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Reaction on a Wing whose Angle of Incidence is Changing Rapidly

Wind Tunnel Experiments with a Short Period Recording Balance

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M.B.E.

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AERODYNAMICS SYMBOLS.

1. General

m	mass
t	time
V	resultant linear velocity
Ω	resultant angular velocity
ρ	density, σ relative density
ν	kinematic coefficient of viscosity
R	Reynolds number, $R = lV/\nu$ (where l is a suitable linear dimension), to be expressed as a numerical coefficient x 10^6

Normal temperature and pressure for aeronautical work are 15° C. and 760 mm.

For air under these conditions $\begin{cases} \rho = 0{\cdot}002378 \text{ slug/cu. ft.} \\ \nu = 1{\cdot}59 \times 10^{-4} \text{ sq. ft./sec.} \end{cases}$

The slug is taken to be 32·2 lb.-mass.

α	angle of incidence
e	angle of downwash
S	area
c	chord
s	semi-span
A	aspect ratio, $A = 4s^2/S$
L	lift, with coefficient $k_L = L/S\rho V^2$
D	drag, with coefficient $k_D = D/S\rho V^2$
γ	gliding angle, $\tan\gamma = D/L$
L	rolling moment, with coefficient $k_l = L/sS\rho V^2$
M	pitching moment, with coefficient $k_m = M/cS\rho V^2$
N	yawing moment, with coefficient $k_n = N/sS\rho V^2$

2. Airscrews

n	revolutions per second
D	diameter
J	V/nD
P	power
T	thrust, with coef
Q	torque, with coef
η	efficiency, $\eta = T$

THE REACTION ON A WING WHOSE ANGLE OF INCIDENCE IS CHANGING RAPIDLY

WIND TUNNEL EXPERIMENTS WITH A SHORT PERIOD RECORDING BALANCE

By W. S. FARREN, M.B.E.

Report and Memoranda No. 1648

15*th January*, 1935

Summary.—A balance has been developed in the Aeronautics Laboratory at Cambridge by which the reaction on a wing whose angle of incidence is increasing or decreasing rapidly can be recorded.

The reactions have been measured on eight aerofoils, including those used in R. & M. 1588[2]. Large " hysteresis " effects at and above the stall have been found in two-dimensional conditions.

It is considered that these form a basis for accounting for certain full scale observations which have not hitherto been satisfactorily explained.

It is proposed to extend the work to three-dimensional conditions.

The work is partly the outcome of that described in R. & M. 1561[1]. It also forms part of the investigation of stalling described in R. & M. 1588[2], and in Professor Jones' Wilbur Wright Lecture, 1934[3].

A short account of the results was given by the author at the Fourth International Congress for Applied Mechanics, Cambridge, July, 1934.

Acknowledgments.—The author wishes to acknowledge the help of Flight Lieutenant J. A. G. Haslam and Mr. F. L. Westwater, who took the records for two of the aerofoils.

The balance was built in the Laboratory workshops by Mr. N. Surrey, to whose skill and workmanship a high tribute is due. Mr. Surrey also gave essential help in taking all the records.

The work was inspired throughout by the advice and help of Professor B. Melvill Jones, to whom the author wishes to express his thanks.

Section I

1. *Introduction and Summary of Results.*—The work described in this report was undertaken in order to investigate more fully certain observations made in previous researches in this Laboratory on the characteristics of wings at or near the stall. In the first place it was established in the work described in R. & M. 1561[1] that when a wing is started suddenly in motion at an angle of incidence well above that at which the stall occurs in steady motion the flow remains unstalled during the first few chords travel of the wing. This suggested that the lift of a wing whose angle of incidence is rising fairly rapidly, from a value below the normal stalling angle to one well above it, may considerably exceed that measured at fixed angles of incidence above the stall. Attention was drawn to this inference, and to other evidence* consistent with it in a note dated February, 1931,† where the importance of such a phenomenon, if of appreciable magnitude, in relation to the control and the strength of aeroplanes was emphasised.

2. In the second place the experimental study of stalling described in R. & M. 1588[2] made it clear that over a certain range of angle of incidence above the stall large fluctuations with a relatively long mean period occur in the forces on a wing and in the associated flow round it. The existence of similar fluctuations on the full scale has been confirmed by experiments in flight, which were briefly described by Professor Jones in the Wilbur Wright lecture, 1934[3], and will form the subject of a later report. Moreover they were found to be associated with a type of behaviour of the aeroplane which is undesirable and may be dangerous.

3. It was accordingly decided to construct a wind tunnel balance which would enable both these phenomena to be investigated in greater detail. In this balance (Fig. 3), which is described briefly in Section II, the wing spans the (closed) working section of the tunnel and is therefore, as in both the previous pieces of laboratory work referred to above, in substantially two-dimensional conditions. It is supported on stiff springs whose deflection is recorded photographically. The mechanism can readily be modified to give either (I) a record of normal and longitudinal force when the angle of incidence is changing at various rates or (II) a record of the variations of these components against time, the angle of incidence being held fixed at any desired value. The natural frequency of the moving parts was arranged to be high enough to cope with the anticipated mean frequency of the fluctuating reaction on the wing, and sufficient electrical damping was incorporated to ensure a reasonably true record. Experience has shown that the frequency of the balance might with advantage be raised but the results already obtained in both classes are thought to be of sufficient interest to warrant a report at this stage.

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* A list of references is given in R. & M. 1561.

† T.3075 (unpublished). "The Lift on a Wing whose Angle of Incidence is Changing Rapidly."—W. S. Farren.

4. The results are described in more detail in Section III, but they may be briefly summarised as follows :—

Class I.—(Angle of incidence increasing or decreasing).—A large " hysteresis "* effect exists above the stall for all the types of wing tested, which include all those used in R. & M. 1588[2] and two additional shapes.† The force-angle curve is a function of both the rate of change of angle, and of the sense of the change, i.e., whether increasing or decreasing. The magnitude of the effect depends to some extent on the shape of the wing profile. It is convenient to express the rate of change of angle as the inverse of the number of chord lengths which the wing travels while the angle changes by 1°. The highest rate used in the experiments was $\frac{1}{2\cdot5}$—a change at the rate of 1° per 2·5 chords travel. This rate may easily be exceeded during certain manoeuvres on the full scale.‡ The general nature of the results is indicated in Fig. 1, where the lift curve for substantially zero rate of change of angle is shown by the broken line and the " fluctuating " region by a band (cf. R. & M. 1588[2]).

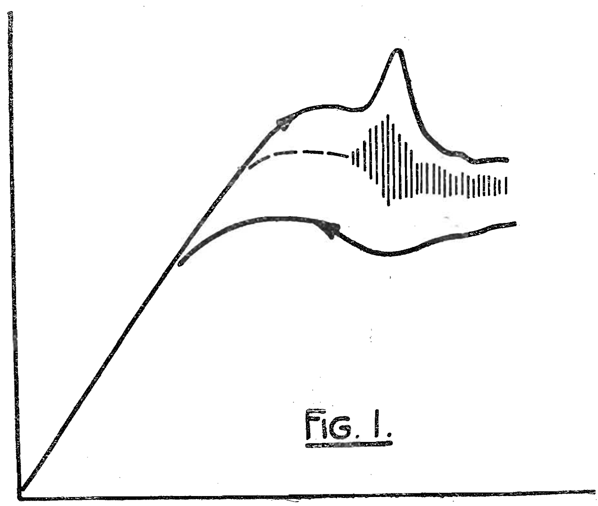

FIG. 1.

* The term " hysteresis " may be considered hardly appropriate, but it has been widely used to denote that a function of some variable goes through a series of values when the variable is increasing which are *different* from those through which it passes when the variable is decreasing without any essential implication as to the relation between the two series of values and the underlying mechanism.

† A (R.A.F. 32), B (Clark YH), C (R.A.F. 28 thickened 7 per cent.), D (R.A.F. 30), E (Airscrew 4), F (Circular arc of camber 0·115 with flat undersurface) ; and Clark YH thickened to 20 per cent., and Göttingen 387. The profiles are approximate only (*see* Fig. 10).

‡ Ref. 4. Landing experiments at Martlesham Heath (R. & M. 1406) give examples of 4½° in half second at 70 ft. per sec. (Fig. 1) and 7° in one second at 85 ft. per sec. (Fig. 9). These correspond approximately to 1° in 1·2 chords and 1° in 2 chords, respectively, and the estimated maximum lift coefficients are some 50 per cent. in excess of the normal.

At a rate of $\frac{1}{2\cdot5}$ the lift follows the full lines. No consistent difference appears on the linear part of the curve, but the whole of the stalled part of the curve lies above the mean curve for steady angles when the angle is increasing, and below when it is decreasing (starting in this case from a large angle—about 35°). Near the "fluctuating" region there is, with increasing angle, a marked "*peak*", very high lift coefficients being recorded over a small range of angle. For the first four aerofoils (A–D *see* Fig. 10) the extent of this phenomenon may be summarised as follows:—In the neighbourhood of the angle at which "fluctuations" (at fixed angles) are most violent, there is, when the angle is increasing at a rate of 1° per 2·5 chords travel of the wing, a period corresponding to a travel of 5 to 10 chords during which the recorded lift exceeds the mean lift at fixed angles by *more than* 15 to 20 per cent., and a period of about 2½ to 5 chords during which the excess is *more than* 30 per cent. The maximum excess is 40 to 55 per cent. For profiles A and B (Figs. 11 and 12) this "peak" occurs some 8° beyond the angle of maximum lift. For profiles C and D (Figs. 13 and 14) the peak occurs practically at maximum lift.

The curve for decreasing angles has probably only a limited practical significance, since the initial conditions (a very large angle of incidence) are seldom reached in flight, except in spinning, and further experiments were therefore made in which the initial angle was in or near the "fluctuating" region. The results of these are of the type shown in Fig. 2. There is still a large hysteresis effect.

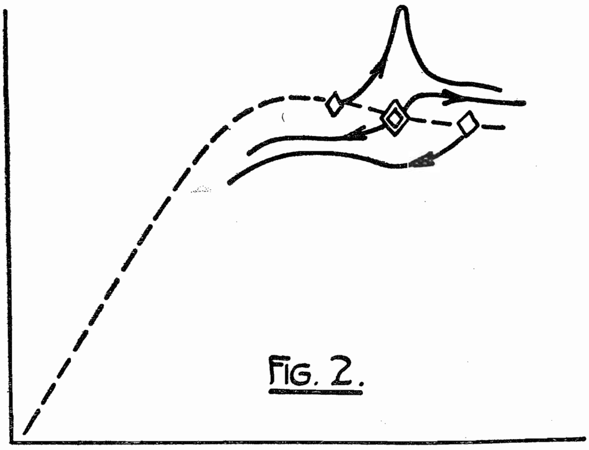

FIG. 2.

5. The full scale inferences to be drawn from these results must remain for the present largely a matter for speculation. The Reynolds number of the experiments was low (about $1\cdot2 \times 10^5$). The condition of the wings was nominally two-dimensional, so that

the effect of a finite span is not represented. On the other hand the effect of the tunnel boundary layer and of end leaks, though probably of small magnitude, makes it impossible to regard the numerical results as more than an approximation to the two-dimensional values. Further the tunnel is small in relation to the wing, and the blocking effect of the stalled wing is appreciable and its precise interpretation in terms of " free air " condition is uncertain. Nevertheless there does not seem to be any reason to believe that the general nature of the phenomenon described can be largely influenced by any of the considerations mentioned, though its extent may of course depend appreciably on Reynolds number.

If the " peak " at increasing angles of incidence exists on the full scale, and if its magnitude is of the order mentioned above, its effect in a landing carried out as recorded in R. & M. 1406 " Take-off and Landing of Aircraft "—D. Rolinson, would be appreciable. Rates of rotation considerably greater than 1° in 2·5 chords were recorded in those experiments. A 30 per cent. excess of lift over weight enduring while the aeroplane travels 5 chords, or about ½ sec. at stalling speed, would produce an upward velocity of 5 ft. per sec., sufficient to delay the final drop on to the ground very noticeably.

It is not suggested that these figures can be applied with any great confidence in this way. But the effects described are of the right order of magnitude to serve as a basis for explaining both these full scale observations and others of a less precise nature but none the less well authenticated, such as the " ground effect ".

Considerable extensions of the present work, on lines described in Section IV, will be required before it will be safe to discriminate between aerofoil profiles and classify them as " good " or " bad " in their properties above the stall. But it is probable that on general grounds one may fairly regard the " peak " as a fundamentally undesirable phenomenon. It is true that some use might be made of it in landing—indeed it is difficult to resist the conclusion that it has long been normal practice to do so. But it may well have been partly responsible for " wing dropping " since it is precisely the kind of phenomenon which would be sensitive to slight asymmetry. And it must in any case give rise to a type of behaviour of the aeroplane which the pilot can hardly anticipate, and to stresses for which the designer cannot with certainty provide. One is therefore led tentatively to the same conclusion as emerged from the work of R. & M. 1588—that profiles such as A and B, in which the " peak " is postponed to angles which will seldom be reached in practice, are on this ground to be preferred to those such as C and D where it occurs at maximum lift.

6. *Class II.*—(Time records of fluctuations at fixed angles of incidence.)—The fluctuations in the reactions described in R. & M. 1588[2] were observed but proved generally to be rather more rapid

than had been anticipated. The natural period of the balance was hardly short enough to enable all their details to be traced accurately, but their amplitude could be determined without difficulty, and was found to be in good agreement with the estimates of R. & M. 1588[2] (*see* Figs. 20 and 22). An example is shown (Fig. 21A) in which the fluctuations were both slow and large enough for an analysis (Fig. 21) to be made. Here the changes in both components of the reaction are approximately harmonic and amount to about ± 15 per cent. in normal force and ± 50 per cent. in longitudinal force. They were moreover nearly in quadrature in time, so that the end of the force vector traverses an approximately elliptic path (Fig. 21) in a time corresponding to about 13 chords travel of the wing—1 to $1\frac{1}{2}$ seconds on full scale. It is not without significance that it is precisely to this profile* and angle (R.A.F. 28 $\times$ 1·07 at 14°) that the remark on page 5 of R. & M. 1588[2] refers, the fluctuations being so large and persistent that the methods there used to define their limits were only partially successful.

Other examples in general agreement with this phase relation of the components have been obtained, but a further discussion of the phenomenon is deferred to a later report as it is desired to obtain more experimental information. The present report is mainly confined to results of experiments in Class I, and the chief reason for mentioning the above result is that it furnishes a basis for correlating the fluctuations in force components observed in these experiments, without which it is not possible to compare the measurements with those of R. & M. 1588[2] (in which lift and drag, and not normal and longitudinal force, were measured) except over those parts of the range of angle in which the forces are practically steady.

In Section III §16 a tentative explanation of the development of the "peak" in normal force is put forward and it is suggested that the type of variation of flow there pictured (Fig. 24) may serve to account, in a general way, for the "fluctuations" observed at fixed angles of incidence. It must be emphasised that this explanation is of a speculative character, since no observations of flow have been made.

Section II

Description of Balance.—1. The balance is shown in photographs Figs. 3, 4 and 5, and certain features in outline in Figs. 6, 7 and 8. The wing (6 in. chord) spans the width of the tunnel (28 in.), coming within about 1 mm. from the wall at each end.

At the *drive* end (Fig. 5) it is supported by a tubular extension, passing approximately through the centre of pressure, in a chuck mounted on spring gimbals, which convey the couple required to

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* The profile is also the one used on the aeroplane referred to in Professor Jones' Wilbur Wright lecture.

rotate it without any appreciable backlash and with a constraint in bending about any axis perpendicular to that of the couple which is of negligible amount and is in any case almost perfectly elastic. The rotation of the wing (for experiments in Class I) is provided by means of the variable reduction gearing shown in Fig. 5 and a final connecting rod with ball bearing ends, forming a parallel motion with a maximum range of about 60°.

At the *balance* end (Fig. 4) there is first a repetition of the large bearing on the drive end. On this is a sleeve to which an equal rotation is conveyed by a shaft which passes through a faired tube well behind the wing, visible in Fig. 3. It would of course have been preferable to carry this shaft below the tunnel, but it was not possible to do so without altering the general structure of the tunnel to an extent which was undesirable in view of the other purposes for which it exists. The cross tube is, however, in such a position that it can produce no appreciable interference on the wing.

Angular movements of the wing are given by a scale on the drive end (Fig. 5) and it is of course essential that there shall be no appreciable backlash between the rotating parts on the two sides of the tunnel. The records show no sign of such a defect.

2. An outline of the arrangement of the whole apparatus is shown in Fig. 6 and some details of the force measuring scheme, similarly numbered, in Figs. 7 and 8. On the main sleeve (1) are mounted *first* the force measuring springs (2), to which is connected by thin steel strips (3) the tubular extension (4) fixed to the wing, coaxial with the similar extension at the drive end; and *secondly* the lamp (5), lens (6) and disc (7) in which is cut a thin slit parallel to the direction of deflection of the springs (2). The image of a horizontal slit (perpendicular to the plane of the paper as seen in Fig. 6) in the cover surrounding the lamp (5) in a mirror (8) attached to the springs (2) is focussed on the disc (7) so as to cross the (vertical) slit, producing a spot of light on the photographic film (9) immediately behind the disc. The film ($6\frac{1}{2}$ in. $\times$ $4\frac{3}{4}$ in.) is carried in an ordinary dark slide which is mounted on a carrier so as to rotate about an axis which can be adjusted into coincidence with the axis of rotation of the wing. The carrier (*see* Fig. 3) is driven by crossed steel tapes and pulleys at *twice* the rate of rotation of the wing in the *reverse* direction.

The diagram produced (*see*, e.g., Fig. 11A) is therefore a polar one, a deflection of the measuring springs appearing as a radial line on the film. Angular movements of the wing are magnified three times, a 30° change in angle covering 90° on the film.

The whole arrangement of springs, mirror, lens, etc., described above is duplicated at 90°. Since the whole balance moves with the wing it measures components of the reaction relative to axes fixed in the wing. These axes can however be chosen to have any desired relation to the profile.

The film is so arranged in relation to the axis of rotation that approximately one-half is covered by the record of normal force and the other by the record of longitudinal force, but a certain amount of over-lapping ($\pm 5°$) produces no confusion (*see* Fig. 11A). The radial lines at every 5° are produced by auxiliary mirrors which can be pushed into position just in front of the mirrors (8) and rotated through the necessary small angle by a single movement of an ordinary photographic shutter release. The "zero" lines are produced by rotating the balance with the wind off. They are not circles on account of the variable components of the weight of the wing, etc.

A time record (1/10 second) is superposed on the record and an attempt was made to record airspeed (or rather the tunnel pressure) by the capsule shown in Fig. 3. This was abandoned owing to the difficulty of obtaining enough deflection with the capsule available. This refinement is not really essential but it is highly desirable, as the taking of records was made appreciably more difficult by the necessity for reading an alcohol manometer (in the dark-room which was built round the balance end) immediately before and after each record.

3. In Figs. 7 and 8 are shown certain details which may be of interest. The connection of the wing to the steel strips (3) is entirely by friction. The tubular extension (4) is split and forms with the nut (11) a chuck which grips a circular spindle (10) made of four quadrantal segments which fit round the strips. The outer end of the complete spindle is threaded and the four parts are finally pressed together by a nut (12). The scheme is very convenient, as small adjustments of the initial position of the wing can be made by sliding the strips (3) through the split spindle (10) before tightening. No trouble has ever been experienced with slipping. It is possible to remove and replace a wing in less than an hour.

In order to prevent the tension in the strips (3) from ever becoming zero an initial set is applied to the main springs (2) by an auxiliary support (not shown) which can be screwed in or out so as to produce the desired initial tension in (3) and can also be moved bodily along slides parallel to the springs (2), thus altering their effective stiffness and hence both the scale of the record and the natural frequency of the moving parts. These adjustments can all be made while the balance is working.

The damping is by means of eddy currents generated in an aluminium vane (13) shown in Fig. 8, whose centre moves about four times as much as the ends of the main springs. There is little or no available data on the design of eddy current damping devices of this type, and in this instance the proportions were guessed. It was found that the desired damping was reached with a current which the windings will carry comfortably for periods of about a minute. As a considerable amount of information which may be useful in the design of such an arrangement was obtained in the development of this apparatus, it is proposed to analyse the results in some detail in a later report.

4. The whole balance has given very little trouble in use. There are no knife edges or other loose connection throughout the whole of the moving parts. A linear calibration is obtained over the full working ranges and there is no detectable zero shift. Separate calibrations by weights were made for each wing, but they varied so little that in the final reduction an average was taken to apply to all records. For the "normal force" springs the deflection on the film for a force of 1 lb. at the centre of the wing was 16·2 mm., the corresponding deflection of the ends of the main springs (2) being about 0·38 mm. (i.e., a magnification of about 42). The maximum force measured is about 4½ lb., giving a deflection on the record of about 7 cm. and 1·7 mm. on the springs. The corresponding natural undamped frequency was almost exactly 20 per second. The damping finally used was such that the amplitude of natural oscillations decreased in the ratio 0·05 in a complete period, corresponding to a value of 0·45 for the ratio μ/p in the equation of natural oscillations ($\ddot{x} + 2\mu\dot{x} + p^2 x = 0$). This is about the most favourable ratio for such work as was in view.

For the longitudinal force springs the scale was slightly increased, the deflection on the record for 1 lb. being 18·9 mm. The longitudinal forces are of course as a whole much less than the normal forces, (about 1/4 in the stalled region) but the scale could not conveniently be made more open without reducing the natural frequency to an undesirable degree. In the development of this work it will probably be necessary to provide a higher optical magnification for the longitudinal force balance.

5. The whole of the "balance side" of the apparatus is enclosed in a collapsible dark room built round the side of the tunnel. This has the convenient result that the "camera" can be left open to visual inspection. The side of the disc (7) (Fig. 6) remote from the film can easily be seen and the images of the illuminated slits can be inspected directly and the necessary adjustments and trial runs made with the film covered. This reduces spoilt records to a negligible proportion, and also enables the angles of incidence at which the fluctuations seem to be of most interest to be selected directly, for experiments in Class II. To change the balance over for this type of work it is necessary only to uncouple the mechanism which drives the film holder from that which rotates the wing and to drive it by a separate motor and reduction gear. The hand wheel operating the clutch can be seen in Fig. 3, coaxial with the large pulley carrying the crossed steel bands.

A complete series of experiments of both classes, involving exposing about 10 films and calibrating the balance, takes less than an hour.

Section III

Analysis of Records.—1. In Figs. 11–18 are shown the results of experiments in Class I on the eight aerofoils referred to in Section II. The first six are those used in the work described in R. & M. 1588[2]. The last two have not yet been examined by the methods of that report. Table 1 contains particulars of the profiles and references to the corresponding diagrams and sample records, and in Fig. 10 outline tracings from the templates to which the aerofoils were made are collected together in order that the range of profiles covered by the work may be more clearly appreciated. The aerofoils were made as accurately as possible to the nominal profiles, of mahogany laminated at right angles to the chord, the surface being painted with cellulose paint, well rubbed down to give a smooth, though not a highly polished, finish. They show remarkably few signs of distortion from the templates, but their general order of accuracy of their construction is of course less than that of metal aerofoils.

Table 1

Aerofoil.	Nominal Profile.	Reduced Results. Fig. No.	Sample Records. Fig. No. and (Record No.).
A	R.A.F. 32	11	11A (141) 11B (143).
B	Clark YH	12	12A (118) 12B (123).
C	R.A.F. 28 × 1·07 . .	13	13A (150).
D	R.A.F. 30	14	14A (158) 14B (160).
E	Airscrew 4	15	—
F	Circ. Arc. upper, flat under.	16	—
G	Cl. YH 20 per cent. thick.	17	—
H	Göttingen 387 . .	18	18A (130).

2. The position of a line on the records can generally be determined by direct measurement to within $\frac{1}{2}$ mm., which represents about 0·007 in k_z or k_x. It is not claimed that the coefficients are determined with this accuracy since there are other sources of error, some of which have been referred to in Section I. The extent to which the figures can be relied on is probably best judged by the comparison made in §14 of this Section with certain results from R. & M. 1588[2].

The diagrams were plotted directly from the records, except that for convenience measured deflections were increased or decreased in the ratio of a standard tunnel pressure to that observed at the start* of each record. There is no fine control on the tunnel pressure,

* For increasing angles : with decreasing angles the corresponding reading is that at the end of the record (— 5°).

and voltage fluctuations, together with heating of the coarse-control rheostat, causes the pressure to vary $\pm$ 10 per cent. Deflections so corrected are plotted so that 1·7 mm. on the diagrams represents 1 mm.

The "blocking" effect of the stalled wing becomes appreciable above about 15°. (The chord of the wings was 6 in. and the depth of the tunnel 20 in.) As there is no really satisfactory way of allowing for this effect, and as it is the *relative* values of the forces at any given angle, at the various rates of rotation, rather than their absolute values, which are of interest, it was decided to leave the records translated as above without any further correction at large angles of incidence, but to draw on the diagrams lines of constant force coefficient calculated on the assumption that ρV^2 varies as the observed tunnel pressure when conditions are allowed to become steady at each angle. This is also the basis used in R. & M. 1588, where the tunnel pressure was determined at each angle for each profile. In the present work, in view of the uncertainty as to the significance of an allowance of this form when the angle is changing rapidly, it was thought sufficient to use the same allowance for all the profiles, determined by a detailed measurement for one profile together with the records for all the profiles of the pressure at the start and end of each experiment.

This suggests that some of the observed hysteresis, or the "peak" in the N.F.* curves, may be due to the blocking effect, but examination of the records shows that not only do very large "peaks" occur when the blocking effect is negligible (Fig. 13 and 14) but even for wings in which the "peak" is postponed to larger angles (Figs. 11 and 12) the blocking effect is still quite small. It is only at angles above about 25° that appreciable uncertainty exists as to the value of the force coefficients, but they are then generally of less interest.

The diagrams give coefficients of N.F. and L.F. (k_z and k_x)† the axes being perpendicular to and along the line joining the centres of curvature of the leading and trailing edges. It may be remarked that *lift* coefficient k_L can be estimated without serious error by reference throughout to the scale of k_z *which applies up to* 10° as the transformation causes k_L to fall below k_z by approximately the same amount as the blocking correction raises k_z above its value on this scale.

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* The abbreviation N.F. and L.F. will be used for normal force and longitudinal force, respectively.

† The standard convention for sign of k_z and k_x has been discarded for the sake of greater clearness. k_z is treated as positive when the N.F. is directed from the under surface towards the upper surface, i.e., generally in the same direction as a positive lift. k_x is treated as positive when the L.F. is directed from the nose towards the trailing edge, i.e., generally in the same direction as a positive drag. k_z and k_L are numerically indistinguishable up to about 15°, but for a normal wing k_x is negative from about 2° up to the stall.

The mean tunnel speed throughout was the same as that used in R. & M. 1588[2] and the same factors have been used in allowing for the tunnel calibration and the fact that the ends of the wings are in slower moving air near the tunnel wall.

3. In plotting the diagrams, Figs. 11–18, certain conventions have been used throughout, which may conveniently be summarised here.

The experiments were made at three standard rates of change of angle, namely, 1° in (*a*) approximately 75, (*b*) 12·5 and (*c*) 2·5 chords. The first rate is referred to (where results are given) as "slowly", the wing being rotated by hand through the reduction gear shown in Fig. 5, and the results are considered to be substantially identical with those for an infinitely slow rate.* At the second and third rates the wing was rotated mechanically, and while no special precautions were taken to keep the rates strictly constant at the nominal values mentioned, examination of the time marks shows that they were in fact sufficiently uniform for the results to be regarded as directly comparable.

In any individual record the uniformity of the rate of change can be judged directly from the time marks. It was found to be substantially constant over the range 0° to 30°, the initial acceleration, which was remarkably high, occurring in the previous 5°. (Records were generally made from −5° to 35° or 35° to −5°.)

The mean wind speed was 75 chords/sec. so that the times occupied by a change of 30° were (*a*) 30 seconds, (*b*) 5 seconds and (*c*) 1 second.

The *points* measured from the records are denoted by the symbols shown in Table 2.

Table 2

Rate.	Symbol. Angle Increasing.	Angle Decreasing.
(*a*) 1° in 75 chords	↑ + ↓	↑ × ↓
(*b*) 1° in 12·5 chords ..	+	×
(*c*) 1° in 2·5 chords	•	⊙

A *full line* denotes that the mean position of the line on the record is within ½ mm. of the points plotted (small variations from a smooth curve have been disregarded where they seemed to be trivial).

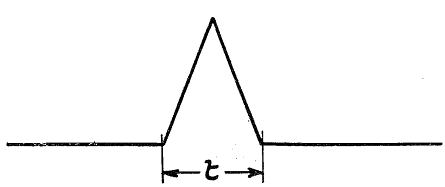
* Except possibly for profiles E and G. *See* §8 of this Section.

A *broken line* denotes that the fluctuations round the mean value plotted are relatively large. It will be seen that broken lines occur mostly where the precise values of the forces are not of great interest.

Where the *range of fluctuation* is of interest (mainly in experiments at rate (*a*)) it is indicated by the length of the symbol in Table 2 and by an enclosing band of broken lines. (*See* in particular Figs. 18 and 22, and the corresponding records Figs. 18A and 22A.) Occasional excursions beyond the general range have been disregarded, and no allowance has been made for the extent to which the fluctuations are incorrectly represented by the records. But for reasons given in the following paragraph it is considered that there is no likelihood of the estimate of the amplitude of the fluctuations being in error by as much as 10 per cent.

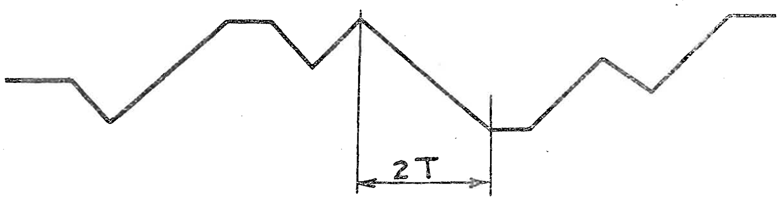
4. It is necessary to consider the extent to which the records misrepresent the fluctuations of the forces recorded. The *undamped* natural period of the balance is 1/20 second, corresponding to a change of angle of the wing of 0·05°, 0·3°, and 1·5°, at rates (*a*), (*b*) and (*c*), respectively. The damping adopted, which causes successive excursions of a free oscillation on either side to decrease in the ratio 0·22, or a reduction for complete period to $0{\cdot}22^2 = 0{\cdot}05$, causes the *damped* period to be some 10 per cent. greater. (*See* Fig. 9.)

One type of rapid fluctuation of great interest (the "peak" in the N.F. curves at rate (*c*)) appears to be of the nature of a sharp rise and fall superposed on a relatively steady value, thus :



If the force actually fluctuated in this extreme fashion the record produced would be as shown in Fig. 9, the time *t* bearing to the *damped* period T the ratios given. Examination of the records (*see* in particular curves for increasing angle at rate (*c*) in Figs. 11–14) suggests that in no case is *t*/T less than 1, so it appears that while the *form* of the fluctuation is probably even more abrupt than the record suggests, its *extent* and *duration* (defined by the width of the "peak" at its mean height) cannot be seriously in error. It is on this basis that the values quoted in Section I, §4 have been arrived at.

Examination of records in Class II (angle of incidence steady) confirms the impression derived from the work of R. & M. 1588[2] that the fluctuations are generally not even approximately harmonic, but in the nature of very irregular changes between fairly definite limits. On the other hand they do not confirm the idea that the force dwells on either the upper or the lower limit for appreciable times, but suggest rather that for most of the time it is changing either upwards or downwards, the time of a complete change from lower to upper limit being of the order of 2T, thus :



In experiments in Class I at the slowest rate (*a*) it is fluctuations of this type which are responsible for the width of the band on the record, and they occur at intervals of the order mentioned above. It seems therefore that their *extent* cannot differ from that of the force fluctuations to which they are due by more than **5** per cent.

In the extreme case of semi-regular fluctuations of this general type with a mean period equal to that of the balance it can be shown that although the record would lag behind the applied force in time, its amplitude would be given within about 10 per cent.

Thus the procedure adopted, in reducing records of this type, of making no allowance at all for what may be termed the balance error seems justified, especially as no great importance is attached to the absolute magnitude of the fluctuations except as an indication of a state of flow of which there is already ample evidence.

5. In describing the reduced records, Figs. 11–18, the idea developed in R. & M. 1588[2] that there are five fairly well defined stages in the lift curve of a wing will be used as a basis.

Stage 1 is the " normal flight " range of angle, in which the lift is almost exactly proportional to the angle from no lift : it extends, e.g., for profile B for about 8° from zero lift : the first signs of a stall appear in

Stage 2, in which the mean lift ceases to increase in proportion to the increase of angle, and there are small fluctuations in the lift of relatively short period. The nominal maximum lift is reached at the end of this stage and the beginning of

Stage 3, in which the mean lift decreases while the angle increases and the fluctuations are of rather larger magnitude. There follows

Stage 4, in which the mean lift continues to fall but the force fluctuations are very marked and of relatively long mean period, due to fluctuations of the flow from that characteristic of stage 3 (in which the region of separation, having spread up from the trailing edge, has nevertheless not reached the leading edge) to that of

Stage 5, in which the flow has separated completely from the back of the profile : in this stage the forces fluctuate to an extent not greatly different from that found in stage 3.

These stages naturally merge into one another more or less gradually, but it is possible by use of the various methods of R. & M. 1588[2] to define fairly closely the range of angles covered by each for any given profile. It was established in that report that profiles differ widely in this respect, particularly in the extent of stage 3.

6. To avoid confusing the diagrams curves for the slowest rate (*a*) have not generally been included, but it may be taken that they lie consistently between the curves for rate (*b*) for increasing and decreasing angle. In regard to the range of angle covered by the various stages (indicated below the N.F. curves), and the extent of the fluctuations, they are generally in good agreement* with R. & M. 1588[2].

Looked at from the point of view outlined in the preceding paragraph the profiles may be divided into four groups, as follows :—

Group 1.—A (Fig. 11) and B (Fig. 12) in which stage 3 extends for about 5° beyond " maximum lift ".

Group 2.—C (Fig. 13) and D (Fig. 14) in which stage 3 is to all intents and purposes absent, so that stage 4 occurs at maximum lift.

Group 3.—E (Fig. 15) and G (Fig. 17) in which stage 4 appears in the extreme form of a double-valued lift curve, though there are no large fluctuations of the force (from one curve to the other) but small and relatively rapid fluctuations round the two possible mean curves. Each of these is fairly stable in itself, but can be reached only when the angle is changing in a particular direction.

Group 4.—H (Fig. 18) in which it seems that stage 4 is hardly discernible. There is at least no suggestion from the present work—the profile has not been examined by the methods of R. & M. 1588—of a *sudden* increase in the extent of the fluctuations in stage 3.

The remaining profile F (Fig. 16) may be regarded as falling in Group 2. It is of no direct practical importance, but exhibits certain interesting features.

7. Considering first only *the curves for increasing angle,* it will be seen that all the profiles show the " hysteresis " and " peak " effects mentioned in Section I, §4, but in varying degrees.

In stage 1 the N.F. curves show no consistent differences.† There is no evidence of a " Wagner effect "—a delay in establishing the lift which is characteristic of the angle when conditions are

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* *See* below §14.

† Except for profiles in Group 3. The differences in stage 1 for these profiles have been observed in several experiments, but they are not entirely in accordance with an effect of the Wagner type. It seems that they must be regarded as part of the generally anomalous character of these profiles.

steady. It seems certain that such an effect exists, and it can only be concluded that the highest rate of increase of angle (*c*) is too low to enable it to be detected by the balance. In this stage only the points measured from the records have been plotted on the diagrams and no lines have been drawn through them, in order to avoid confusion. A line through zero N.F. at a slope π per radian has been drawn on each diagram as a guide. The observed rate of increase of N.F. with angle is slightly less than π, as would be anticipated.

When stage 2 is reached the N.F. curves cease to coincide. The higher the rate of increase of angle the more does stage 1 tend to be prolonged and the larger is the N.F. produced. In stage 3 the N.F. remains above that for steady angles by an approximately constant amount. At rate (*c*) the mean excess for profiles in group 1 is about 0·08.

8. As the region is reached in which stage 3 merges into stage 4 there occurs at rate (*c*) a rapid rise of N.F. followed by a fall to about the original value. The general character of this " peak " has been summarised in Section I, §4, and a more detailed analysis for the profiles of Groups 1 and 2 is given in Table 3.

Table 3

Group and profile.	Per cent. excess of Normal Force over fixed-angle value at same angle.			Duration of mean.	
	Base.	Peak.	Mean.	Degrees.	Chords.
1. A (R.A.F. 32)	15	44	30	2	5
1. B (Cl. YH)	20	52	36	1·4	3·5
2. C (R.A.F. 28 × 1·07) ..	18	46	32	3	7·5
2. D (R.A.F. 30)	17	55	36	1·2	3
Col. 1	2	3	4	5	6

Col. 2 gives the percentage by which the N.F. at rate (*c*) exceeds the steady value (at the same angle) at the point at which the " peak " begins ; Col. 3 the corresponding figure for the top of the peak and Col. 4 the mean of Cols. 2 and 3. In Col. 5 is given the number of degrees over which the N.F. *exceeds* the value of Col. 4 and Col. 6 the travel of the wing in chord during this change of angle.

9. The above remarks apply only to the profiles in Groups 1 and 2 (A to D). Profiles E and G have been placed together in Group 3 mainly because they have one striking property in common—a

N.F. curve which is a function of the *sense* of the change of angle at the lowest rate of change. At the highest rate of increase of angle the behaviour of E is on the whole similar to that of the profiles A to D. The development of a definite " peak " of about $0 \cdot 1$ in k_z when the " hysteresis " effect has already raised k_z to $0 \cdot 9$ is remarkable and the correlation of the fall in L.F. with the preliminary slight fall in N.F. lends support to the explanation of the " peak " put forward below in §16.

Profile G shows in stage 1 a hysteresis of the opposite kind, (i.e., of the Wagner type) but in stage 2 the N.F. ultimately rises and its subsequent history is similar to that for profile E. A small " peak " develops as the L.F. falls.

It will be noted that the two profiles differ greatly in total thickness, but their upper surfaces are on the whole very similar in shape. They do not seem likely to be of much importance on the full scale, but they are useful in that they throw additional light on the whole problem.

10. The single profile H in Group 4 (Göttingen 387, Fig. 18) is remarkable in that stage 4 is postponed to a very large angle (about 26°, or 31° from zero lift). The fluctuations at rate (*a*) show no signs of a *sudden* increase or decrease in this region. This is consistent with the explanation put forward in R. & M. 1588[2], in that the N.F. has decreased (in stage 3) nearly to the " completely stalled " value, the whole process of separation having occurred gradually from the rear. The L.F. developed in this process is very large.

It was noted in R. & M. 1588[2] that for this profile the pressure distribution over the front part of the upper surface shows no large rising gradient up to force coefficients of as much as $0 \cdot 75$. The evidence of the present report is thus consistent with the anticipation of R. & M. 1588[2] that this profile would show a much greater stability of flow than those (in particular in Group 2) in which at even lower force coefficients the rising pressure gradient near the leading edge is very steep.

At the highest rate of increase of angle (*c*) there is in the first place some evidence of a " Wagner " type of hysteresis in stages 1 and 2 (*see* in particular the L.F. curves) but later the N.F. rises above the steady value, as for profile G.

Between 20° and 25° there is clear evidence of a fluctuating type of flow, suggesting that, while at fixed angles the fluctuations over this range of angle are not particularly marked, the flow is nevertheless in a sensitive state. It will be noted that it is over this range that the mean L.F. at rate (*a*) decreases steadily, and shows appreciable fluctuations. Examination of the record of all the profiles shows that this condition is generally associated with the beginning of stage 4, and it seems that with this profile the transition from stage 3 to stage 4 occupies some 5°. Above 25° the N.F. continues to rise, and the L.F. does not finally fall till 28°, when there is a small "peak" in the N.F. curve.

It is interesting to note in passing that it is this profile for which the maximum lift coefficient, as measured in the C.A.T., falls with increasing Reynolds number, whereas for all other profiles so far tested it rises.

11. Profile F (Fig. 16) has been included partly for the sake of completeness and partly because when inverted (flat side uppermost) it provides an opportunity for observing the effect of a high rate of increase of angle on a profile for which separation must necessarily occur at the extreme leading edge at very low k_z.

When tested with the curved side uppermost, as in R. & M. 1588[2], it shows good agreement with the results of that report at the slow rate (*a*), being generally similar to profiles of Group 2. At the high rate (*c*) the outstanding point is the large oscillations which develop, suggesting that the instability of the flow is so great that even at this rate of increase of angle the large fluctuations characteristic of fixed angles persist, and attain a very large magnitude.

Inverted, it will be seen that the N.F. continues to rise linearly at rate (*c*) for some 5° beyond the point at which front separation occurs at the slow rate (*a*).

12. The curves for *decreasing angle* for all the profiles at rate (*c*) are given mainly in order to emphasise a characteristic which appears to be common to all the profiles, namely, the inability of the flow to return from the completely stalled state (all experiments began from 35°) until the angle has fallen nearly to that characteristic of the same N.F. in the completely unstalled state (stage 1). The behaviour of the N.F. in this process is generally very erratic.

13. In order to judge whether the "peak" phenomenon is likely to be of importance in full scale conditions (assuming for the moment that no scale effect intervenes to remove it entirely) it is important to know how far it is a definite and repeatable phenomenon, and how far its extent depends on the previous history of the angle of incidence. In the first place it may be said that for several profiles repeat experiments have been made and have generally given results in good agreement with those shown. But perhaps a more important investigation on this point is shown in Fig. 19 where records at rate (*c*) are shown for profiles A, C and D, in which the starting point was in or near the fluctuating stage 4. The lines without experimental points show the results at the same rate from Figs. 11, 13 and 14. The diagram needs little comment, except perhaps to draw attention to the definite *fall* which occurs when the angle is decreased from a starting point within stage 4.

The rate of change of angle was naturally not absolutely uniform at the beginning of these experiments, but this seems to have a relatively small effect on the subsequent history of the N.F.

14. *Direct Comparisons with Force Measurement of R. & M.* 1588.—In Fig. 20 the full lines are those of Fig. 2 of R. & M. 1588 and the crosses represent the result of calculating the lift and drag coefficients from the mean of the two curves at rate (*b*) on Fig. 12 (records 118 and 119). These were used in preference to the record at rate (*a*) since the difference between them is small and they are more clearly defined. The extent of the fluctuations is indicated for the lift only, for reasons explained below. The agreement is generally good.

In attempting to estimate the corresponding drag fluctuations it was apparent that it was essential to know the phase relationship between the recorded fluctuations of N.F. and L.F., at least approximately.

The character of the fluctuations recorded in experiments in Class II (fixed angles) is generally not even approximately harmonic, but a survey of all those in which the fluctuations were well marked led to the conclusion that the N.F. was a maximum when the L.F. was approximately at its mean value and decreasing (numerically) ; in other words the components were roughly in quadrature. One example was found—profile C, record 155, Fig. 21A—in which the fluctuations of both components were sufficiently large and persistent to admit of a fairly satisfactory analysis, which is shown in Fig. 21. The small oscillations of N.F. which appear to be superposed on the main ones have been smoothed out. Their period is approximately that of the balance itself, and it is impossible to say how far they are due to actual force fluctuations. Their inclusion would not appreciably change the result. Apart from this smoothing Fig. 21 is simply a reproduction of Fig. 21A in rectangular co-ordinates. The N.F. and L.F. have been placed in the correct relative position with the aid of the fiducial lines A and B which are made on the record for this purpose. The deduced force vector is also shown.

It is considered that taken in conjunction with other examples of the same kind, though not so striking in magnitude or so suitable for analysis, it supplies a basis upon which the *width* of the traces on the records of N.F. and L.F. at rate (*a*) can be used to estimate the drag fluctuations. (The fluctuations of L.F. have a negligible influence on lift.) This has been applied to profile D, for which a particularly clear record at rate (*a*) existed (No. 163, Fig. 22A) and the results are shown in Fig. 22 compared with the corresponding force measurements from Fig. 4 of R. & M. 1588[2]. In some respects the agreement is not quite so good as in Fig. 20 but on the whole it is satisfactory.

15. A graphical representation of the process is shown in Fig. 23, for angles between 10° and 15° and the results at rate (*c*) are included for comparison. The left-hand diagram A shows the locus of the end of the force vector relative to body axes, i.e., it gives measured N.F. plotted against measured L.F. The right-hand diagram B gives the locus relative to " wind axes ", i.e., it is simply a true " polar "

curve for the reactions on the wing. On the locus at rate (*a*) in diagram A are drawn ellipses whose axes represent the measured fluctuations from the mean. In diagram B each vector is swung through the appropriate angle.

It will be seen that at rate (*a*) in diagram A the fluctuations of the two components are very small at 11°, the angle at which the collapse of the L.F. begins. At 12°, when the L.F. has decreased to about half its value at 11°, both the components fluctuate much more, but the fluctuations of the L.F. are the greater—the vector fluctuates mainly in *direction* and only to a small extent in *magnitude*. At 13° and over the mean L.F. is nearly zero, and its fluctuations are about half as great as at 12°, but the N.F. now fluctuates violently—the vector fluctuates mainly in *magnitude* and only to a small extent in *direction*. At rate (*c*) the collapse of the L.F. from 11° to 14° is accompanied first by a rise in N.F., reaching a maximum at 14° where the L.F. is zero, and then by a fall from 14° to 15° to practically its value at 11°.

In the polar diagram B it appears that the drag fluctuations are greater than those of L.F. for angles above 12°, the larger fluctuations of the N.F. having a considerable effect. This diagram brings out the point that at the " peak " of the *lift* curve at rate (*c*) there is also a peak of the *drag* curve.

16. *Tentative Explanation of the Development of the " Peak " in Normal Force.*—Examination of the diagrams Figs. 11 to 18 shows that they are all consistent with the example analysed in Fig. 23, in that the rise of N.F. to a peak is accompanied by a fall in L.F., at first slow and then more definite, and that when the N.F. finally falls the L.F. remains practically unchanged at about zero.

One is led by these observations to the following tentative description of a progressive change in flow which might produce the " peak ". It is desired to emphasise that no observations of flow have been made to substantiate the diagram which accompanies this description. There exists at present no technique for making such observations, and the diagrams, though generally consistent with the force fluctuations, are therefore conjectural in character and may well need revision at a later date.

It is known from the full scale experiments described briefly in Professor Jones' Wilbur Wright lecture[3]—*see*, e.g., Fig. 16[3]—that a type of flow is possible in which there is turbulence for a considerable distance from the surface over the forward third of the wing, while towards the rear there is no large depth of turbulence, though there are rapid fluctuations superposed on an otherwise generally smooth flow, characteristic of a region in which the air has suffered a considerable loss of total head. One may describe this broadly as a flow which separates from the surface near the nose and rejoins it at some distance down the upper surface. It is suggested that a progressively changing flow of this type develops, in which the point at which it rejoins the surface moves comparatively slowly towards the trailing edge. In Fig. 23, for example, it is suggested that the process starts at 10° and finishes at 14° and develops along the lines shown diagrammatically in Fig. 24. It is important in considering the explanation put forward to realise that the change in flow pattern is relatively gradual. In Fig. 24 the wing travels $2\frac{1}{2}$ chord lengths in each interval between the successive diagrams.

A local separation near the nose implies an increase in the curvature of the flow in that region, and a substantially uniform pressure where separation has occurred. Thus the N.F. might be expected to rise slightly, though the L.F. would hardly be affected (10°–11°). As the region of separation increases in size a fall in L.F. would be expected and a further rise in N.F. (11°–14°). This is what is observed in Fig. 23 (diagram A at rate (*c*)).

At 14°, in the above example, the region of separation is pictured as reaching nearly to the trailing edge, and it is suggested that the mechanism which governs the pressure on the upper surface in the "completely stalled" state then comes into operation. The nature of this mechanism is not understood, but there is ample evidence that it is incapable of maintaining a suction on the upper surface greater than about $0 \cdot 5\rho V^2$ for profiles of the type under consideration. This is less (numerically) than that required to produce the large N.F. observed at 14°, and it may be supposed that the flow will swing rapidly up into the form sketched at 15°. The L.F. would be hardly affected, since the suction over the upper surface would remain approximately uniform, though its intensity would be reduced; but the N.F. would necessarily fall. This is again in accordance with what is recorded in Fig. 23.

It seems probable that a definite eddy would leave the region of the trailing edge between 14° and 15°, carrying away with it a circulation corresponding to the fall in lift. Such a process can be observed without difficulty, though at a very low Reynolds number, in the smoke tunnel when the angle of a wing is suddenly increased.

It is interesting to consider, in the light of the above account, the "fluctuations" observed at fixed angles in the same range of incidence. These occur at intervals which are of the same order as that occupied by the complete "peak", viz., 10 to 15 chords travel. It seems probable, therefore, that they are associated with flow fluctuations of the same general character as that pictured above, but that when the angle is fixed the flow can return approximately to its original form in some way which is not at present understood. A rough outline of a process which is in general consistent with the observed fluctuations of N.F. and L.F. is sketched in Fig. 25, referring particularly to the exceptionally regular example already analysed in Fig. 21, where the complete cycle occupied about 13 chords travel.

It is suggested in Fig. 25 that when the region of separation near the front of the wing has spread down to the position indicated roughly at point 3, a new region of separation forms near the nose, so that from point 4 onwards the flow may be described as joining the wing again in the neighbourhood of the centre of the upper surface. This would be consistent with the observed rise in L.F. Between points 7 and 1, when both N.F. and L.F. are observed to rise, it is suggested that the region of separation over the rear part of the upper surface decreases in extent, the turbulent air passing away downstream.

The absence of observations of flow makes the above tentative explanation, and Figs. 24 and 25, almost entirely conjectural. It must be remembered in addition that the fluctuations in the reactions are generally much less regular than is suggested in Fig. 25, so that there must in any case be considerable variations from any such simple scheme.

Section IV

Conclusions—Future Developments.—1. The chief conclusions from the experiments in Class I (changing angle of incidence) have been summarised in Section I, §4. No deductions can be made from them which can be applied with certainty to full scale conditions for reasons which have also been given. But the general agreement of the results of R. & M. 1588[2] with observations in flight[3] makes it difficult to resist the inference that the "hysteresis" and "peak" effects must exist in some degree on the full scale. If the result of a large increase of Reynolds number were to reduce the *magnitude* of the effects to trivial proportions, then the phenomena would be of academic interest only, but in view of the independent full scale evidence* which really implies the existence of such effects of very considerable magnitude, it seems that it is unlikely that the scale effect on the phenomena will be of that type. Moreover on general grounds it seems improbable that an effect which arises virtually from a temporary suspension of the normal action of a rising pressure gradient on the boundary layer, observed at a moderately low Reynolds number, will disappear at a high Reynolds number. One might anticipate that it would be accentuated.

2. The full scale consequences of such phenomena need little emphasis. Some have already been referred to. With profiles of Group 2 some of which have been widely used, the "peak" effect would lead to estimates of landing speeds and force in very rapid manoeuvres of certain types appreciably different from those based on the nominal maximum lift. Even with less extreme profiles (e.g., Group 1) the "hysteresis" effect would be appreciable when landing. Current ideas on the whole manoeuvre of landing would

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* *See* footnote page 2.

need some revision, since the pilot would have at his disposal a reserve of reaction for checking his final descent of which the "static" lift curves give no suggestion.

Many of the more complex manoeuvres involving rates of change of rolling of the wings would also be affected, and in fact nearly every non-steady condition of flight of an aeroplane would need considering in the light of the results which have been described.

Finally, no one concerned with the structural side of aeroplane design can fail to be impressed with the implications of a lift curve such as Figs. 13 and 14, even if it applies only to non-steady conditions of flight.

3. It is therefore necessary to consider what developments of the work are needed in order to make these inferences less speculative.

The equipment at Cambridge is very limited in size, but it is capable of dealing at least in certain respects with the following extensions of the work :—

(1) *The Effect of a Finite Span.*—It is proposed to use a half-wing, so that the balance will measure rolling moments.

(2) *The Effect of a Biplane.*—It is proposed to experiment in two-dimensional conditions first and then along the same lines as in (1).

(3) *The Effect of Higher Rates of Rotation of the Wing.*—It is proposed to take one or two typical profiles and explore more fully the "peak" effect up to rates as high as can be attained—probably up to 1° in $\frac{1}{2}$ chord. (There is a full scale landing record[4] of 1° in 1·2 chords.)

(4) *The Effect of Very High Rates of Rotation of the Wing.*—This is being investigated at the N.P.L. and it is considered that the task of raising the natural frequency of the Cambridge balance to an entirely different range would hardly be worth while. This aspect is of importance in connection with the problem of stresses caused by very sharp gusts.

(5) *The Effect of Reynolds Number.*—So far as laboratory work is concerned it seems that the only prospect of attaining a really high Reynolds number would be in the 24 ft. tunnel at R.A.E. One hesitates to suggest attempting work of this kind in the C.A.T., but on a larger *scale* many of the difficulties which beset the present work would be reduced.

On the full scale there may be an opportunity of making some flight experiments at Cambridge with a recording accelerometer, but the work would necessarily be rather elaborate.

It is also proposed to explore more fully the behaviour of the forces at fixed angles of incidence (Class II) but this is unlikely to lead to results of so much direct practical importance, though it may be valuable in throwing light on the mechanism which governs all the phenomena described both here and in R. & M. 1588.

REFERENCES

[1] R. & M. 1561. "The flow near a wing which starts suddenly from rest and then stalls." Aeronautics Laboratory, Cambridge.

[2] R. & M. 1588. "An experimental study of the stalling of wings." Aeronautics Laboratory, Cambridge.

[3] Wilbur Wright lecture, Journal of the Royal Aeronautical Society, September, 1934.

[4] R. & M. 1406. "Take-off and landing of aircraft." D. Rolinson.

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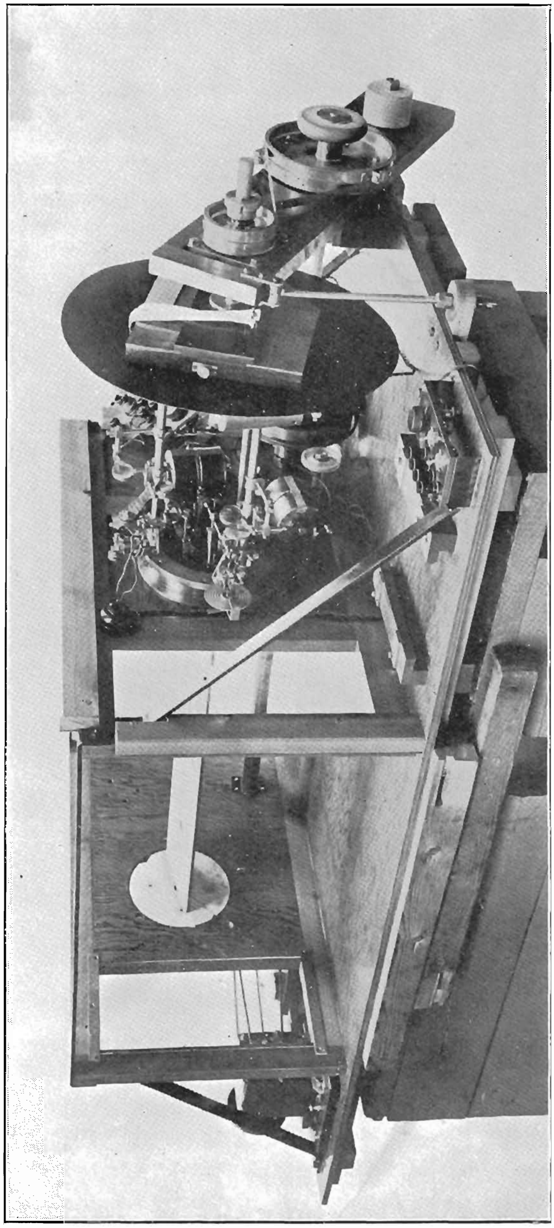

Fig. 3.—General View of Wing and Balance.

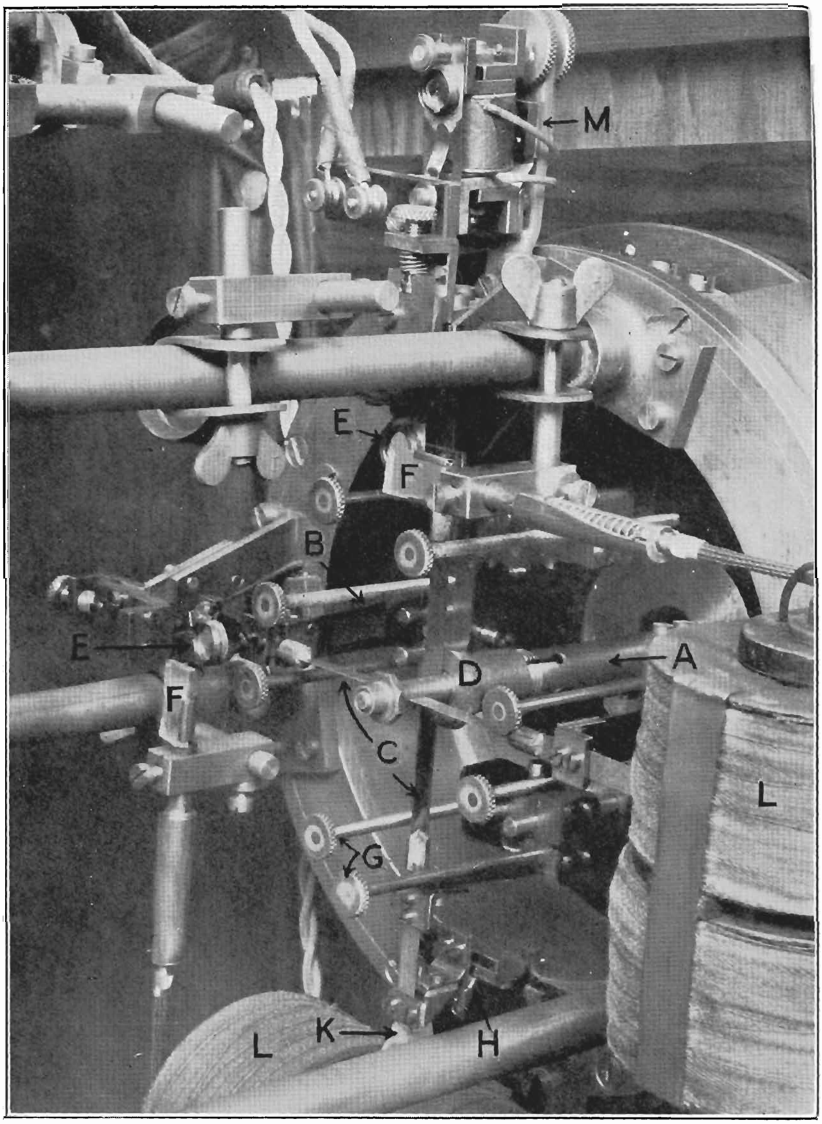

FIG. 4.—Balance Head for Measuring Normal and Longitudinal Forces.

A. Hollow spindle attached to wing.
B. Force measuring springs.
C. Cross connecting springs.
D. Chuck for connecting A. to C.
E. Mirrors connected to springs B.
F. Auxiliary mirrors for producing fiducial lines.
G. Gear for adjusting initial tension and stiffness of springs B.
H. Cross spring hinge for damping vane.
K. Damping vane.
L. Damping magnet.
M. Time recording magnet.

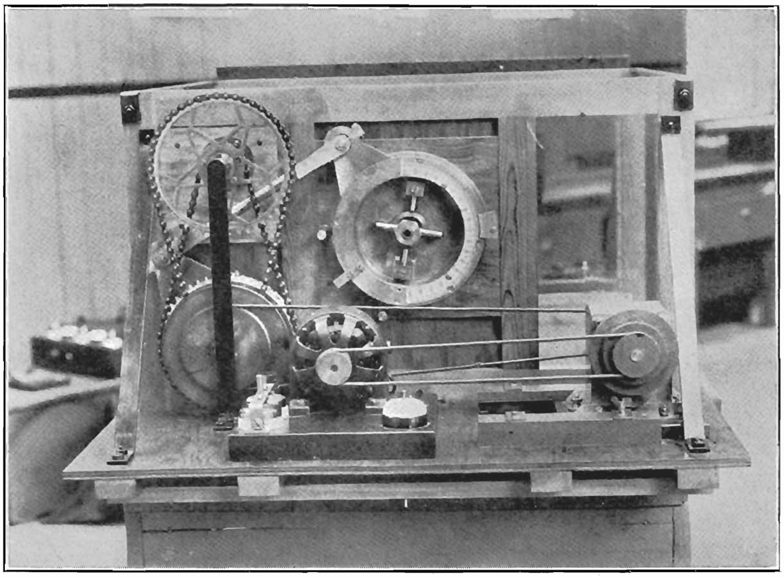

FIG. 5.—Drive end showing spring gimbal and Driving Mechanism.

OUTLINE GENERAL ARRANGEMENT OF BALANCE.

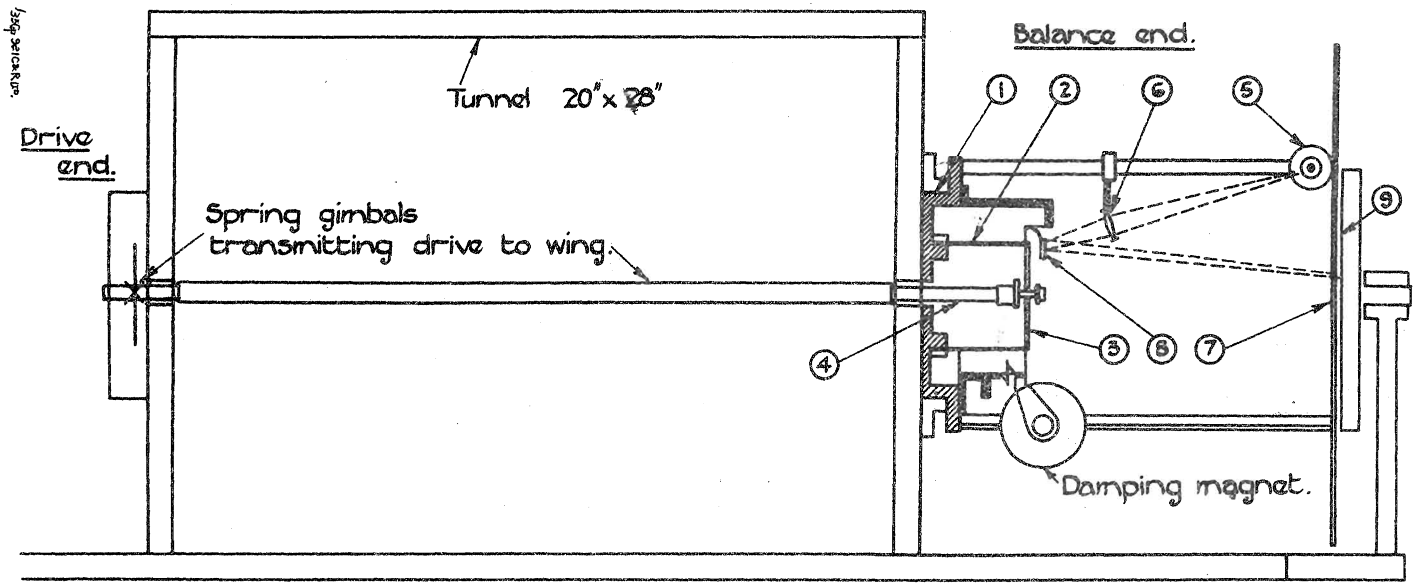

FIG. 6.

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ARRANGEMENT OF BALANCE UNIT. FIG. 7.

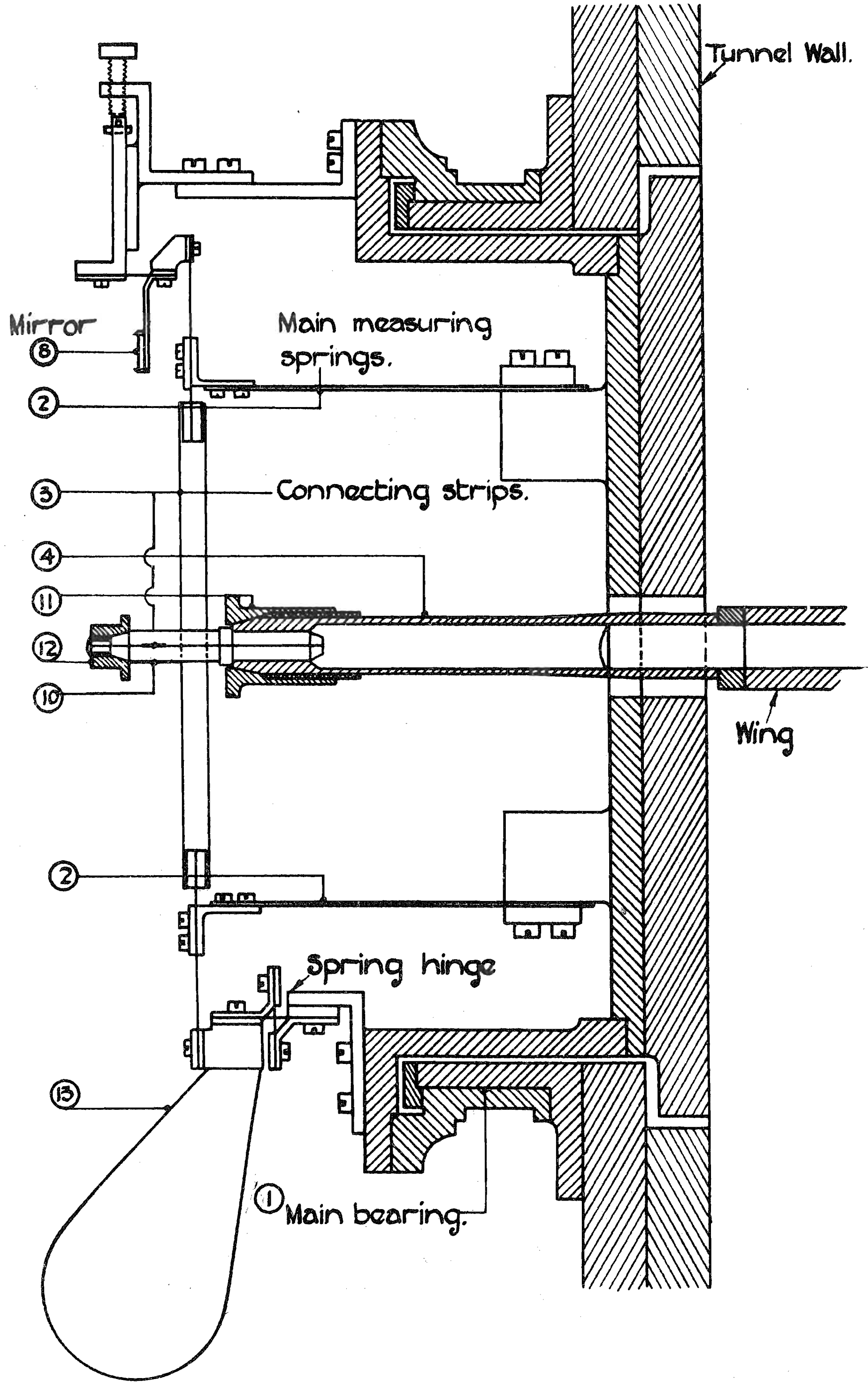

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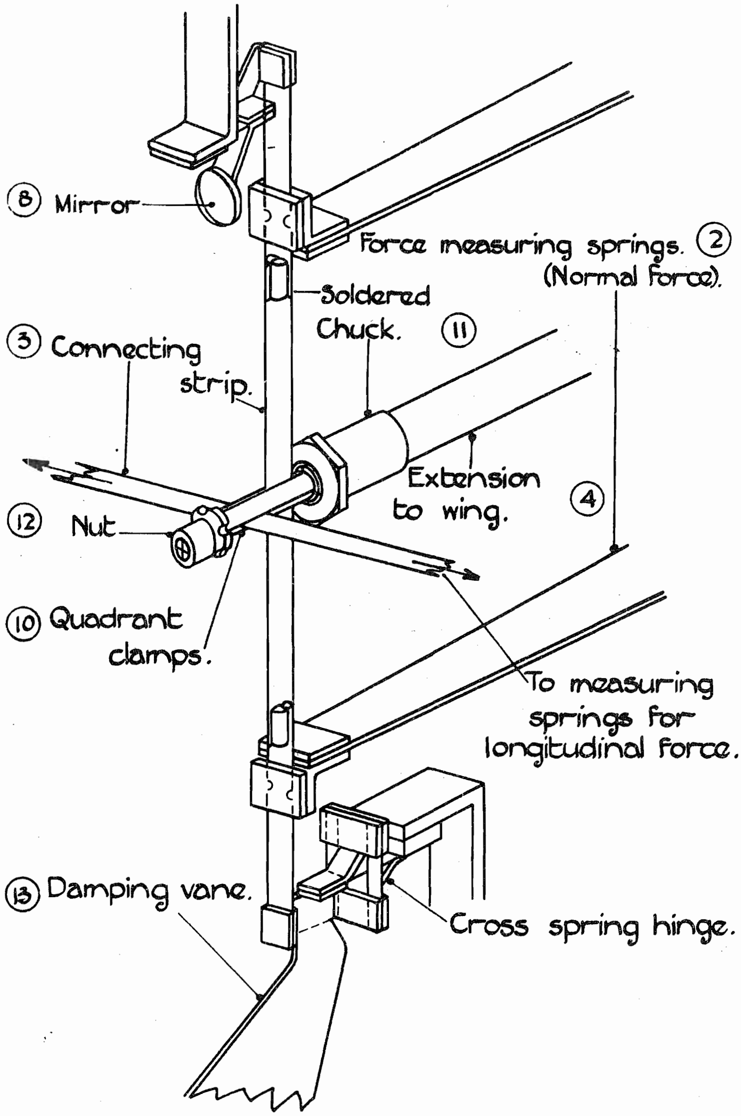
FIG. 8.

DETAILS OF BALANCE UNIT.

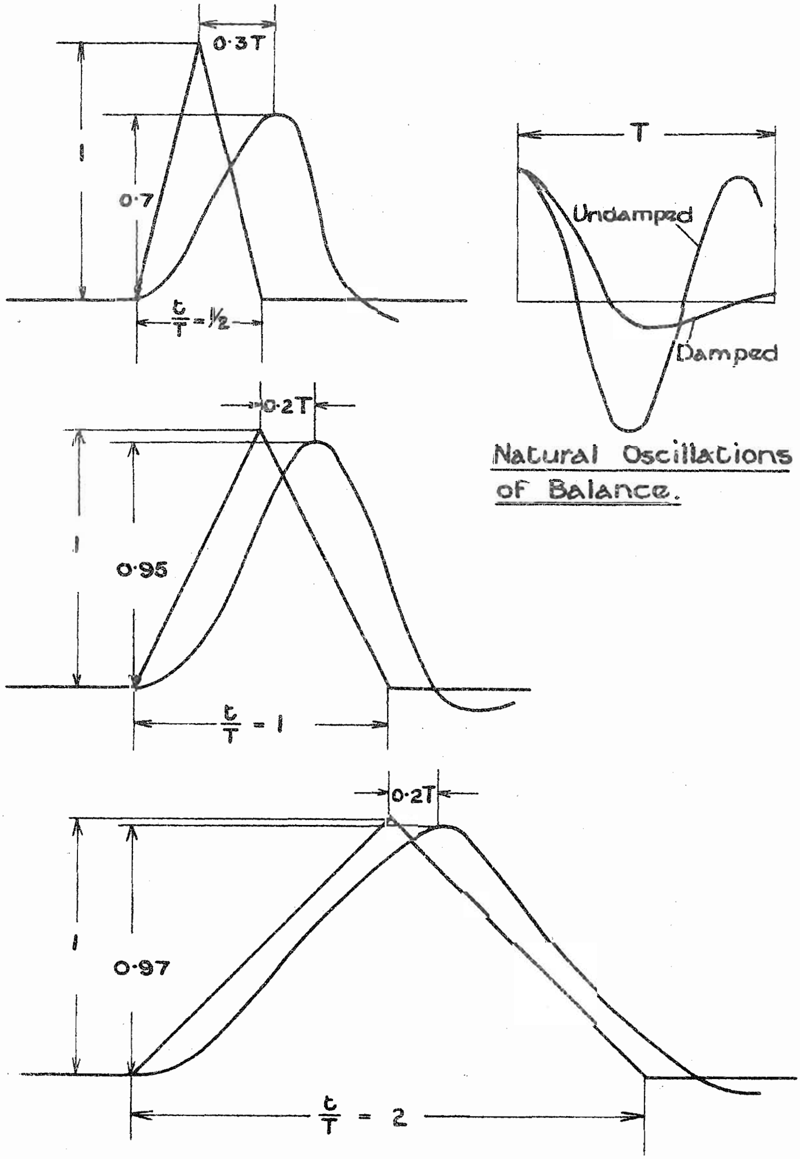


Note. Screws omitted.

E.E.M.

FIG. 9.

BALANCE CHARACTERISTICS— RESPONSE TO FORCE FLUCTUATIONS OF VARIOUS TYPES.



Natural Oscillations of Balance.

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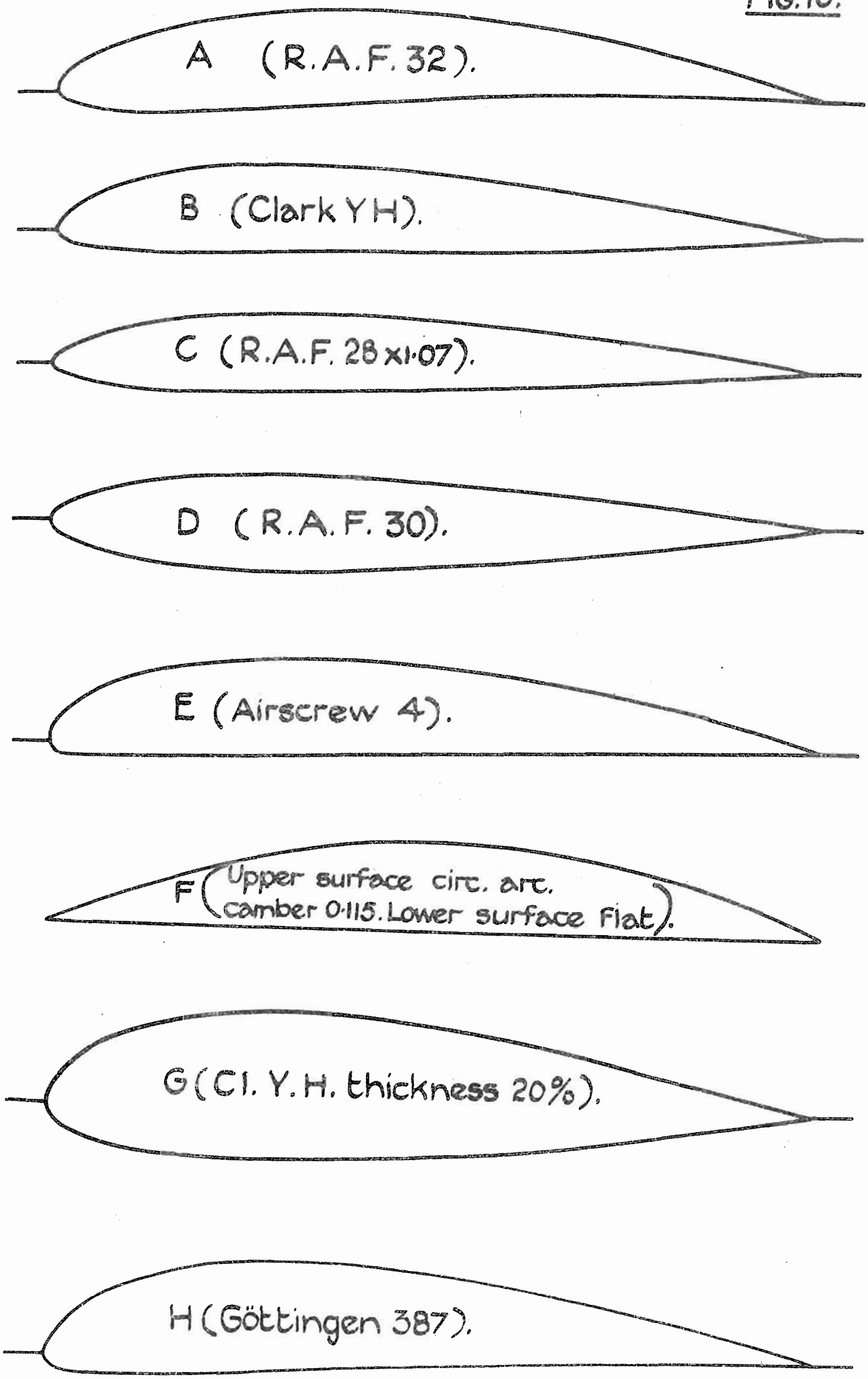
APPROXIMATE SHAPE OF PROFILES TESTED.

FIG. 10.



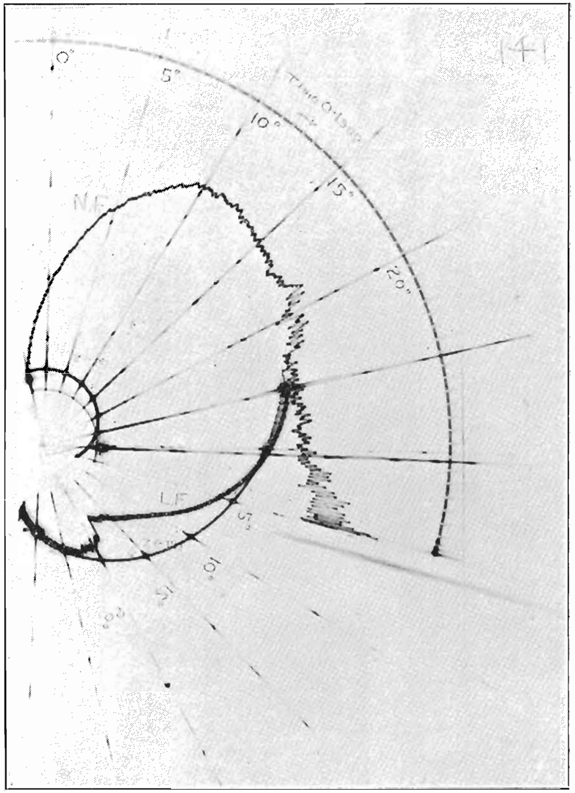


Fig. 11A.—Record 141. Profile A. Angle increasing. Rate (*b*).

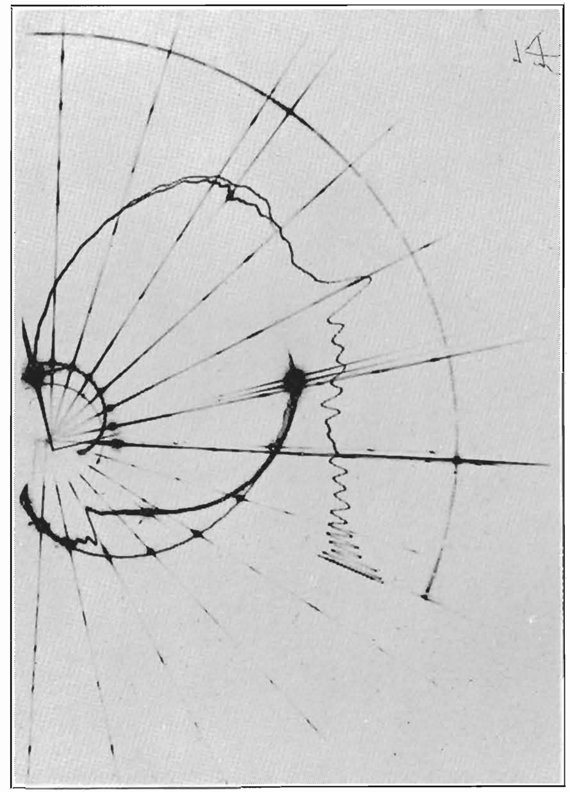


Fig. 11B.—Record 143. Profile A. Angle increasing. Rate (*c*).

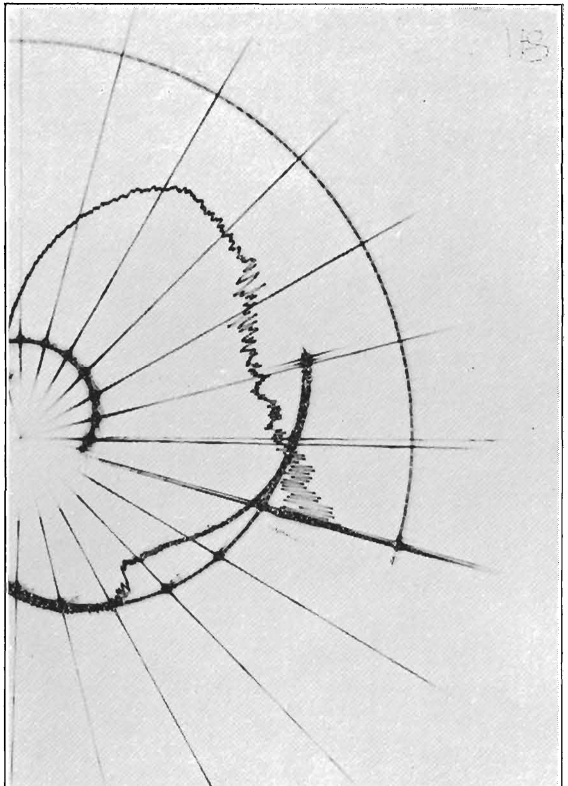


FIG. 12A.—Record 118. Profile B. Angle increasing. Rate (*b*).

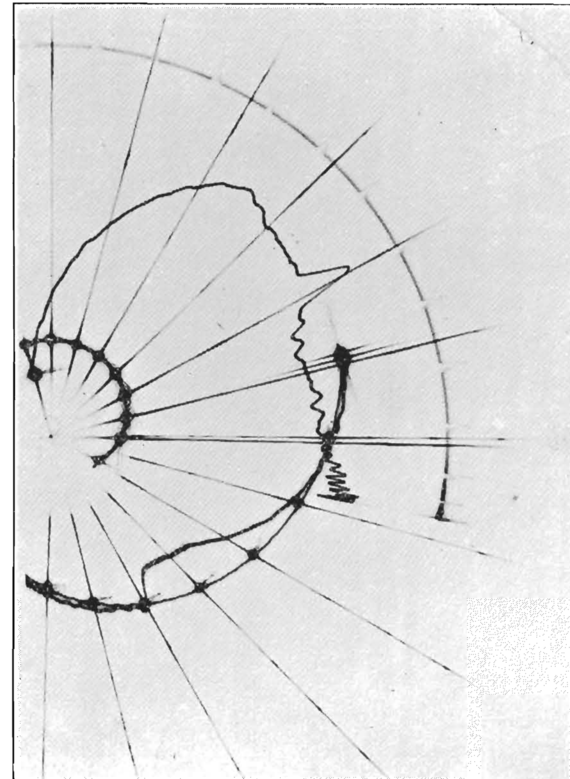


FIG. 12B.—Record 123. Profile B. Angle increasing. Rate (*c*).

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Fig. 12.

REDUCED RECORDS OF NORMAL AND LONGITUDINAL FORCE FOR PROFILE B.

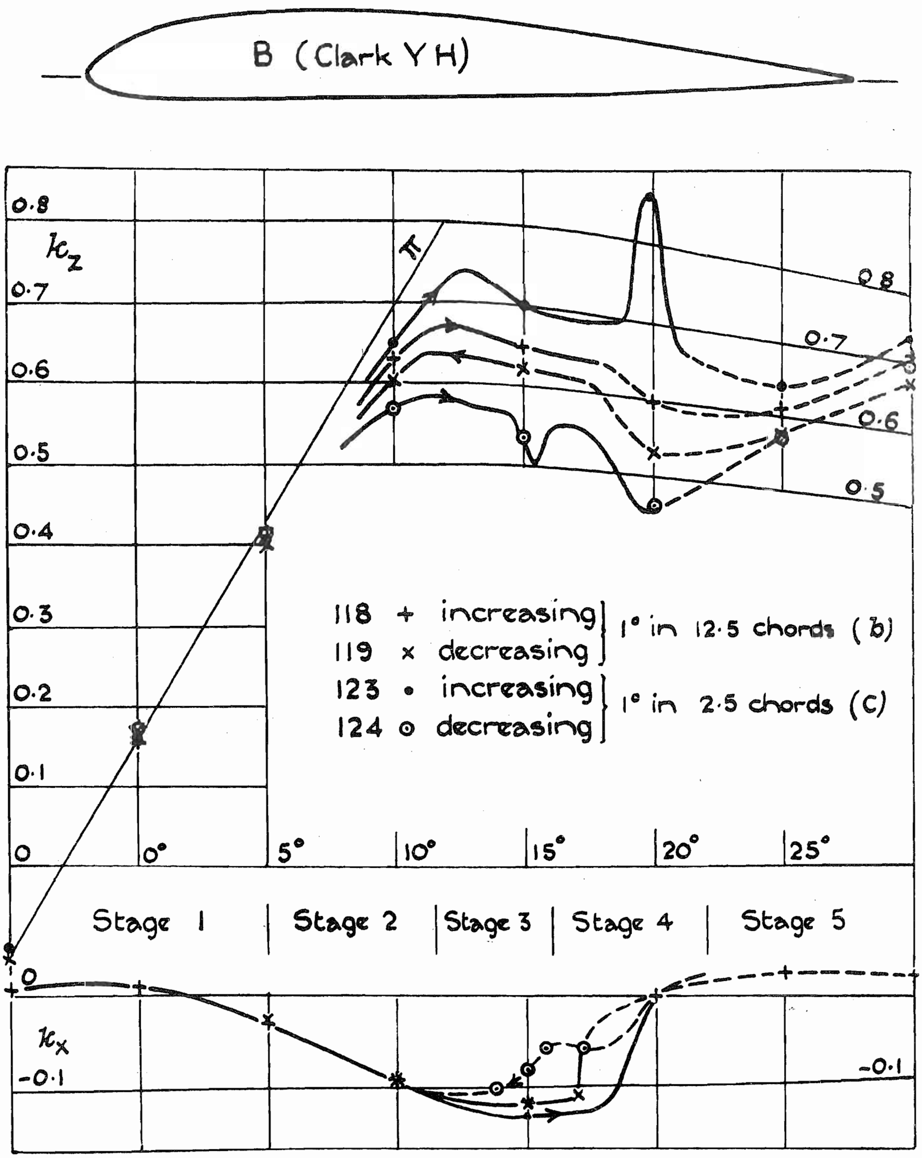

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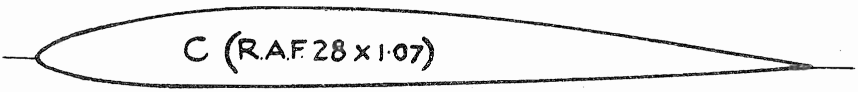
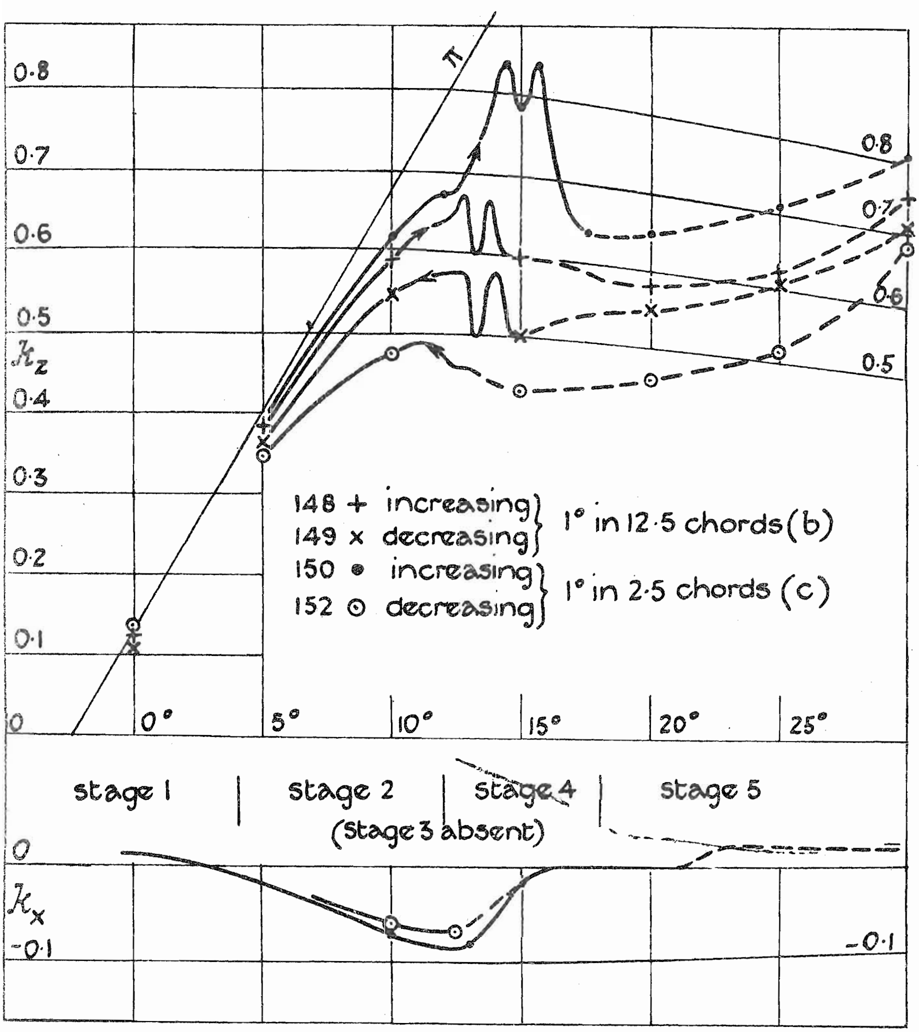
FIG. 13.

REDUCED RECORDS OF NORMAL AND LONGITUDINAL FORCE FOR PROFILE C.





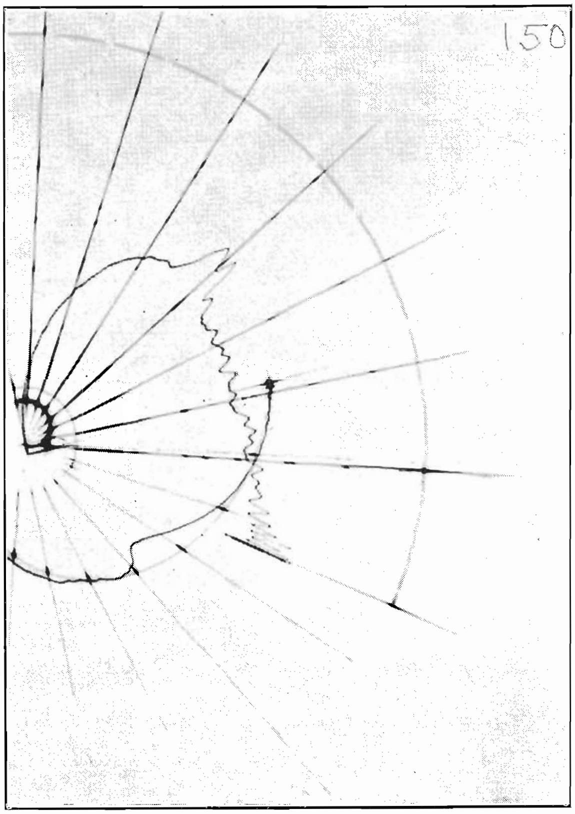


FIG. 13A.—Record 150. Profile C. Angle increasing. Rate (*c*).

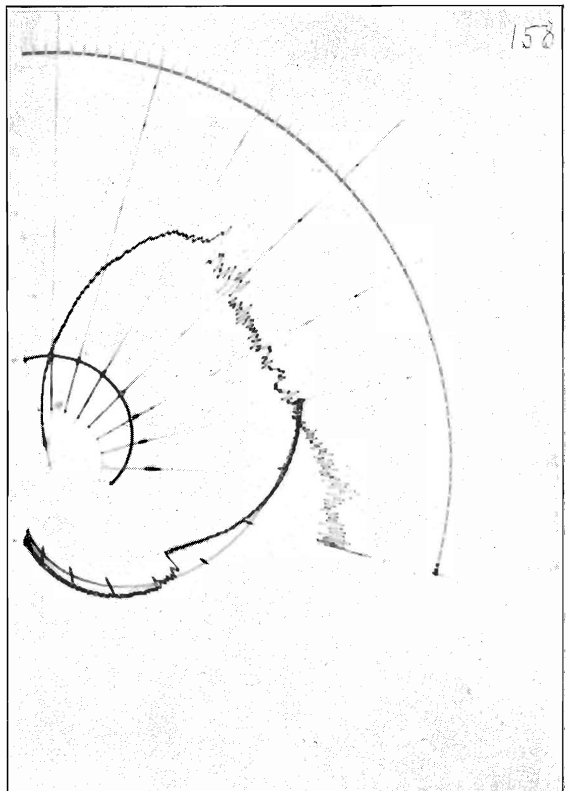


FIG. 14A.—Record 158. Profile D. Angle increasing. Rate (*b*).

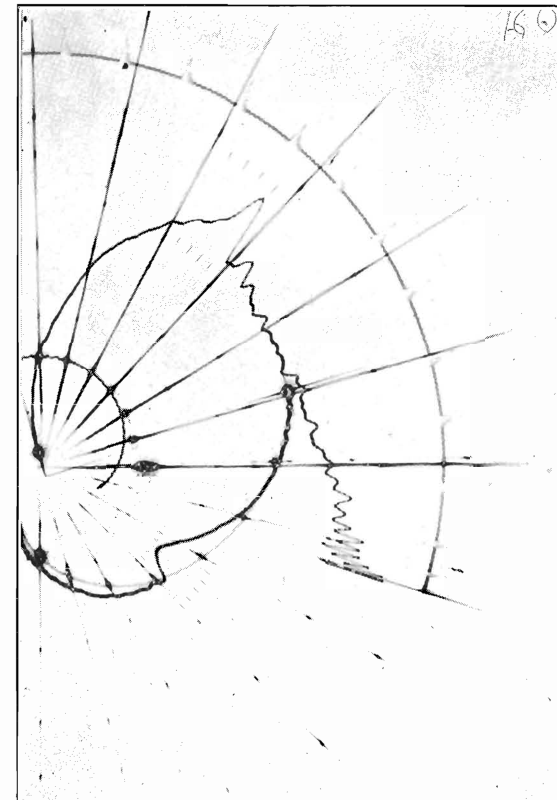
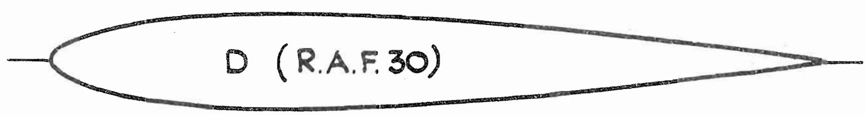


FIG. 14B.—Record 160. Profile D. Angle increasing. Rate (*c*).

FIG. 14.

REDUCED RECORDS OF NORMAL AND LONGITUDINAL FORCE FOR PROFILE D.



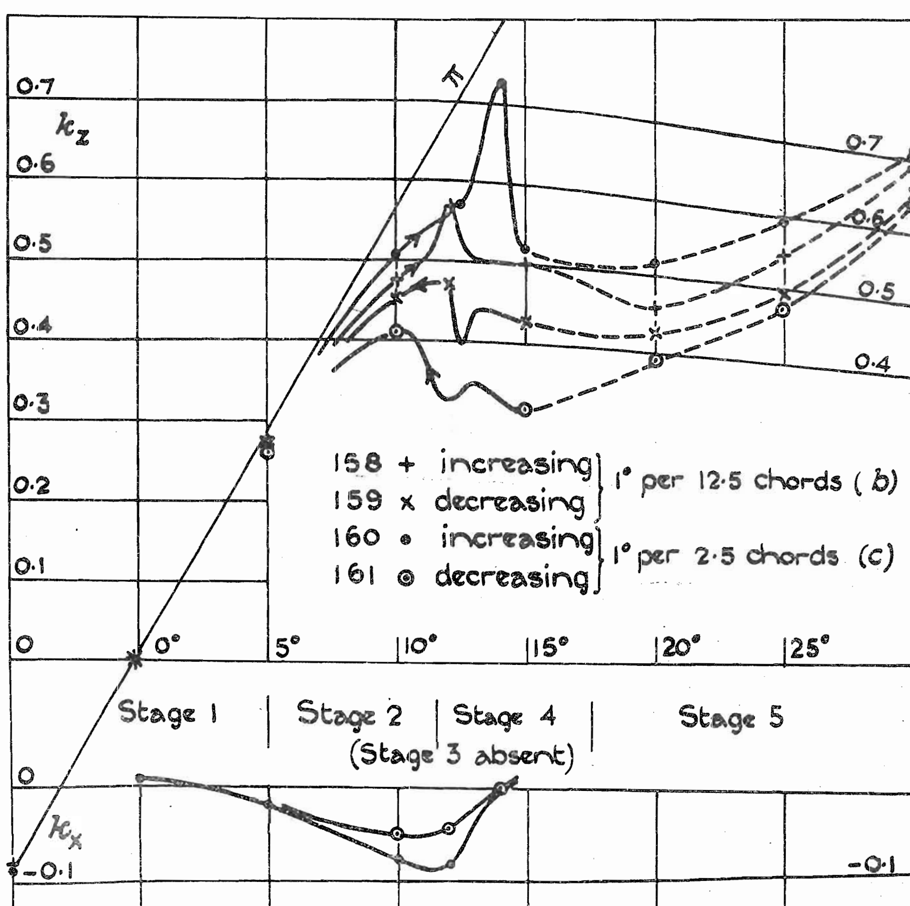


FIG. 15.

REDUCED RECORDS OF NORMAL AND LONGITUDINAL FORCE FOR PROFILE B.

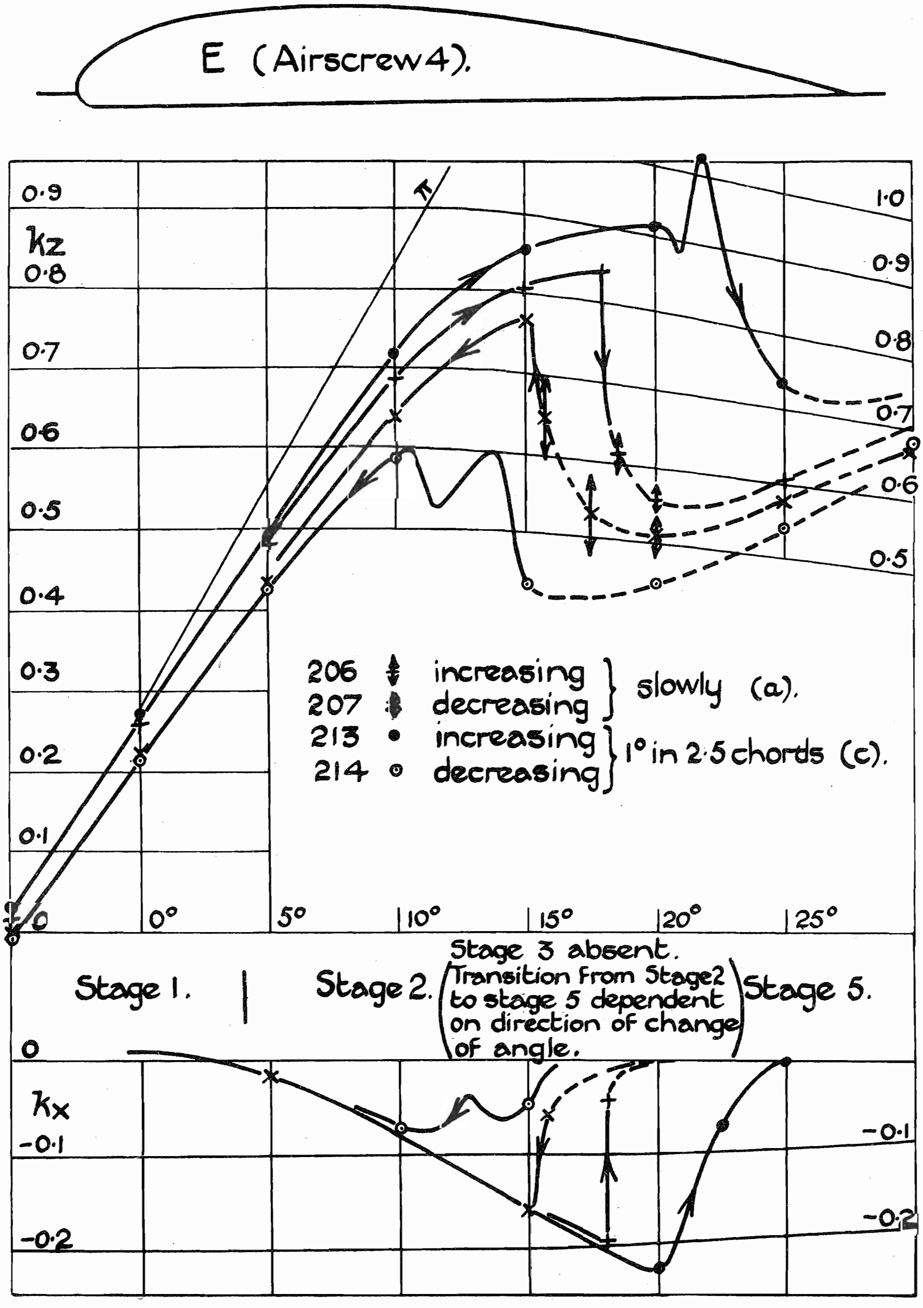


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FIG. 16.

REDUCED RECORDS OF NORMAL AND LONGITUDINAL FORCE FOR PROFILE F.

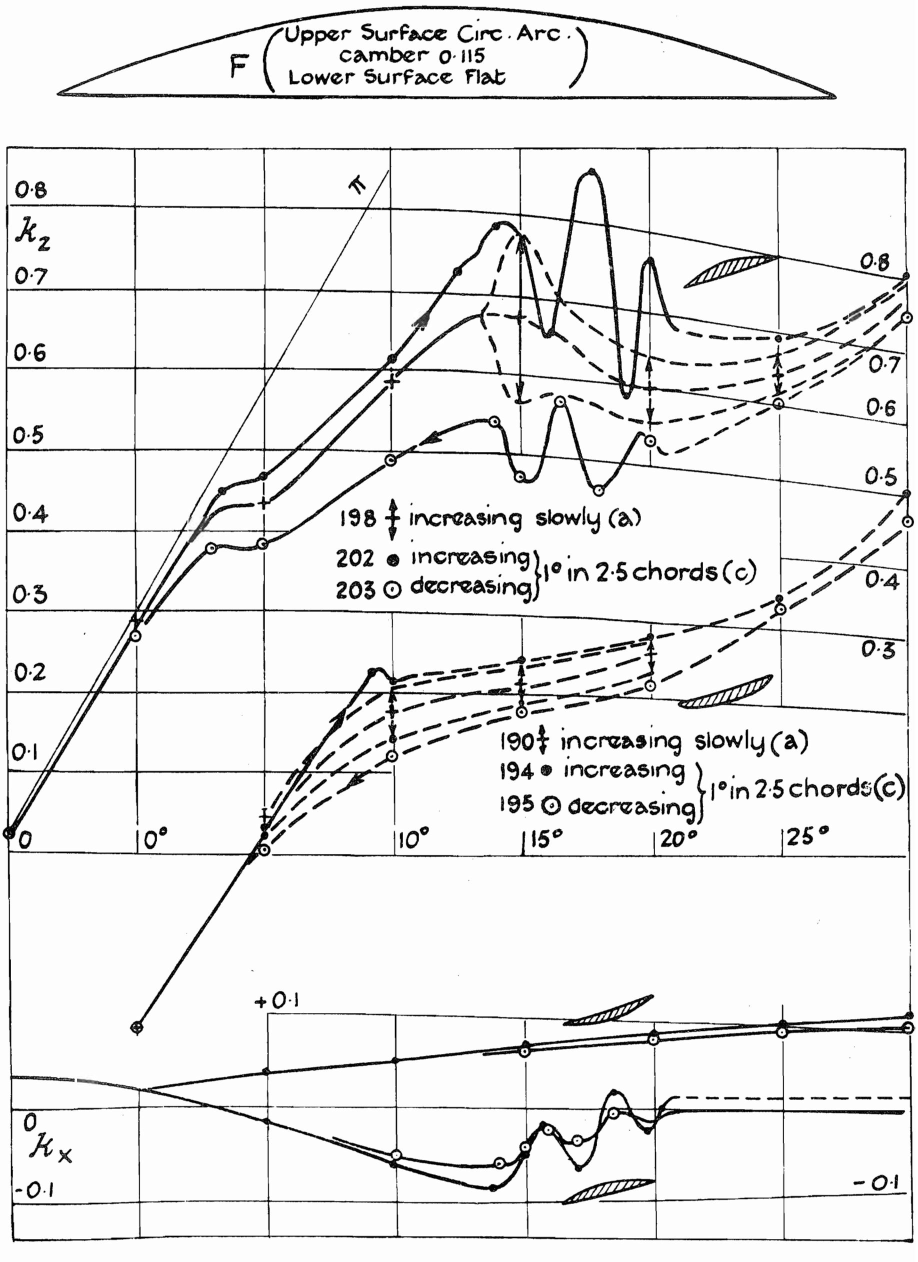
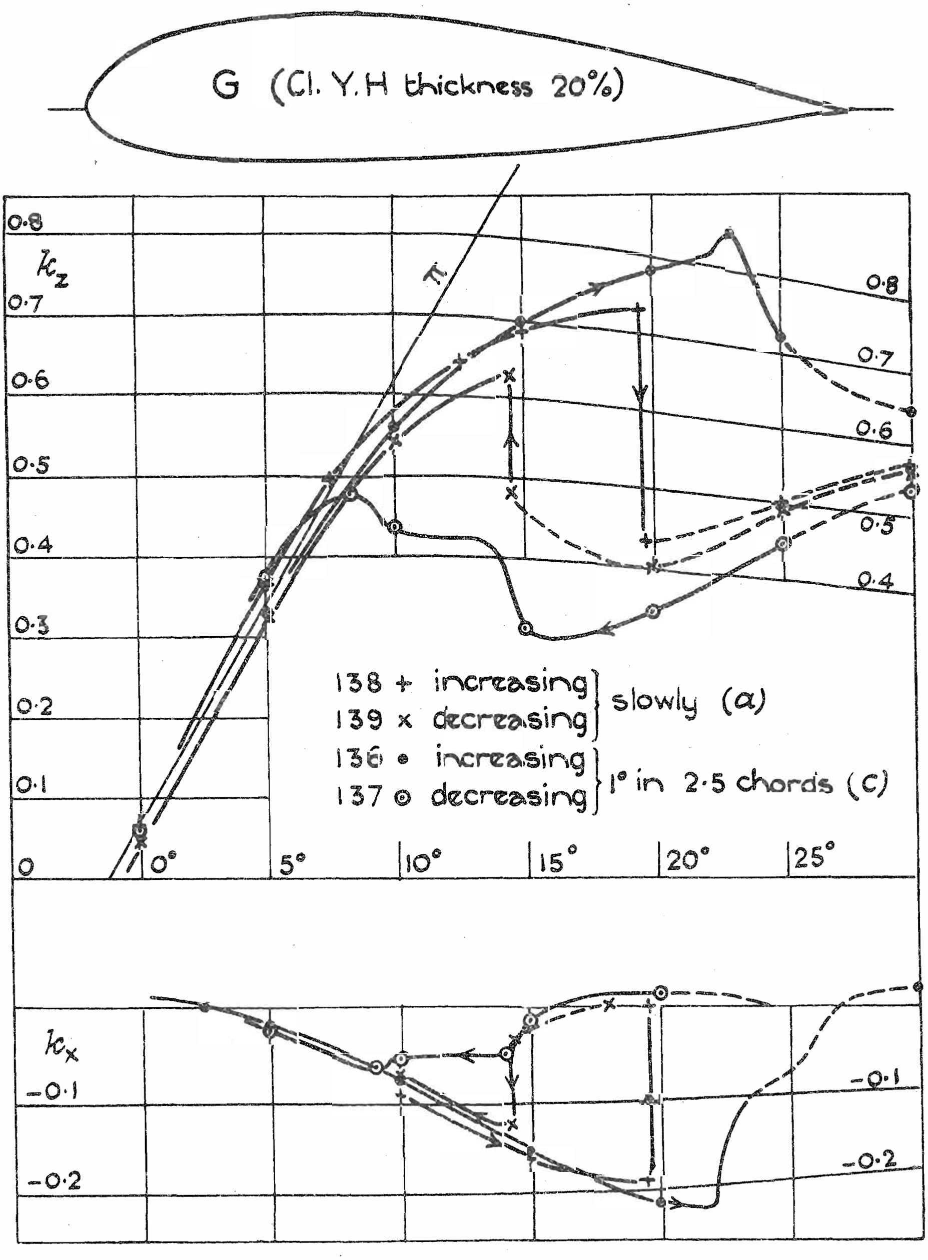


FIG. 17.

REDUCED RECORDS OF NORMAL AND LONGITUDINAL FORCE FOR PROFILE G.



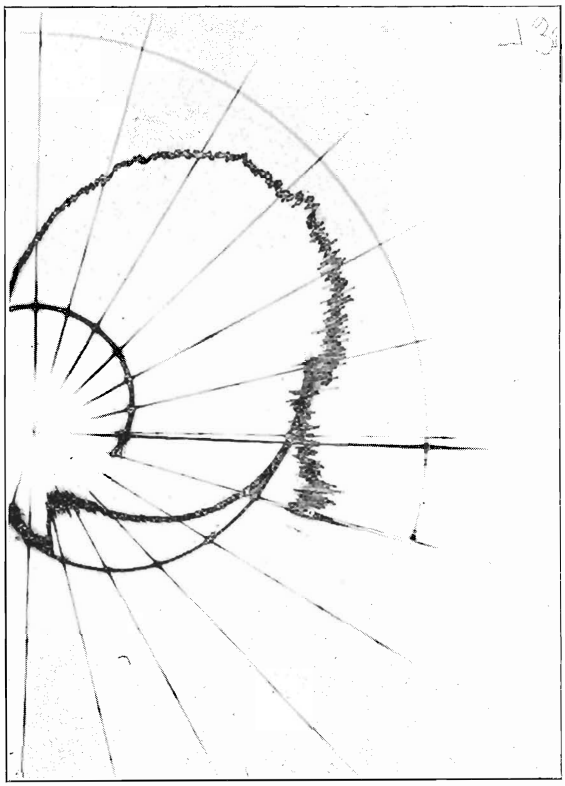


FIG. 18A.—Record 130. Profile H. Angle increasing slowly. Rate (*a*).

R. & M. 1648.

REDUCED RECORDS OF NORMAL AND LONGITUDINAL FORCE FOR PROFILE H.

FIG. 18.

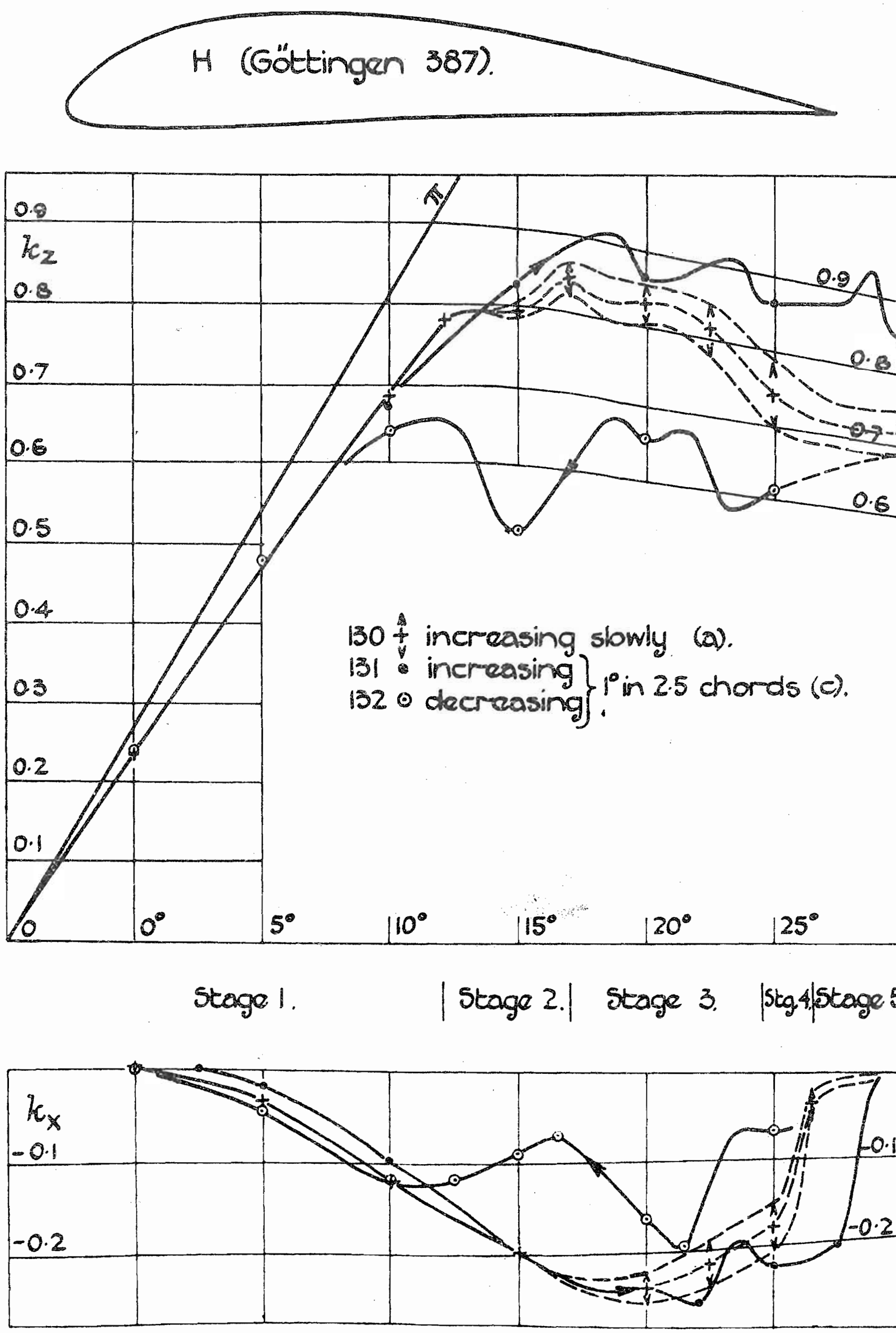
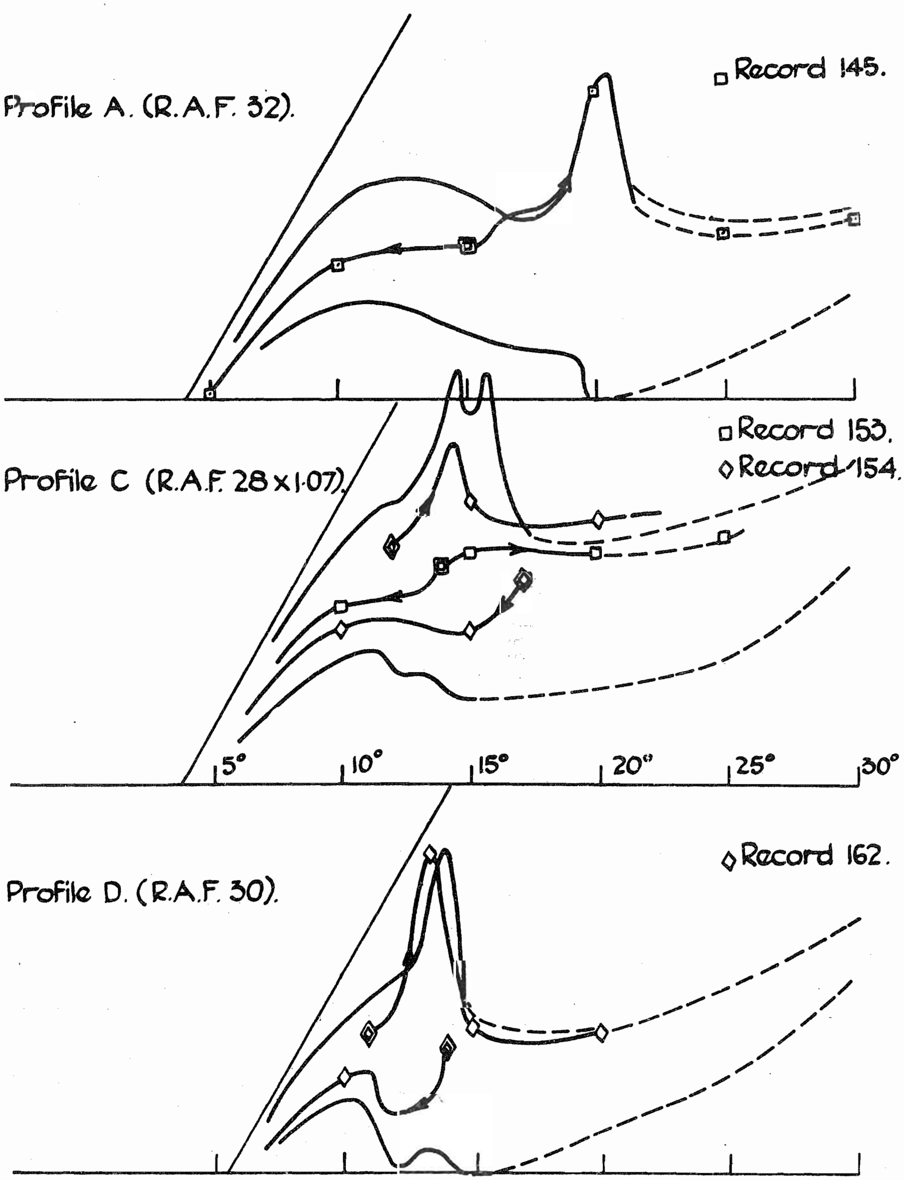


Fig. 19.

REDUCED RECORDS FOR PROFILE A, C AND D AT RATE (a), ANGLE BOTH INCREASING AND DECREASING FROM STARTING POINT IN OR NEAR FLUCTUATING REGION (SEE SECT. III § 13).



E.E.

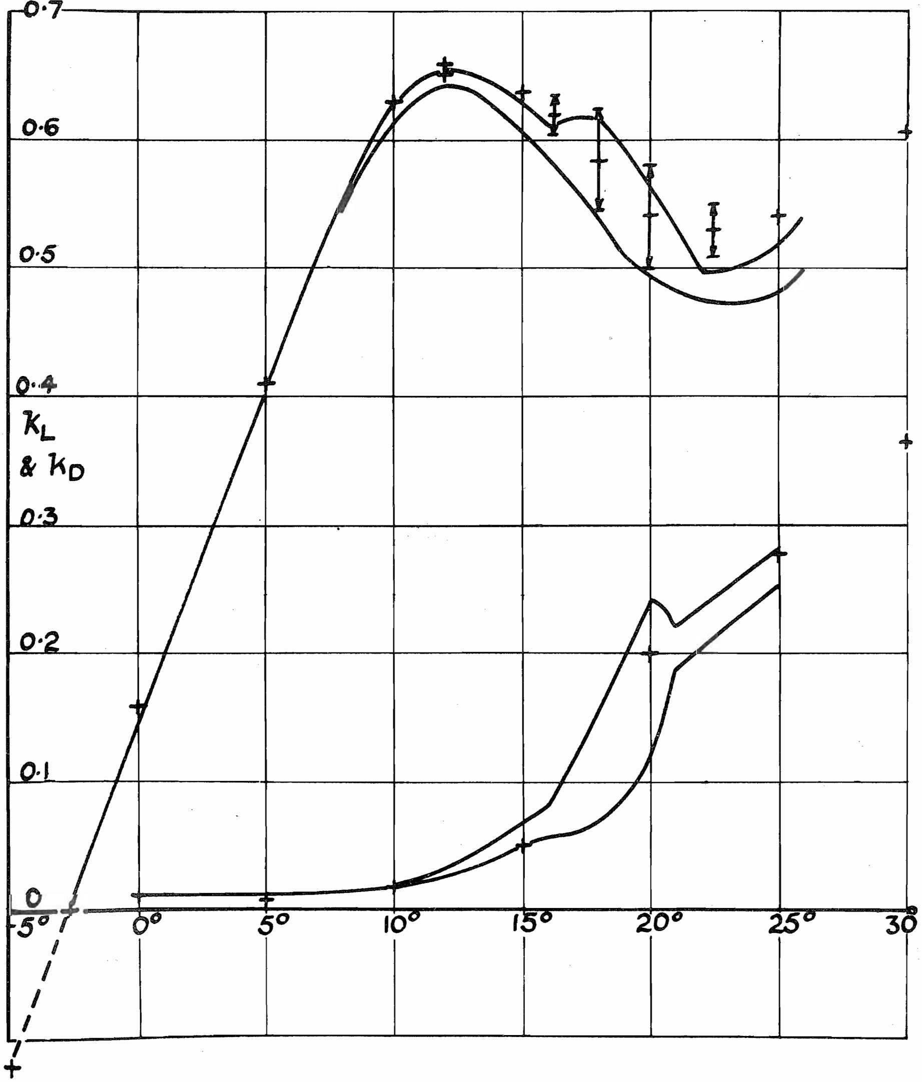
R. & M. 1648.

COMPARISON WITH FORCE MEASUREMENTS OF R. & M. 1588. — PROFILE B.

FIG. 20.

Full lines — limits of fluctuations of lift and drag from Fig. 2. R. & M. 1588.

ǂ mean lift and drag, and limits of fluctuations, calculated from mean of records 118 & 119. See Fig. 12. (see section III § 14).

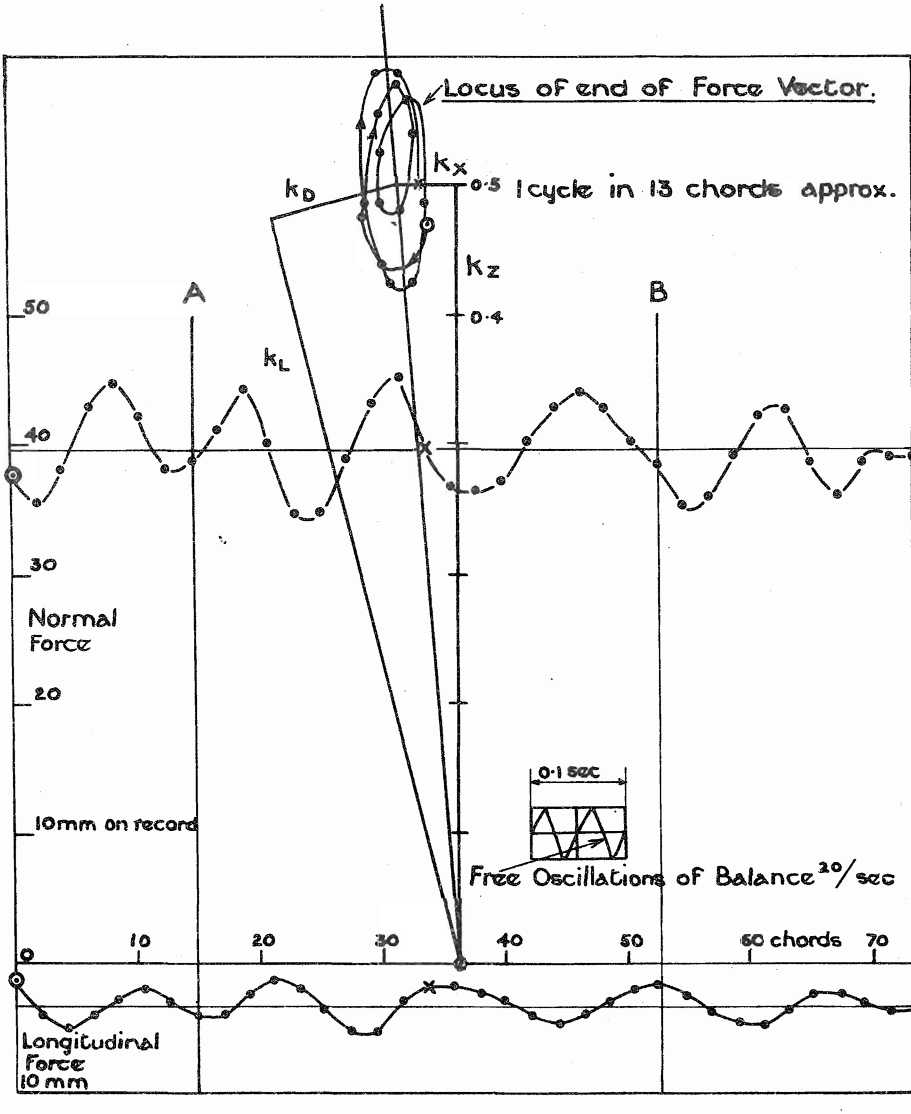


R. & M. 1648.

FIG. 21.

FORCE FLUCTUATIONS AT FIXED ANGLE OF INCIDENCE. PROFILE C (R.A.F. 28 x 1·07) AT 14°. RECORD 155.

(See Sect III § 14).



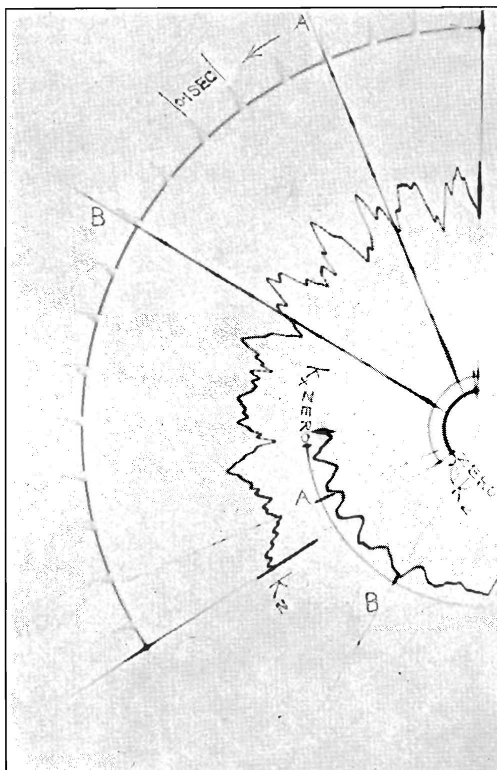


FIG. 21A.—Record 155. Profile C. Force Fluctuations at 14° Incidence.

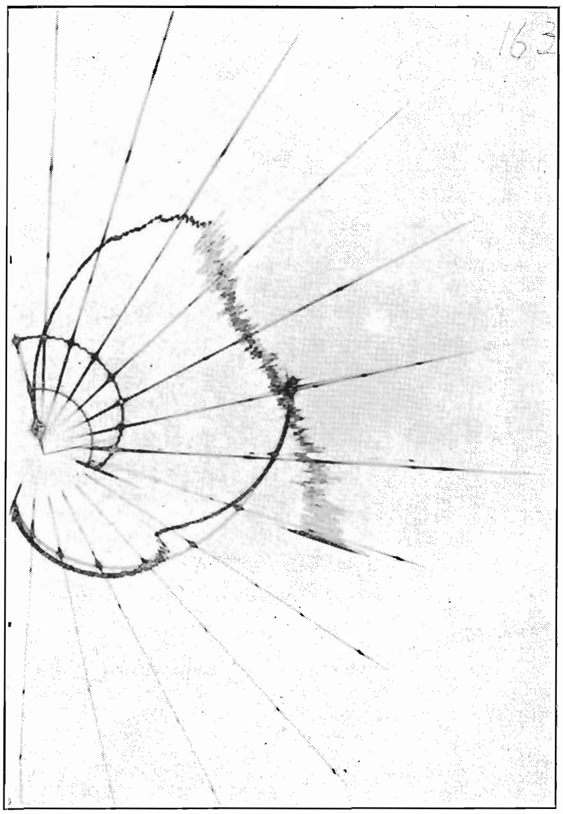


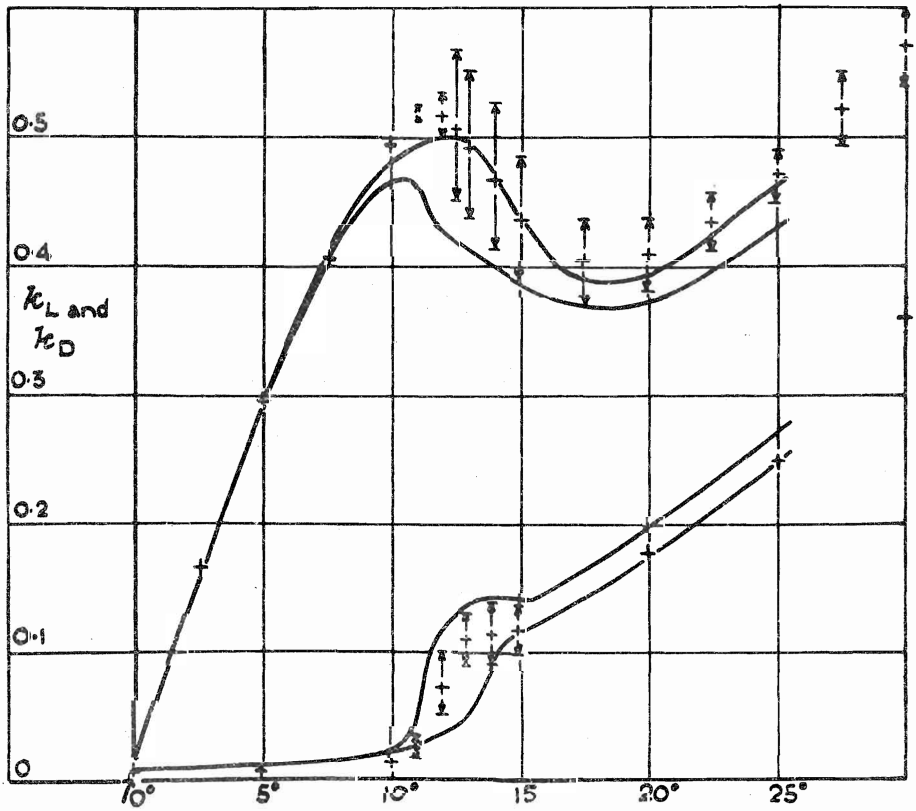
FIG. 22A.—Record 163. Profile D. Angle increasing slowly. Rate (*a*).

FIG. 22.

COMPARISON WITH FORCE MEASUREMENTS OF R. & M. 1588. PROFILE D.

Full lines – limits of fluctuation of lift and drag from Fig. 4, R. & M. 1588.

↕ + mean lift and drag, and limits of fluctuations, calculated from record 163 (Fig. 22A). (see Sect. III § 14)

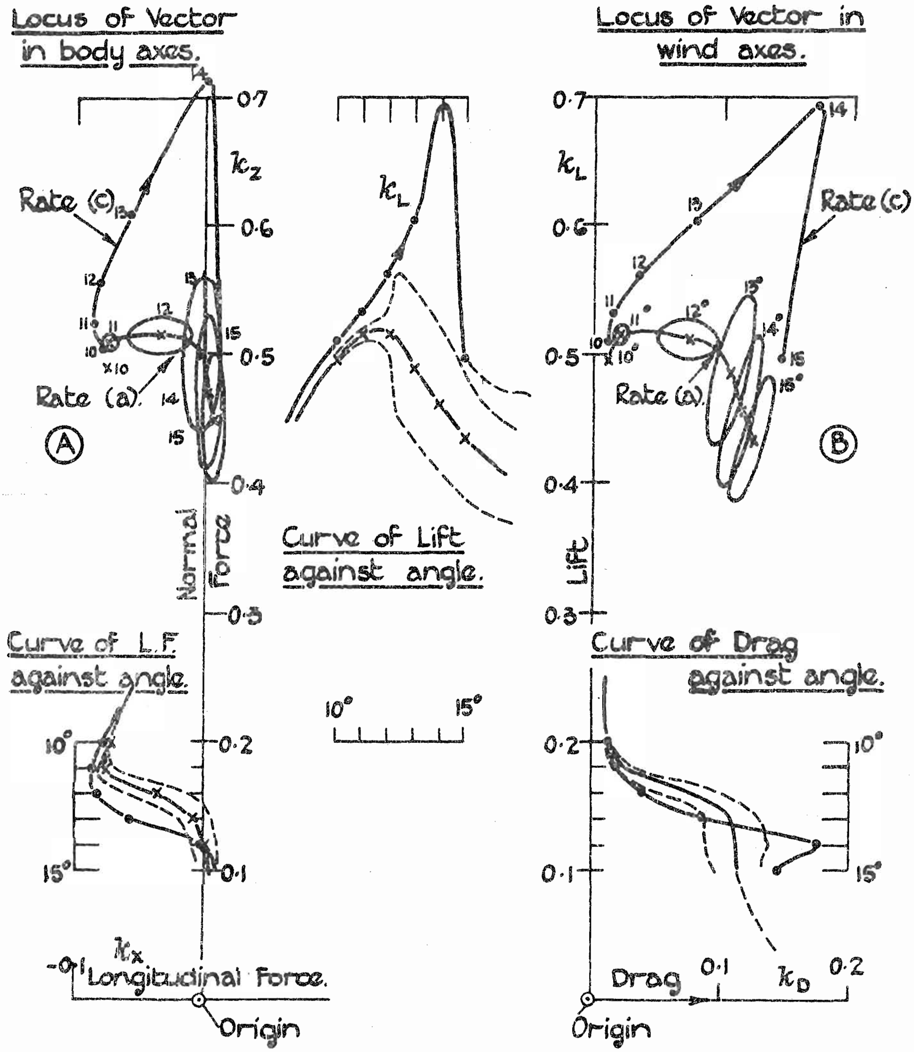


F.J.C.

R. & M. 1648.

FIG. 23.

VECTOR DIAGRAMS OF REACTIONS ON PROFILE D BETWEEN 10° & 15° AT RATES (a) & (c). (SEE SECT. III § 15).

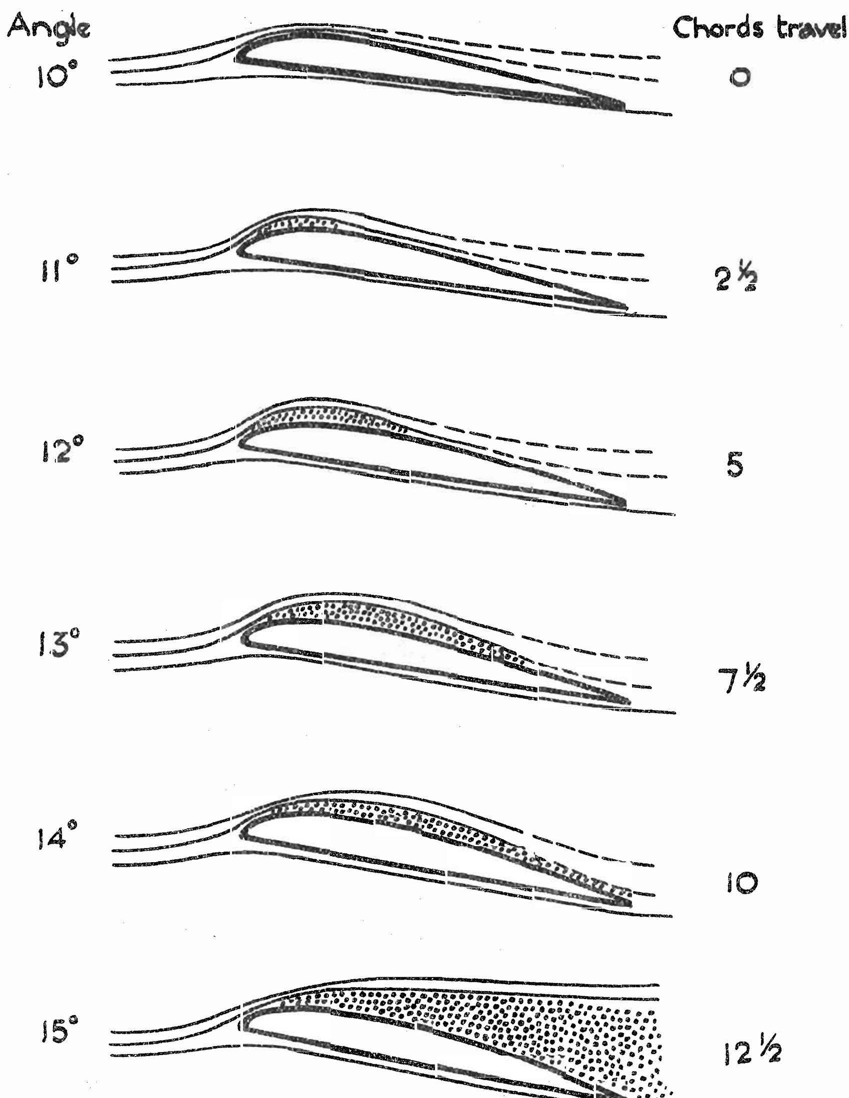


E.E.M.

R. & M. 1648.

Fig. 24.

DIAGRAMS ILLUSTRATING A TENTATIVE EXPLANATION OF THE "PEAK" OF NORMAL FORCE. SEE SECTION III § 16.



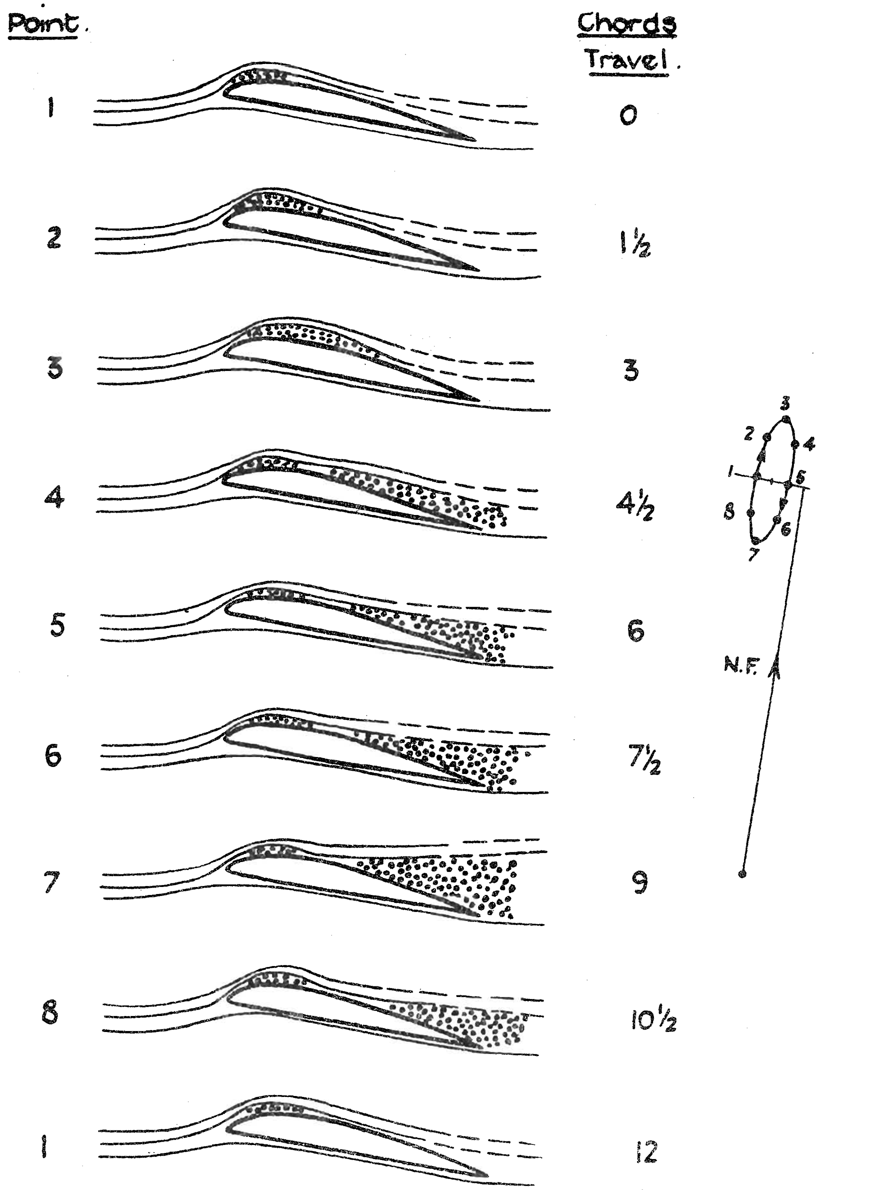
Note. These sketches are conjectural only, and do not represent observations of flow.

F.J.C.

R. & M. 1648.

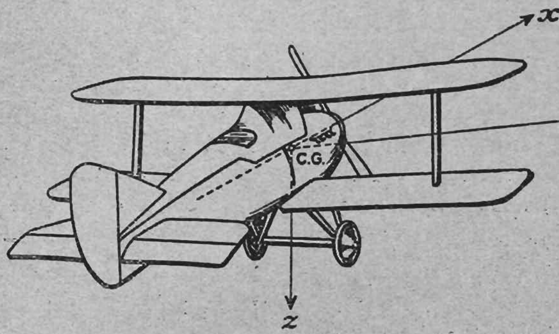
DIAGRAMS ILLUSTRATING A TENTATIVE EXPLANATION OF THE FLUCTUATION OF NORMAL AND LONGITUDINAL FORCE – SEE SECTION III §16.

FIG. 25.



Note. These sketches are conjectural only, and do not represent observations of flow.

SYSTEM OF AXES.



Axes	Symbol Designation Positive direction	x longitudinal forward	y lateral starboard	z normal downward
Force	Symbol	X	Y	Z
Moment	Symbol Designation	L rolling	M pitching	N yawing
Angle of Rotation	Symbol	ϕ	θ	ψ
Velocity	Linear Angular	u p	v q	w r
Moment of Inertia		A	B	C

Components of linear velocity and force are positive in the positive direction of the corresponding axis. Components of angular velocity and moment are positive in the cyclic order y to z about the axis of x, z to x about the axis of y, and x to y about the axis of z.

The angular movement of a control surface (elevator or rudder) is governed by the same convention, the elevator angle being positive downwards and the rudder angle positive to port. The aileron angle is positive when the starboard aileron is down and the port aileron is up. A positive control angle normally gives rise to a negative moment about the corresponding axis. The symbols for the control angles are :-

- ξ aileron angle
- η elevator angle
- η_T tail setting angle
- ζ rudder angle

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TECHNICAL REPORT of the Aeronautical Research Committee for the year 1931–32, with Appendices—		
Vol. I. Aerodynamics, Airships and Meteorology	35	0
Vol. II. Stability and Control, Spinning, Strength of Construction, Materials, etc. - - - -	27	6
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