EXPERIMENTAL DATA WITHOUT A WIND CHANNEL

Paper read by Major O. T. Gnosspelius, A.C.G.I., A.F.R.Ae.S., Honours Member, at a meeting of the Institution held at the Engineers' Club, W.1., on December 12th, 1922. Mr. H. B. Molesworth in the Chair.

MAJOR GNOSSPELIUS said :—

In the year 1920 it became evident to me that it was very necessary, if improvements in existing aeroplanes were to be made, to increase our knowledge of the aerodynamic forces by means of which we fly, and in order to do this it became necessary to measure these forces oneself.

In discussing this question with Mr. Jones, the very able chief draughtsman of Messrs. Short Brothers, Ltd., he brought to my notice an article in "Aeronautics," of November, 1911, where the writer, Mr. Ellis Williams, B.Sc., describes a method of measuring these forces by means of swinging models of the desired shape on the end of a pendulum. This seemed a hopeful method and at any rate well within the means at my disposal, which consisted of labour and material which I could acquire in the works.

The first rough experimental pendulum was constructed of a piece of wood about 2 ins. by 1½ ins. cross section and about 11 ft. long, suitably pivoted. With this we found it was possible to measure lift and drag forces, but the speeds attained were very low: it was necessary to increase the speed. We then constructed a pendulum about 20 ft. long to swing in the large shop; this gave higher speeds, the pendulum being dropped from the horizontal plane, but we found that air currents and flexibility made the movements too erratic to be of any use for measurements.

We then decided that we must work in a lower, more sheltered shop with a shorter pendulum, and increase the speed by other methods. It was evident that the method of dropping from the horizontal was practical, and it appeared that by raising the centre of gravity of the pendulum to the highest possible point the time of swing would be decreased and the velocity at the bottom of swing increased.

It must be understood that the method adopted in nearly all these experiments was to hold the model so that the plane of flight was in the plane of the

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pendulum, lift being measured by the horizontal deflection of the pendulum at the lowest point of swing, and drag by the length of swing of the pendulum.

The section of the pendulum arm must be cylindrical in order to avoid effects on lift readings due to the pendulum not travelling in a plane path. The pendulum arm was therefore constructed of tube.

For high speeds it is necessary to keep the centre of gravity of the pendulum high, the lower part of the pendulum must therefore be light, and we constructed it of duralumin tube of $1\frac{1}{4}$ ins. diameter, extending for about two-thirds of the length of the pendulum. The top third was a steel tube of $1\frac{3}{8}$ ins. diameter telescoping over the duralumin tube. The pivot originally was constructed with two bearings at right angles, one allowing for the normal swing of the pendulum and the other allowing for lateral deflection for lift readings. We found, however, that, with this second pivot, the deflections for lift were much too great for practical purposes; we therefore fixed this pivot, the lateral deflections of the tube under the lift forces being quite sufficient for measurement. These deflections are of the order of 3 ins. for maximum lift on normal 18-in. by 3-in. sections.

The force causing the deflection can be found with great ease by direct calibration of deflections against known loads.

To obtain high speeds we loaded the pendulum by casting a lead weight of about 35 lbs. round the top tube as near the pivot as possible. With this combination and a normal weight model we were able to obtain a speed of from 45 to 50 ft. sec. at the bottom of the swing depending on the weight of the model.

The drag forces are measured by the height of swing of the pendulum at the end of the first swing. Attempts were first made to observe this value by recording a trace of the end of the swing by a marking mechanism on the pendulum, but it was found that, as this measurement was required with great accuracy, and the drag forces are very small, the varying frictional forces of the marking mechanism were sufficient to affect seriously the drag measurements. This method was therefore abandoned in favour of a hit-or-miss method, where a pin inserted in a scale was either knocked out or left untouched by the pendulum. With several swings of the pendulum we found that the top of the swing could be located to at least 1-16 in., which gave very fair accuracy in these measurements.

Lift forces are converted into absolute co-efficients by calculating the maximum speed of the pendulum as given in the addendum.

Drag forces are calculated from an integration of the speed of the pendulum throughout the swing. The mathematical solution of this problem is also in the addendum.

Initial Drag.—It is obvious that the length of swing of the pendulum is a measure of the combined drag of the model and pendulum. It is now necessary to subtract the resistance of the pendulum. To do this in principle it is only necessary to detach the model and replace it by a mass equal to that of the model, with its centre of gravity on the same radius of swing as that of the model. This

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mass must offer no air resistance. The height of swing of the pendulum must then be observed.

This problem developed the method of holding the model in a frame, as shown in Figure 2. The frame is tubular, and the mass takes the form of lead weights inserted in the arms of the frame. After a time all models were tested in this way on account of observations when pressure plotting, which indicated that air-flow at the ends was affected by end support.

The angle of the model is measured from a protractor fitted on a stand under the vertical position of the pendulum.

A light arm carrying a recording pencil is mounted crossways on the bottom of the pendulum. This records lift on a piece of paper held on a suitable frame to the side of the path of the pendulum.

ADVANTAGES OF METHOD.—The air through which the model passes is still, and there can be no question of turbulence or steady flow.

Wall effect, which may be great in an ordinary wind tunnel, is greatly reduced.

The cost of running the apparatus is very small.

The apparatus is cheap and the power required is one-man power.

The accuracy of the measurement appears high. Repeat experiments usually agree to about 1 per cent.

DISADVANTAGES OF METHOD.—The motion is not steady, but accelerated.

The motion is not rectalinear.

These two facts may cause the apparatus to give erroneous results, but it should be observed that when tests are made on forms tested by the N.P.L. the results are in very fair agreement.

Only on some thick sections the results are not the same; on the other hand, Handley-Page effects are very obvious

DESCRIPTION OF METHOD OF CARRYING OUT TEST.—The model is placed on the frame and run at varying angles for lift, the usual increments of angle are by 2.

The model is then set at O° Incidence and run for initial drag. The model is then removed and replaced by weights, and the pendulum drag measured. The model is then replaced and the weights removed to check for initial drag, and if any discrepancy is noted the experiment is repeated. This test for initial drag is most important, and should be carried out with the greatest care. The model is then run through at varying angles for drag measurements.

PRESSURE PLOTTING.—This can be carried out satisfactorily on this apparatus.

When the necessary holes and passages have been made in the model they must be connected to a small tube carried up the pendulum. This tube is coupled up by means of a thin, flexible rubber pipe to a small inclined U tube filled with alcohol. If the tube is small the necessary mass of alcohol is reduced, and the inertia effect of this mass also reduced. The pendulum is swung in the ordinary way and the motion of the alcohol noted. With practice this can be read to 1-100 in., with a possible error of + 1-100 in.

A correction has to be applied for the centrifugal force of the air in the tube down the pendulum. When this correction is applied the results are in agreement with those obtained at the N.P.L. on the same section. The work is a

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little tedious, but a section can be plotted in one day and invaluable results obtained.

These results show our want of a satisfactory theory. Progressive modifications of form do not produce the expected alterations of pressure, and no general conclusions can so far be stated.

MOVEMENTS OF CENTRE OF PRESSURE.—So far no attempt has been made to measure this quantity, as time and money has not permitted, but it does not seem impossible to devise an apparatus to carry out this work if necessary.

FURTHER POSSIBILITIES.—With the pendulum it is possible to observe to a certain extent the effect produced on the air by the passage of any body under test through it. For this it is necessary to create a smoke cloud and swing the model through it.

Wing-tip vortices, first, I think, suggested by Lanchester and later developed by Prandtl, can be observed. These vortices exist, but appear to be not quite as assumed by theory.

The vortex is non-existent at the angle of no lift, and increases in size and probably in velocity up to the burble point, where the motion changes. With square-ended planes the centre of the vortex occurs on the line of the wing tips, but apparently below it. As far as can be observed the whole of the rotational effect is below the wing.

With tapered wing tips the centre of the vortex comes in nearer the centre of the model, approximately 1-6th of the span, and the vortex obviously increases in size and apparently decreases in speed of rotation.

With a bi-plane two vortices are formed which rotate separately and finally round one another; here the vortices appear smaller.

The vortices persist for a long period after the passage of the model. They have been observed for 800 or 900-chord lengths.

FURTHER SMOKE OBSERVATIONS.—When a model passes through the air a distinct kick is given to the air at considerable distances from the model; this is especially noticeable on the upper side, where the effect is visible up to 8 ft. from the model. What the nature of the kick is is not clear, but it looks like the first swing of a very heavily damped vibration This may have a bearing on tunnel-wall effect.

Finally I should like to try and impress on you gentlemen the effects which making experiments such as these have on anyone who undertakes them.

They were started with the dim idea of learning a little more of the dynamic forces with which we are dealing. Gradually I became impressed with the fact that usually accepted theories break down when one attempts to explain by their means observed facts; any systematic series of experiments will give in the end contradictory results. It therefore seems that modifications of our present theories are necessary, but, so far, what these modifications are, I do not know. The quantity $\frac{vl}{y}$ appears to be one of the most doubtful, and when the reasons for the adoption of this expression are studied it appears founded on rather a doubtful base.

The method of dimensions, whilst no doubt excellent for checking an equation obtained from other reasoning to see if it is the right shape, seems

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hardly satisfactory when applied to the construction of an equation. If in the construction of this equation the resistance depends also on other quantities beyond the three quantities v, l and y, the whole reasoning breaks down.

The very idea of viscosity seems rather out of agreement with observed facts.

This is, of course, theoretical and very interesting, and correct assumptions would help us to progress, but, if you turn to the practical side, the experiments, whilst no doubt exasperating on account of the apparently illogical results obtained, are intensely interesting as they continue to indicate more and more strongly the possibilities of increasing the aerodynamic efficiency, gliding angle or L/D ratio of the forms which we use. Gliding angles of 1 in 18 are certainly attainable, and I am convinced from experimental evidence that gliding angles of 1 in 50 or even more can also be attained if you treat the air correctly. Let us look a little into the past.

A flat plate has a gliding angle of 6.3 to 1. Lilienthal found that a curved surface gave better results, and a curved plate of 6 to 1 aspect ratio gives us a gliding angle of about $10\frac{1}{2}$ to 1.

Further experiments have improved this figure with a standard 6 to 1 aspect ratio to approximately 18 to 1.

Slightly higher figures have been attained, but I give a conservative figure, and it is to be noted that sections of considerable thickness give superior figures to very thin sections. These are figures for wind alone: the general theory is that by adding a body you must add resistance: I have doubts on this point; there is certain evidence that the opposite is true and I have produced a model with a body and tail which, as far as I can measure, on many occasions has as good a gliding angle as any standard wing I have so far tested.

That you can go much further I am firmly convinced. What has Mr. Handley Page done? He has made a few rough feathers and put them what Nature considers the wrong way about, and at once he multiplies his lift forces by about 3; unfortunately at the same time he has multiplied his drag forces by a figure nearer 9, so the gliding angle becomes extremely bad and the phenomenon becomes of less practical use.

Does this not indicate that if we do the right thing we can probably reduce our drag forces—the really important point.

One thing is obvious: to achieve this we must not copy that which has been done before, by doing that we can only obtain the same results as attained before. We must have a little imagination, and as we have at present no theory to help us, the only help we can gain is from the study of that very wonderful structure the wing of a bird, as I for one am convinced that these creatures have an extraordinary fine gliding angle. This structure has one outstanding point of interest: the wing has no back spar and the front spar is practically the leading edge. It seems doubtful if nature really prefers a structure carrying a heavy unnecessary torque to the simple expedient of moving the spar back and, if there is no torque on the bird's wing spars, slight study of pressure diagrams shows that this must mean that the centre of pressure is much further forward than we achieve.

To my mind it seems probable that in some way the bird has no reversal of travel of centre of pressure such as we experience, and this obviously must mean a great improvement in gliding angle.

As the field open for experiment is so vast and progress must be rather slow, what I would like to see is for all you gentlemen to go away and start measuring these forces for yourselves. It is not necessary to copy the actual method I have described; there are plenty of other possibilities; only think the thing out for yourselves and experiment; being aeronautical engineers, I know you are not without ingenuity, and remember that the aeroplane cannot become the great universal method of transport we all hope for until we make it less wasteful of power, which means improvement of gliding angle. At present aeroplanes are not economic; they cost too much.

I do not wish to conclude, gentlemen, without recording my very deep thanks to my two assistants in this work, Messrs. A. Gouge and W. Falkoner; the former has made the mathematical part of the work possible, as my mathematical knowledge, at no time deep, has become very rusty. He also has very great aptitude for devising apparatus for fine measurements out of the crudest materials. The latter has developed great dexterity in making models to a very high degree of accuracy.

APPENDIX.

Mathematical Analysis of Lift and Drag Forces from Pendulum Observations.

The Drag Force measurement.

Assuming the pendulum to move in one plane and that the resistance varies as the (velocity)^2

Then the equation of motion is—

$$\frac{d^2\theta}{dt^2} = -\frac{mgh}{I}\sin\theta_1 + \frac{K}{I}\left(\frac{d\theta}{dt}\right)^2. \qquad \text{.........(1)}$$

where K is made up of two parts A for the pendulum itself and Bl for the model.

To find the first integral of (1)

$$\text{Let } \frac{d\theta}{dt} = V \text{ then } \frac{d^2\theta}{dt^2} = V\frac{dV}{d\theta}$$

$$\text{Then (1) may be written } 2V\frac{dV}{d\theta} - \alpha V^2 = -\mu\sin\theta \qquad \text{.........(2)}$$

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where $\alpha = \frac{2K}{I}$ and $\mu = \frac{2mgh}{I}$

Integrating (2) we have $V^2 = \frac{\mu}{1+d^2}\left\{\alpha \sin\theta + \cos\theta - ce^{\alpha\theta}\right\}$

$$\frac{d\theta}{dt} = O \text{ when } \theta = \frac{\pi}{2} \therefore O = \alpha - ce^{\alpha\pi/2}$$

$$\therefore c = \alpha e^{-d\pi/2}$$

$$\therefore \left(\frac{d\theta}{dt}\right)^2 = \frac{\mu}{1+d^2}\left\{\alpha \sin\theta + \cos\theta - \alpha e^{-\alpha(\pi/2-\theta)}\right\} \quad \text{.........(3)}$$

This is the expression giving the velocity of the pendulum in terms of θ.

Given the final angle θ_1 of the pendulum α can be calculated for when $\theta=\theta_1$

$$\theta = \theta_1 \; \frac{d\theta}{dt} = O$$

$$\therefore \alpha \sin\theta_1 + \cos\theta_1 = \alpha e^{-\alpha(\pi/2 - \theta_1)} \quad \text{........(4)}$$

Values of α for various final angles θ_1 have been calculated

$\theta_1 = -90°$	$\alpha = .0$
,, = −85°	,, = .0469
,, = −82.5°	,, = .0727
,, = −80°	,, = .1005
,, = −77.5°	,, = .1304
,, = −75°	,, = .1626
,, = −72.5°	,, = .1971
,, = −68°	,, = .2662
,, = −65°	,, = .3179

Let

mh = first moment of pendulum about the axis in ft. lbs.
g = acceleration due to gravity.
l = distance of centre of model to axis in feet.
p = density of aid in lbs. per cubic foot.
A = area of model in square feet.
T = time of a small oscillation of the pendulum and model in sec.

The values of α having been found for a particular model at the various angles of incidence, the value of α for the pendulum alone must be found before the actual resistance of the model can be calculated.

It is essential that the moment of inertia and the position of the centre of gravity of the pendulum alone should be exactly the same as the pendulum and model, before finding the value of α for the pendulum alone.

This is effected by replacing the model with small lead weights whose mass is equal to the mass of the model and fixing them inside the tubes of the frame which carries the model, the centre of gravity of the weights being in the same position as the centre of gravity of the model.

Let α_1 be the value of α found for the pendulum alone.

Let α be the value of α found for the pendulum and model.

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Then we have $a_1\omega^2 = \frac{2A}{I}\omega^2$

and $a\,\omega^2 = \frac{2(A + Bl)\,\omega^2}{I}$

$\therefore (a - a_1)\,\omega^2 = \frac{2\,Bl\,\omega^2}{I}$

or $\frac{I\,(a - a_1)\,\omega^2}{2l} = B\,\omega^2 =$ the force on the model at velocity ω.

And changing from Angular Velocity to Linear Velocity

$\frac{I\,(a - a_1)\,V^2}{2l^3} =$ the force on the model at velocity V.

$\therefore \frac{I\,(a - a_1)\,V^2}{2l^3} = K\tau\rho V^2 A$

$\therefore K\tau = \frac{I\,(a - a_1)}{2l^3\rho A}$

If I be found by small oscillations of the pendulum then I may be written as

$\frac{T^2mgh}{4\pi^2}$

Then $K\tau = \frac{T^2mgh\,(a - a_1)}{8\pi^2 l^3\rho A}$

The lift force measurements.

The lift force is measured by equating the force required to deflect the pendulum the amount measured against $K< \rho'g\ V^2A\cdot$

The value of V being the maximum velocity of the pendulum.

To obtain the maximum velocity differentiate (3) and equate to zero; we thus have $a \cos\theta = \sin\theta + a^2 e^{-a(\pi/2 - \theta)}$.

From this expression, given a, we can calculate the value of θ for which the velocity is a maximum.

Substituting the value of θ thus found in (3) we obtain the maximum velocity in radians per second.

The values of V^2 (linear velocity)² have been calculated in terms of μ for various values of a.

Value of $a = 0$	Value of $V^2 = 152.6\mu$
Value of ,, $= .1$	Value of ,, $= 138.8\mu$
Value of ,, $= .2$	Value of ,, $= 127.5\mu$
Value of ,, $= .3$	Value of ,, $= 117.8\mu$
Value of ,, $= .4$	Value of ,, $= 109.5\mu$

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