the fact that this machine counterbanks when turned by an ordinary rudder.

Now we can get back to Fig. 17. We have ascertained that the tilted aeroplane cannot maintain the position shown, but that, if left to itself, the outer wing will sink towards its normal level, the centripetal force R diminishing towards zero as this occurs. Meanwhile, as we saw before, this wing also tends to hang back, and the inner wing to set itself forward. The machine is striving towards a position of equilibrium for that particular radius of turn, but never reaches it, because as it swings outward and levels up so does the turning radius increase and the centripetal force diminish. Equilibrium is only attained when the radius is once more infinity and the machine is travelling straight ahead on a level keel.

It follows that no matter how narrow or steeply banked the turn, the aeroplane is always striving to reduce the bank and at the same time widen the turn. As a matter of fact, I find in practice that if, as we are supposing, the original tilt had been given by the action of the *ailerons*, the machine levels up just about as fast as you can return those *ailerons* to their normal position.

It is, therefore, impossible for the turn to develop into a spiral dive. Again, no matter how steep the bank, the machine will always turn so as to produce sufficient centrifugal force to give support against gravity. A sideslip is, therefore, impossible, even without calling to our aid the various devices I shall explain later when we come to deal with the purely lateral stability.

Now instead of allowing the tilted machine to spring back level, we can, by means of *ailerons*, ease the lifting and forward-thrusting pressure on the inner extremity by letting the back edge of that part fly up, and reduce the downward and backward-thrusting pressure on the outer extremity by letting the back edge of that extremity drop. In this position we have turning equilibrium. An examination of Fig. 18 will render it evident that if a gust turns the nose of the machine inward, so as to narrow the circle, we shall immediately get an increased counterbanking effect and increased resistance on the outer wing; while, if the nose be turned outward, we shall get the reverse effect. By modifying the geometrical angle of the tips, we have made the radius of turn where the machine can attain equilibrium less than infinity. If we continue to raise the inner back edge and lower the outer back edge, so as to get a definite banking and inward-turning couple, the machine will bank and turn in response until the narrowed circle again brings sufficient counterbanking effect into action to neutralise the new setting of the *ailerons*.

You will perceive from this that, in order to commence a turn, we have to put definite negative pressure on the inner *aileron* and positive pressure on the outer, but that the machine then sets itself to such a position, and turns at such a radius, that the pressure on the *ailerons* is practically nothing, as in normal flight. Throughout the steepest banks and turns, and indeed throughout every manœuvre with this machine, the *ailerons* remain almost exactly balanced; and it is only when one wants to change position *suddenly* that one has to put any realisable pressure on the levers. As a result the machine is probably the most sensitive to control in existence.

Now for the LATERAL STABILITY.

It will be obvious, from what has gone before, that we start out to tackle this problem under unusually pleasant conditions, for we have to begin with the comfortable assurance that it does not really matter to what angle the machine gets blown over—it cannot lose equilibrium, and side-slips and spiral dives are impossible. So far, therefore, as *safety* is concerned, the lateral problem has been adequately dealt with. All that we have to do is to devise some means of ensuring lateral *steadiness*.

Lateral stability devices as a rule consist of combinations of dihedral or kathedral angles or their equivalent fins. A dihedral angle exists where the wings are flexed so as to slope away from the air current; a kathedral where they slope towards that current.

A kathedral angle is dangerous because its action becomes more powerful as it yields to the gust, and so, if it is strong enough to rotate the machine at all, it may roll it clean over. This will be apparent if you look at Fig. 19, which shows a front or back view of a kathedral wing. Obviously the wing will not arrive at a position of equilibrium to the wind represented by the arrow until it has rolled completely over to the position indicated by the dotted lines, the direction of rotation being shown by the curved arrow. A dihedral angle, on the other hand, begins to lose its power the moment it yields, and reaches a position of equilibrium with a comparatively small rotation. Fig. 20 shows such a wing, and it can be seen that a rotation of a few degrees in the direction of the curved arrow will bring it to a position of equilibrium.

Now we use to commence with a dihedral angle which tends to roll the machine towards the windward side. This statement sounds absurd, so we must explain that it is a *negative* dihedral angle. To understand what I mean by this, turn to Fig. 21. It shows a front or back view of a surface which is under negative pressure—that is to say, the wind strikes it from above. If then this wind has a lateral component, as has the arrow representing the wind in the diagram, the surface will roll a few degrees in the direction of the curved arrow, and attain the position of equilibrium shown by the dotted lines. Comparing Fig. 21 with Fig. 19, we see that there is a very considerable difference between a positive kathedral and a negative dihedral, even though both cause rotation in the same direction.

This negative dihedral has all the stabilising properties of the positive dihedral, but operates in the opposite direction. If you will look back to Fig. 4a, you will seethe angle in question is formed by the negative tips of the machine.*

(*To be concluded.*)

* The tips of the "Zanonia" leaf form a negative kathedral, which rolls the leaf the same way as does a positive dihedral, but lacks the stability of the latter.

THE THEORY OF THE DUNNE AEROPLANE.

(*Concluded from page* 994.)

Now opposed to this we have at the front of the machine a very slight positive dihedral effect, due to the coning of the wings making it easier for the air to get away outwards than inwards, and also to the fact that the windward wing opposes a deeper camber to the current than does the leeward wing.

Each of these opposing devices being dihedral, and so—even if unopposed by the other—tending to take up a position of equilibrium, it is not of very great import whether they exactly balance each other or only nearly so. But what is of importance is that since each is strongly resisting the action of the other it effectually damps out any oscillations that other might tend to produce.

We have, however, found no difficulty in so balancing the opposing couples that ordinary side gusts, such as one encounters when flying in moderate winds, produce absolutely no perceptible lateral disturbance.

But side gusts unfortunately are not always steady. We have to deal with fierce gusts, irregular gusts, gusts with an upward trend or a downward trend, local side-puffs striking one portion of the wing and not the other, and narrow-diametered *remous*.

Now we noticed while dealing with the longitudinal stability, that the amount of negative surface exposed depends upon the angle of incidence. If you look again at Figs. 4a, 10 and 11, you will note that there are two points in the span where the leading edges cross the back edges. Inside these points the wings are positive, and would lift the windward side. Outside these points they are negative, and would depress the windward side on account of their negative dihedral effect. You will see that as the mean angle of incidence of the machine grows smaller, these points, where the edges cross, move inwards, increasing the negative dihedral surface and decreasing the positive surface.

You will also note that at normal flight angles the negative dihedral surface is very small. To carry a lot of unnecessary negative surface until you actually needed it would be a source of inefficiency. Our negative dihedral surface develops as it is required. Thus, if, after viewing the machine from in front, you were to step to the right or left, you would notice that as you move round, so does the point on the wing nearest you, where the leading and trailing edges appear to cross, travel more forward towards the bow. For example see Fig. 5, which shows the aspect presented to an unusually strong and sudden side gust, and note that a very large portion of the near wing has become negative, the far wing having practically "vanished."

Now look again at Fig. 4a. If the side gust affects the distribution of pressure on the wings in such a way as to render the negative dihedral couple (*i.e.*, the windward-rocking couple) too powerful: which is equivalent to saying that the negative pressures, in the region of the negative tail tips, are augmented more than those on the positive surfaces: the effect will obviously be not only to roll the machine to windward, but also to *elevate* it.

But elevating the front has, as we have seen, the effect of reducing the amount of the negative (windward-rolling) surface and increasing the amount of the positive (leeward-rolling) surface. Thus the windward roll started by the unevenly distributed gust is almost instantly checked.

Conversely, if the gust accentuates the effect of the leeward-rolling couple, which is equivalent to saying that the positive pressures are augmented, the effect will be not only to roll the machine to leeward, but also to depress the bow—for the centre of positive pressure is behind the centre of gravity. Depressing the bow, as we have seen, increases the amount of the windward-rolling negative surface, and decreases the amount of the leeward-rolling positive surface.

Flying this machine in very "bumpy" air, or side-on to a thoroughly bad wind, one notices little sudden movements, gently checking themselves, about axes which run, roughly speaking, parallel to the backward-sloping wings.

And so we come to our final device. Part of this I have explained so often that I think everyone here must understand it pretty thoroughly; so I will merely point out once more, as briefly as possible, that when the wind strikes this machine somewhat on the side as shown by the arrow in Fig. 4b, the windward wing meets that wind with its broadest side towards it, and the leeward wing meets it in the end-on position.

Now everyone knows that Langley proved experimentally that if you expose two long narrow planes at a small angle of incidence to the wind, the one broadside-on with its longer edge forward and the other end-on with its shorter side forward, the former will experience the greater pressure. Let us refer to this superiority of the broadside-on plane as "Aspect-Ratio Effect."

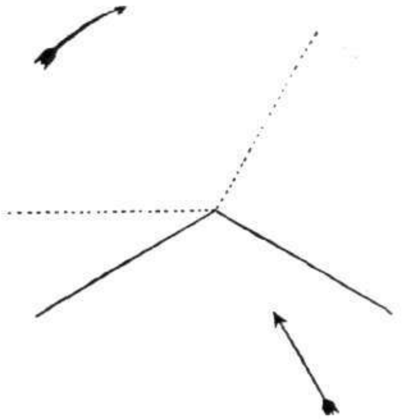

Fig. 19.

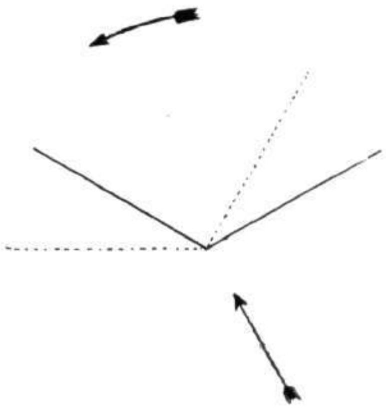

Fig. 20.

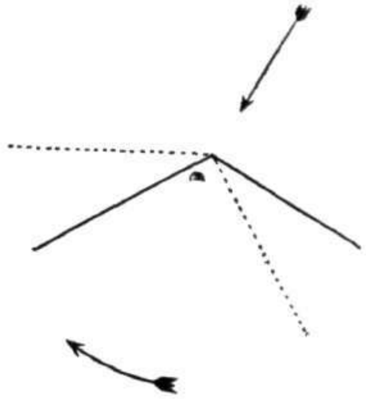

Fig. 21.

Now, curiously enough, hardly anyone seems to have noticed as anything worth remarking, that the experiments showed further that as the angles of incidence are gradually increased, this disproportion in pressure rapidly diminishes, till, when the angles are thirty degrees, the pressures are equal, while beyond that angle the conditions are actually reversed and the pressure on the end-on surface becomes the greater.

So in such a condition of affairs as is depicted in Fig. 4b, the pressures, negative as well as positive, all over the right wing are greater than those on the left wing. Now, if the machine rotates to leeward, the angle of incidence of the positive (leeward-rolling) portion is increased, and so the aspect ratio effect of that part is diminished. But the negative angle of incidence of the negative (windward-rolling) portion is *decreased*, and so the aspect ratio effect on that portion is augmented. Exactly the converse occurs if the machine is rotated to windward by an over-powerful negative dihedral couple.

This damping and stabilising action has to be regarded as superposed upon the various lateral stabilising effects we have already considered, which is, perhaps, a rather complicated idea to absorb.

Under ordinary conditions of flight its action is but slight, and is in general a damping one. It renders the effect of the alteration in the relative proportions of positive and negative surface due to change of mean angle of incidence less sudden in its action, while it adds to the damping effect the opposing dihedrals have on one another.

But its great value lies in this: that apparently no matter how sudden, violent, and unevenly applied be the gust, you cannot possibly be blown over either way to much beyond 30 degrees. I say "apparently," because I have not yet flown the machine in the hurricane which would be necessary to put this quality to actual test, and indeed I find that in this case I have quite a strong conviction that theory is preferable to practice.

To sum up. We have:—

FOR LATERAL SAFETY.—

(*a*) The fact that no matter how the machine be banked, it will automatically supply sufficient centrifugal force to keep up the support against side-slip.

(*b*) The fact that, owing to its tendency to level up from any bank and widen out any turn, it cannot spiral dive.