REPORT No. 70

PRELIMINARY REPORT ON FREE FLIGHT TESTS

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

PREPRINT FROM FIFTH ANNUAL REPORT

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BY

E. P. WARNER AND F. H. NORTON

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By EDWARD P. WARNER and F. H. NORTON.

DESCRIPTION OF AIRPLANE EMPLOYED.

In a series of tests which have been made by the advisory committee's staff at Langley Field during the summer of 1919 with the objects of determining the characteristics of airplanes in flight and the extent to which the actual characteristics differ from those predicted from tests on models in the wind tunnel, and of studying the balance of the machines and the forces which must be applied to the controls in order to maintain longitudinal equilibrium, two airplanes have been employed. Both are advanced training machines of the JN4H type and both are equipped with Hispano-Suiza 150 horsepower engines, but they are somewhat different in structural details. The most important differences in connection with the aerodynamic characteristics of the airplanes are the use of an oil radiator suspended below the body and a reserve gasoline tank mounted in the center section of the upper wing on one of the machines, these accessories being lacking on the other. The machine carrying the oil radiator and the reserve tank will be referred to in this report as No. 1, the other as No. 2. In addition to the differences just noted, airplane No. 1 had the aluminum doors in the sides of the body, just forward of the wings, removed in order to permit of a freer flow of air through the radiator and past the engine, while No. 2 was flown with these doors in place. No cowling over the upper part of the engine was used on either machine, this being freely exposed to the air in order to dissipate as much heat as possible directly to the slip stream as it passed over the cylinder heads. Despite all precautionary measures adopted to prevent overheating, great difficulty was experienced in keeping the engine cool during the summer, and it was seldom possible to climb with the throttle fully open for more than a few minutes without raising the water temperature dangerously near the boiling point.

The two machines used are shown in figure 1, and general arrangement drawings of the JN4H are given in figure 2. The more important areas and the weights are tabulated below:

Areas.	Square feet.
Upper main plane, including ailerons	203.0
Lower main plane	150.0
Ailerons (total)	34.6
Stabilizer	28.5
Elevators	21.8
Fin	3.7
Rudder	11.8
Weights.	**Pounds.**
Airplane No. 1, tanks and radiator full, seats empty	1,906
Airplane No. 2, tanks and radiator full, seats empty	1,844

The difference in weight is due to the larger amount of gasoline and oil carried by No. 1 and to the extra tank and oil radiator provided on that machine.

The propellers used on the two machines were nominally exactly alike, both being made from the Air Service's design No. 13,279, having a diameter of 8 feet 6 inches, and being designed for an effective pitch of 5.22 feet. Actually they were quite different, the propeller which was used on machine No. 2 in most of the work having warped so that the pitch was

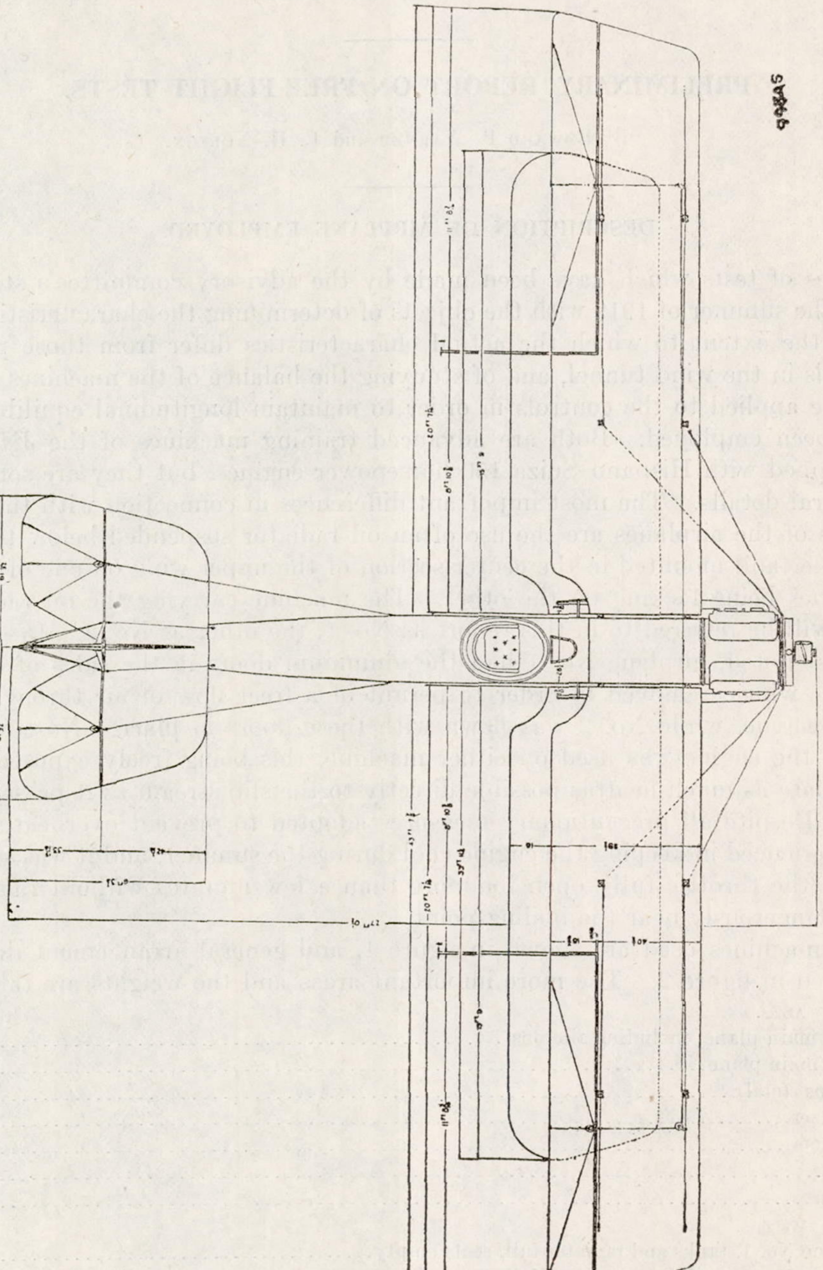
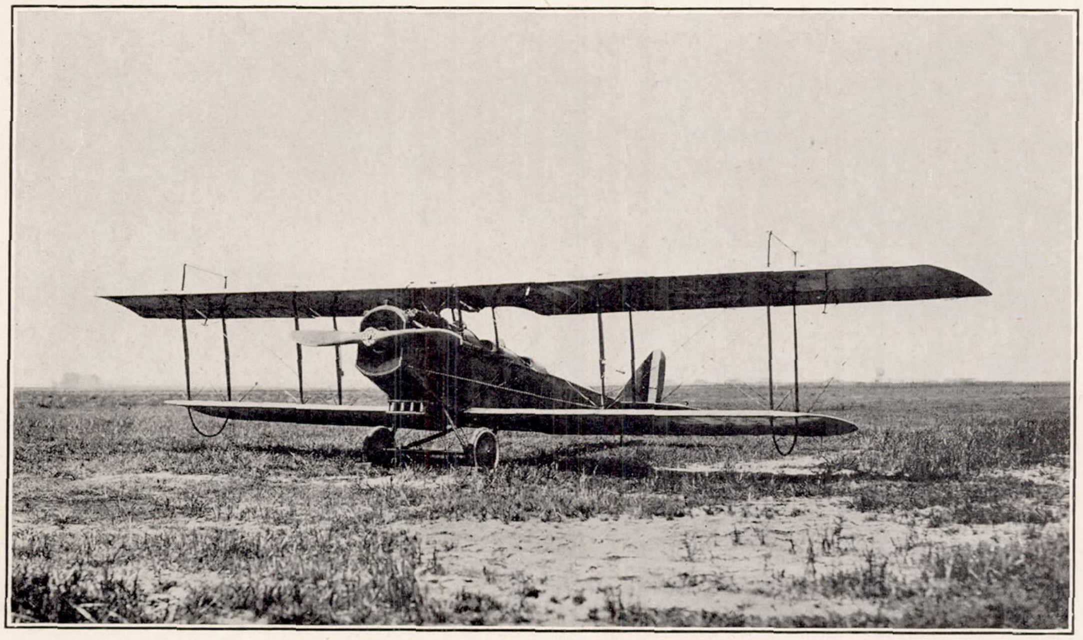


FIGURE 2 (a).



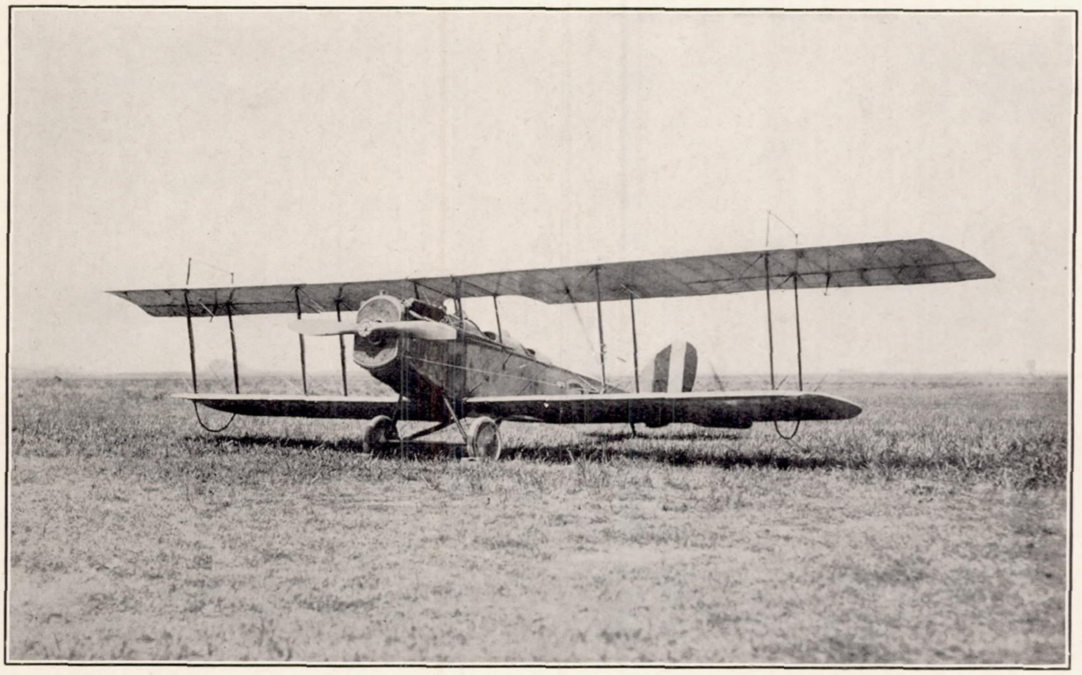


FIG. 1.

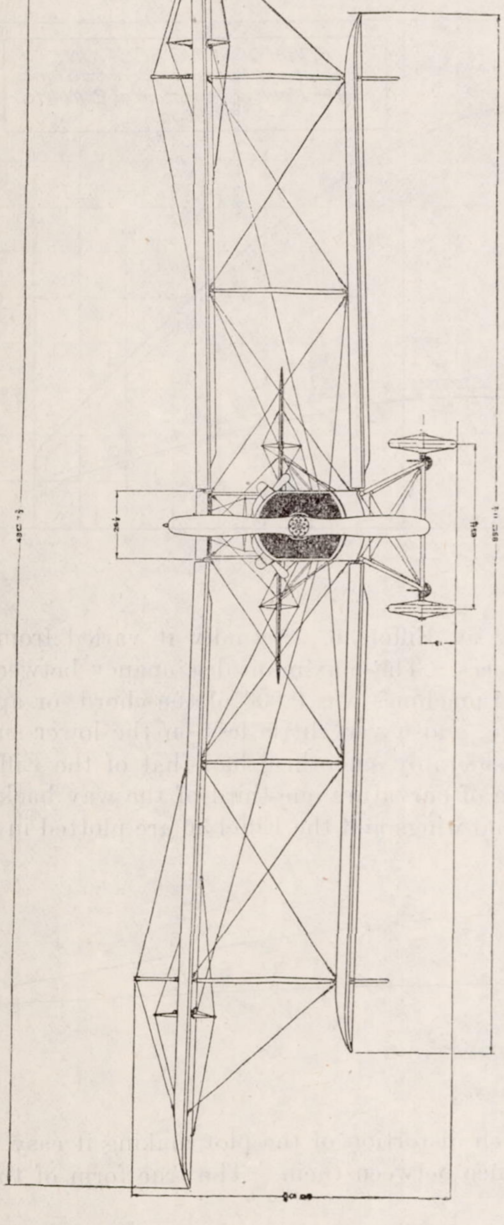


FIGURE 2 (b).

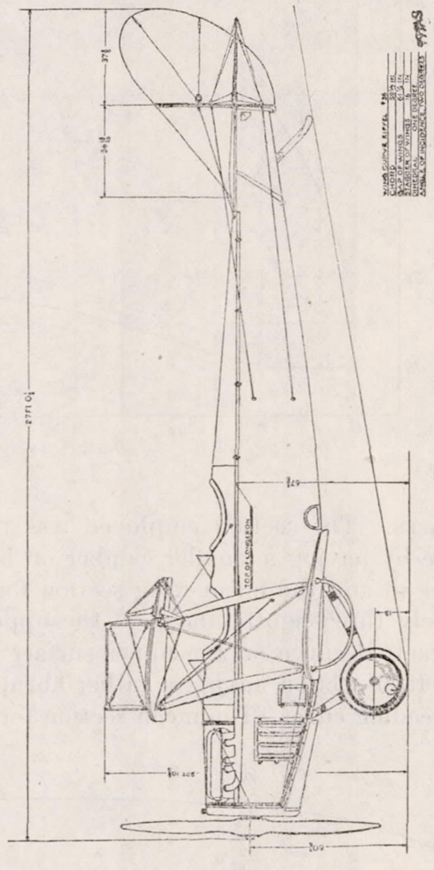


FIGURE 2 (c).

considerably less than it was supposed to be. The other propeller checked extremely well with the drawings, the mean blade angles for the two blades being correct within 0°.1 at all radii except within three inches of the tip, where the angle of setting was too large by 0°.35. The effect which this difference between the two propellers had on the results of the tests will be discussed elsewhere.

The most important factor from an aerodynamic standpoint is, of course, the type, form and arrangement of the main supporting surfaces. The wing section was accordingly checked up by direct measurement at several points on each machine, a frame being used which encircled the wing and provided base lines for measuring the cambers on both the upper and the lower

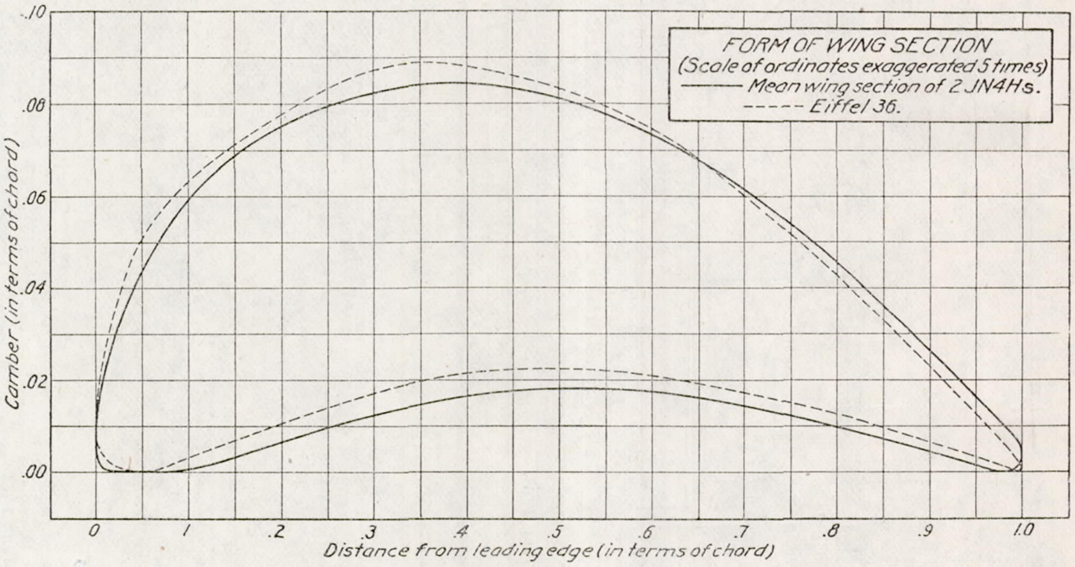


FIGURE 3.

surfaces. The section employed was nominally an Eiffel 36. Actually it varied from that curve by having a smaller camber on both surfaces. The maximum discrepancy between the Eiffel 36 and the mean wing section for the two machines was 0.006 of the chord, or approximately three-eighths inch, on the upper surface, and a very little less on the lower surface. The actual curve on the upper surface was considerably smoother than that of the Eiffel 36, the latter section having a rather abrupt change of curvature one-third of the way back from the leading edge. The mean section for the actual wings and the Eiffel 36 are plotted in figure

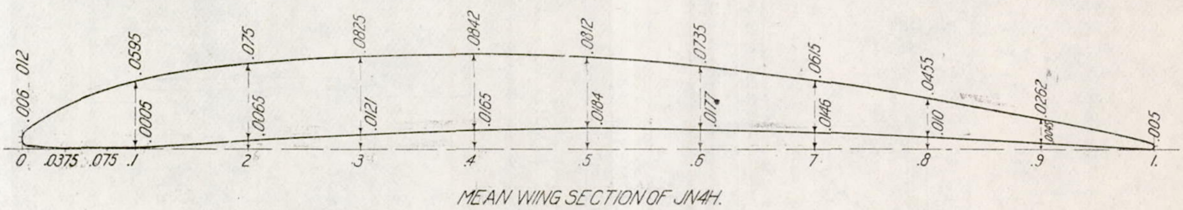


FIGURE 4.

3 with the ordinates very much exaggerated, such distortion of the plot making it easy to detect any unfairness of the curves or any difference between them. The true form of the section used is given in figure 4.

The difference between the mean sections for the two machines was negligible, being less than 0.002 of the chord at every point, and less than 0.001 at most points. Airplane No. 2 had a smaller camber than No. 1 on the whole upper surface and on the larger part of the lower one. Although the differences happened to counterbalance each other so that the mean sections were nearly identical, the extreme divergencies between the cambers at corresponding points on the different wings were by no means negligible. For example, the ordinates for one lower wing on No. 2 were uniformly greater than those for the other lower wing on the same machine, the difference sometimes amounting to as much as 0.004 of the chord. It is improbable that wings can be manufactured by ordinary production methods with a greater uniformity of section than that found in these two machines, and, even if they could be made originally with greater accuracy, wooden ribs will not hold their curvature exactly when submitted to varying climatic conditions. Wind tunnel experiments indicate that the effect of changing the camber of an aerofoil by 0.004 of the chord is seldom serious, so long as the surface retains a smooth curvature, except in very thick sections such as are used in propeller blades and in internally braced airplanes such as the Fokker biplane and triplane. It appears to be fair to assume that the differences in section among the wings used on these machines will have no effect on their characteristics and that the mean section, as shown in figure 3, can be assumed to exist at all points.

The discrepancy between the actual form of the wing section and the curve on which it was supposed to be based points a dual lesson. In the first place, it draws attention to the need of making wind-tunnel models to represent the airplane as it is actually built, or to be built, not merely according to specifications which the shop may find itself quite unable to follow. It is of little use to construct model aerofoils accurate to within 0.002 inch if the full-sized wing which they represent departs by as much as three-eighths of an inch from the section which it is supposed to follow. Secondly, these measurements should serve to remind experimenters engaged in the design of wing sections of the futility of drawing forms which it is impossible to construct by ordinary methods. For instance, no airplane wing is constructed with the upper and lower surfaces running out until they intersect in a perfectly sharp trailing edge. Indeed, it is practically impossible to construct a model aerofoil for the wind tunnel with such a trailing edge, yet aerofoils are repeatedly drawn up in such forms. The result is that the model maker exercises his own judgment as to the extent to which the trailing edge should be rounded over, the airplane builder introduces a strip of wood or of steel tube for a trailing edge, and the drawing, the model, and the full-sized wing are likely ultimately to be of three quite different forms.

In the JN4H, the thrust line is parallel to the top longerons and the stabilizer, which is flat on its lower surface, lies directly on the longerons. A detailed discussion of the actual form and setting of the tail surfaces is of interest primarily in connection with the longitudinal balance of the machine, and it will be reserved for treatment in connection with that subject. The wings are nominally set at an angle of 2° to the top longerons, but the mean angle of incidence in both of the machines used in this work was somewhat greater than that, being 2°.25 in No. 1 and 2°.4 in No. 2. The variation of incidence along the wing, due to warping, to slightly imperfect rigging, and to the droop provided in the left wing to balance the propeller torque, was about 0°.3. The ailerons were rigged as nearly as possible to form a continuation of the upper wing, so that, when the stick was centered, the angles of incidence of the portions of the upper wing which carries the ailerons were very nearly the same as for the inner part of the wings. A small change in the rigging of the ailerons when in the neutral position has a marked effect on the lift and drag coefficients of the wings.

CALIBRATION OF INSTRUMENTS.

The first step in the making of any tests is necessarily a study of the accuracy and a determination of the calibration curves of the instruments employed. The standard instruments, used in all tests, are the altimeter, the tachometer, and the air-speed meter. The altimeter can readily be calibrated in the laboratory under a bell jar. Since the altimeter was used, in most of these experiments, only for determining the density correction, and since most of the work was carried out at less than 4,000 feet altitude, the permissible percentage error in altitude determination was quite large. An error of 130 feet in the altimeter reading, or more than 4 per cent at 3,000 feet, affects the density determination by only one-half per cent. The effect of such minor factors as the decrease of static pressure in the cockpit, due to the slip-stream velocity, can therefore be neglected. It is usually possible, at the time of calibrating the altimeter, to adjust the instrument so that the errors are negligible in such work as this at altitudes of less than 4,000 feet, and the scale readings can therefore be used directly without resort to a calibration curve.

The tachometers used were made by the Van Sicklen Co., and were of the chronometric type. No calibration of these instruments was adjudged necessary, as the readings of the instruments in the front and rear checked, and as a chronometric tachometer can generally be counted on to give readings very nearly correct so long as it gives any readings at all. If anything goes wrong the instrument usually stops recording entirely.

The calibration of the air-speed meters presents a much more serious problem than does that of either of the instruments just discussed, for several reasons. There are several possible sources of error in the air-speed determination. In the first place, the meter itself may be in error initially or may go wrong after some use. Errors of this type can be determined by calibration of the meter in a wind tunnel. In the second place, the pitot or venturi tube used for measuring the velocity head being located close to the machine and in air disturbed by the passage of the wings the velocity of the air past this tube is, in general, different from the velocity of the airplane relative to the undisturbed air. For example, the vortex theory of sustentation declares that there is, superposed on the rectilinear flow of air relative to the wing, a cyclic flow around the wing, so that the relative air speed above the wing is higher, and that below the wing lower, than the speed through undisturbed air. An air-speed meter having its head placed close above the wing would therefore give too high a reading, no matter how closely the instrument might have calibrated in the laboratory. Finally, the air-speed meter will not give a perfectly correct reading if the axis of the head is not parallel to the relative wind direction at that point. Inclination of the head to the relative wind results from the diversion of the air flow by interference, a diversion which extends to a considerable distance forward of the wings, and also from the changing attitude of an air-speed meter head fixed in the machine as the angle of attack is altered.

Since practically all free-flight testing requires the determination of the air speed from a meter the accuracy of that instrument is of great importance. In the determination of lift coefficients, for example, an error of one-half mile an hour in the measurement of the air speed at its mean value (about 65 miles per hour for the JN4H) has as bad an effect on the final result as would an error of 400 feet in the altitude determination. It is essential, therefore, that the instrument be calibrated in place on the airplane and that the calibration be repeated at intervals to guard against changes in the meter.

The air-speed meters used in these tests were Bristol instruments. They were graduated with a division at each mile, but the scale was uniform enough and open enough so that it was easy to estimate the reading to half a mile an hour. The heads were pitot-venturi tubes of the standard Army type, and were mounted on the left inner forward interplane strut, about 18 inches above the lower wing. The inner strut is preferable to the outer one because of the smaller length of tubing required to make connection to the meter and also because the flow of air at the inner strut is more nearly parallel to the plane of symmetry of the airplane, the relative air velocity at the outer strut having a considerable component parallel to the Y axis, which would cause the air to strike the tubes obliquely and so give false indications.

There are two classes of methods used for calibrating air-speed meters in position. The first, much used by the British, involves the use of a camera obscura for the determination of speed over the ground. The speed with which the image of the airplane crosses the field of view can be measured with great accuracy, but the ground speed for a given rate of travel of the image is directly proportional to the altitude, and the altitude must therefore be determined within one-half per cent or better, an accuracy beyond the reach of any altimeter. The altitude can best be determined by the use of a second camera obscura or of a theodolite in conjunction with one camera obscura, the vertical angles of the plane as seen from two different points at the instant when it crosses a line connecting those two points giving the necessary data for computing the altitude. The effect of the wind can be determined and corrected for either by measuring the velocity of a puff of smoke fired from the airplane or by flying across the field of view in three different directions, one after the other, and measuring the ground speed in each direction. There is only one camera obscura at Langley Field, and it was not deemed advisable to secure another. The camera obscura therefore has not been used for calibrating the air-speed meters in these tests.

The second method, and the one so far used in the work of the National Advisory Committee, is simpler and more direct, requiring only the timing of the airplane over a measured course. The course laid off at Langley Field is 5,600 feet long, and two horizontal wires, one directly above the other and about 3 feet apart, are carried on poles at each end. One of these observing stations is shown in figure 5. The airplane was flown over the course at an altitude of from 200 to 1,000 feet, the higher altitudes generally being used at the lower speeds, where there was some danger of stalling or side slipping or starting a spin. The pilot kept the speed as nearly constant as possible and the observer recorded the air-speed meter reading every 5 seconds. Two or three runs were made in each direction at each speed, the speeds at which the meter was calibrated being spaced about 5 miles per hour from the maximum down to the minimum. The ground speed of each run is determined by observers at the ends of the course, the two stations being in telephonic communication. The effect of the wind is eliminated, assuming that its direction and velocity do not change between runs, by computing the mean air speed for successive runs made approximately at the same speed and plotting it against the mean ground speed for the same runs. This method is much more satisfactory, when the pilot is skillful enough to make his runs at air speeds very nearly uniform and close to the desired speeds, than any attempt to measure the component of wind velocity along the course and correct each run for the effect of that component, as both direction and velocity of the wind are so subject to change with altitude that measurements within 50 feet of the ground give little information as to the conditions existing at three or four hundred feet. If the wind is blowing across the speed course, or at an angle to it, the machine should be kept pointed along the course and allowed to drift rather than being headed into the wind in such a way that the path over the ground will be parallel to the course. The right and wrong methods are shown in figures 6a and 6b, where W is the vector representing wind velocity, A the air speed, and G the resultant speed over the ground. In figure 6b the air speed is greater than the component of ground speed parallel to the course, in whichever direction flown, and the timing over the ground of a machine flown in this manner would therefore give too low a mean true speed. In figure 6a, on the other hand, the two quantities just mentioned are exactly equal.

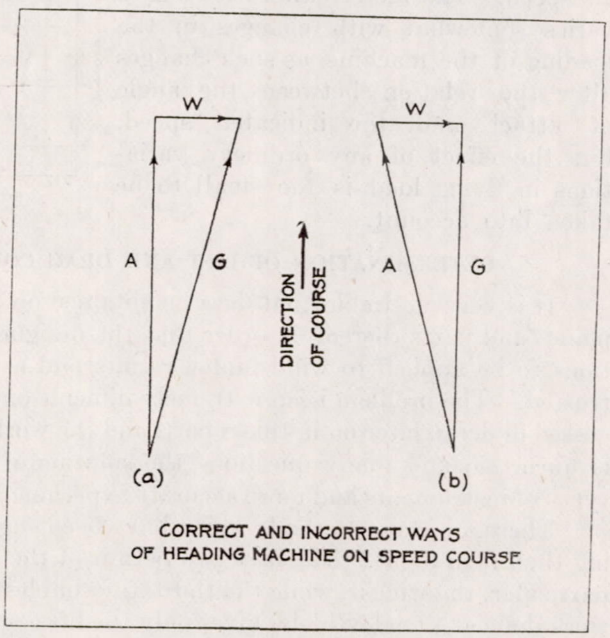


FIGURE 6.

The calibration curves found in this way for the meters in the rear cockpits of the two machines are plotted in figure 7. It will be observed that they follow the same general form, the relative displacement between the two curves probably being due to an error in one of the instruments. It might be expected that the meter would read low at very low speeds and large angles of attack, due to the inclination of the head to the relative wind, but it actually appears to read high. This result has been obtained in tests on both airplanes, and there is little doubt of its accuracy, although the error in calibration at low speeds is greater than that at high, both because the effect of wind variations is more marked at low speeds and because it is difficult for the pilot to hold a straight course over the ground while flying at large angles of attack. In figure 8 the corrections to be applied to the air-speed meter reading are plotted against indicated speed, these curves serving to give a clearer idea of the extent of the errors involved in the direct application of uncorrected meter readings than do those of figure 7.

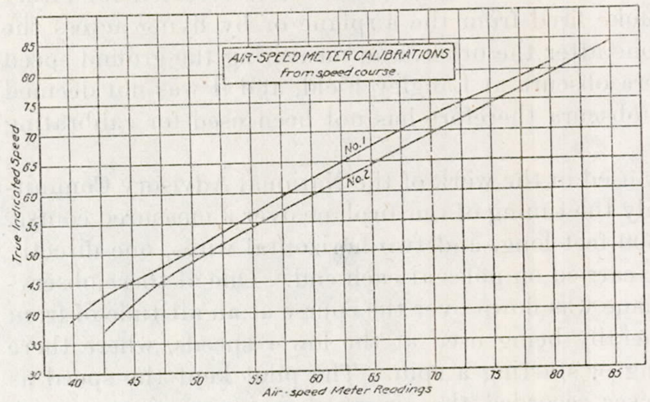


FIGURE 7.

When tests are made at high altitudes, where the difference between the indicated and true air speeds is large, the meter calibration correction should be applied to the indicated speed first, and the result thus obtained should be multiplied by the density correction to give the true speed. This order of procedure is necessary because the flow of air about the wings, and therefore the interference effect on the instrument readings, depends on the indicated, not the true, air speed. The meter calibration curve varies somewhat with changes in the loading of the machine, as such changes alter the relation between the angle of attack and the indicated speed, but the effect of any ordinary variations in flying load is too small to be taken into account.

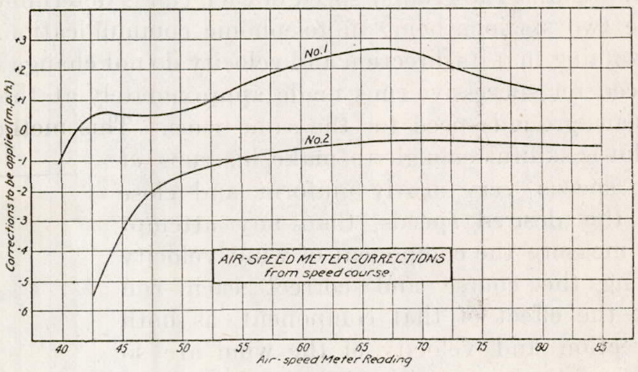


FIGURE 8.

DETERMINATION OF LIFT AND DRAG COEFFICIENTS: METHODS EMPLOYED.

It is very desirable that data be obtained on the lift and drag in free flight of full-sized airplanes and parts thereof, in order that the designer may gain some knowledge as to the corrections to be applied to wind-tunnel results and as to the extent to which those results can be trusted. The problem is an extremely difficult one for many reasons, some of which will be discussed in detail later on in this report, and the work which has so far been done leaves much that is uncertain and many questions the solution of which can not even be attempted until new types of instruments and more accurate experimental methods have been devised.

There are three methods which have been suggested and employed to some extent for finding the lift in flight. The first two permit of the determination of the lift of separate parts (in particular, the wings), while the third, the simplest, and the only one which has been used in the work done at Langley Field, gives only the lift coefficients for the airplane as a whole. The first and most obvious of these methods proposes the measurement of the lift of any part by the interposition of weighing devices between that part and the remainder of the airplane. For example, the wing hinges might be attached to the body through the medium of springs. There has been a great deal of discussion of the possibilities of this method, but the mechanical difficulties are considerable, and not much actual work has been done. The second method depends on the measurement of the pressure at a large number of points on the surface of the wings (and, if desired, on the tail of the body) and the determination of the total lift by the integration of these pressures over the whole surface. This has been used to some extent in England, and similar work is planned for Langley Field during the coming year. The pressures can be measured, once the apparatus is satisfactorily constructed, with great ease and accuracy, and the only errors to which the method is subject are those inherent in all free-flight measurements.

The third method is, as was just noted, the simplest, in that it requires the least special apparatus. In the equation $L=L_c\times\frac{\rho}{g}\times V^2$ it is known that L is equal to the weight of the machine when the flight path is horizontal, and that it departs only very slightly from that figure for any ordinary inclination of the path (short of a steep dive). Since ρ can be computed from measurements of the pressure and temperature, the determination of L_c requires only the measurement of V. As a matter of fact, since the air-speed meter records not the true speed but the product of $V\times\sqrt{\rho/\rho_0}$, the term ρ/g can be eliminated by the substitution of indicated for true air speed, and the equation above can be written:

$$L=L_cCV_i^2$$

Where C is a correction constant taking into account the gravity constant g and the conversion factor changing V_i from miles per hours to feet per second. Although a small part of the lift is due to the body and the tail surfaces have a substantial effect at some angles, it is convenient to divide the lift by the wing area and write the above equation in the form

$$L=L_cCAV_i^2$$

With a good meter and careful calibration the air speed can certainly be determined with an error of less than 1 mile per hour and probably less than ½ mile per hour, and the lift coefficient at any given instant during a flight can therefore be computed very accurately. In substituting for L in the characteristic equation, allowance has to be made for the progressive diminution of weight by the comsumption of fuel and for the direct balancing of part of the weight of the machine by the vertical component of the propeller thrust.

Since the lift coefficient is a function of angle of attack, it is of very little use to compute the value of the coefficient at any instant during a flight unless this angle at the same instant is known, and it is in the determination of this angle that the greatest difficulties arise. The conventional type of "incidence indicator," embodying a pivoted vane and two Pitot tubes at a considerable angle to each other or a sphere pierced with two holes, is useless unless some other means is employed to calibrate it in position, as the instrument has to be placed in air disturbed by the passage of the airplane, and the motion of the instrument relative to this disturbed air, as already noted in connection with the calibration of the air-speed meters, may be of quite a different nature from its motion relative to the air at a great distance. The disturbance of the airby the wings extends to so great a distance (three or four chord lengths) in front of the leading edge that it is impracticable to carry the incidence indicator far enough forward entirely to escape this disturbance.

Since the angle of attack is the inclination of the wings to the relative wind, it is equal to the difference between the inclination of the wings to any fixed reference plane and the inclination of the relative wind to the same plane. In particular, the angle of attack can be determined if instruments are available which will give the angles between any line fixed in the airplane and the horizontal and between the relative wind and the horizontal. The first of the these angles is given, provided that the machine is in steady rectilinear flight, by a liquid longitudinal inclinometer. The second can not readily be determined directly, but the inclination of the flight path to the horizontal is given by a rate-of-climb meter in conjunction with an air-speed meter, and this is equivalent to the inclination of the relative wind if the movement of the air is exactly horizontal. In the particular case where the flight path is level the rate-of-climb meter can be replaced by a statoscope. The largest error in the determination of angle of attack by this method arises from the assumption that the air moves only horizontally. An ascending current having a velocity of only 1 foot per second changes the angle of attack, for a given attitude of the machine relative to the earth, by nearly 0°.7 at an air speed of 60 miles per hour. This is a very gentle ascending current, and it will be shown later that vertical currents which have actually been encountered during these experiments have affected the apparent angle of attack by more than 1°.

The statoscope used is shown in figure 9. The tube was kept separate from the vacuum flask, instead of mounting both in one case as is customary, in order that the flask might be placed behind the instrument board and the space occupied on the board be kept down to a minimum. The use of the statoscope makes it practicable to keep the mean rate of climb or descent down to 20 feet per minute except at very large angles of attack, and a rate of climb of 20 feet per minute affects the angle of attack at 60 miles per hour by less than 0°.25.

The ordinary commercial type of longitudinal inclinometer proved unsatisfactory, first, because the scale was not open enough to permit the angles to be read as closely as was desired, and, second, because the face of the instrument was perpendicular to the instrument board. The observer's eye being well above the board, the observer looked down on top of the meniscus and across it at the scale behind, and the parallax error was large. An instrument was designed to obviate these difficulties, and is shown assembled in figure 10. Figure 11 illustrates the tube removed from the case. The front tube and scale make an angle of 20° with the surface which rests against the instrument board. The mean distance between the two surfaces of the column of liquid is 8 inches. The scale is divided in degrees, the divisions being roughly one-eighth inch apart, and it is easy to estimate to 0°.1. The liquid is a mixture of glycerin and alcohol, colored with red ink. The damping of oscillations depends on the viscosity of the liquid, and this can be controlled by varying the proportions of alcohol and glycerin. The tube is constricted at one point to increase the damping. Parallax was avoided by mounting a mirror beside the instrument, the observer bringing the reflection of his eye in line with the meniscus.

It unfortunately has not been possible to base the measurements of the drag entirely on data obtained in flight, as no satisfactory means of measuring the propeller thrust is available as yet. It is therefore necessary to rely on a wind tunnel test for the propeller characteristics. A partial check can be obtained on the wind tunnel results by measuring the slip-stream velocity, as described in another section of the report. Knowing the revolutions per minute and the true air-speed, the value of $\frac{V}{ND}$, the propeller slip function, can be computed, and the thrust can then be determined from a curve of T_c against $\frac{V}{ND}$. The equation for thrust is:

$$T = T_c \times \rho/g \times V^2 \times D^2$$

Since, as in the case of the lift $\frac{\rho V^2}{\rho_0}$ is equal to V_i^2, this may be written:

$$T = T_c \times C \times V_i^2$$

where C is a constant including correction factors for units and D^2, which is constant for a given propeller. A model of the propellers used has been tested at the Leland Stanford Jr. wind tunnel, and the curves of T_c and efficiency are reproduced in figure 12. Plotting the thrust against the angle of attack, and dividing the total lift by the horizontal component of thrust, a curve of L/D can be obtained.

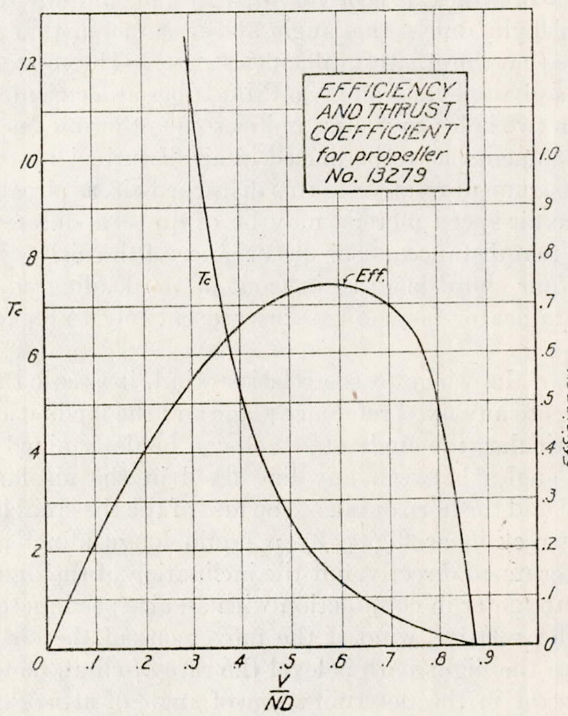


FIGURE 12.

Serious as are the errors which ascending and descending currents produce in the lift curve, they are trifling compared with those which appear in the thrust computations, due to the same cause. An inclination of the relative wind has the effect of rotating through a corresponding angle the axes of lift and drag, so that the drag of the airplane is opposed not only by the thrust but also by a component of the weight. An ascending current having a velocity of 1 foot per second diminished the thrust required for level flight by 9 per cent if the L/D for the complete airplane is 8 and the machine is flying at 60 miles per hour. The error is directly proportional to

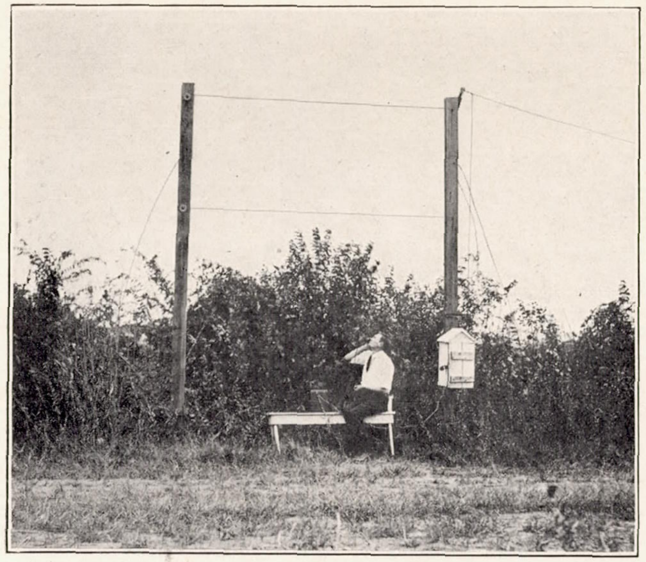


FIG. 5.—SPEED COURSE OBSERVATION STATION.

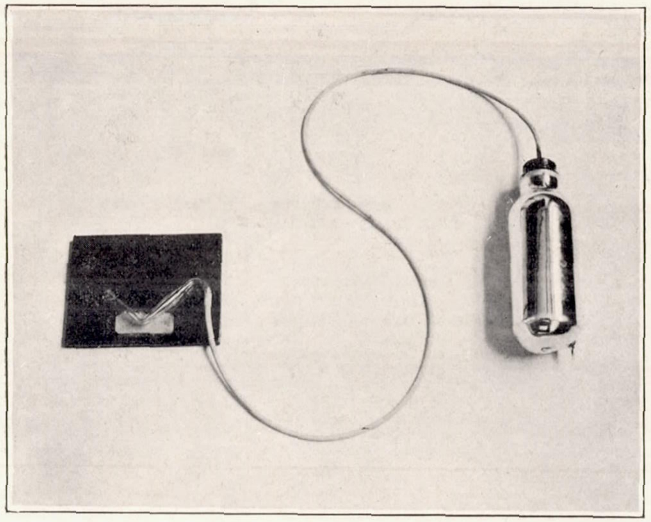


FIG. 9.—STATOSCOPE.

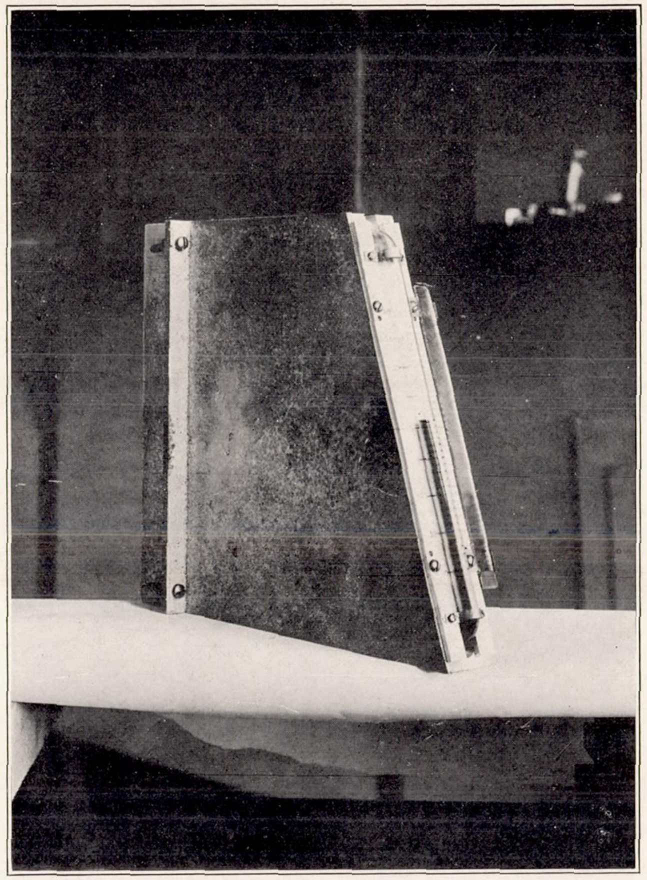


FIG. 10.—INCLINOMETER.

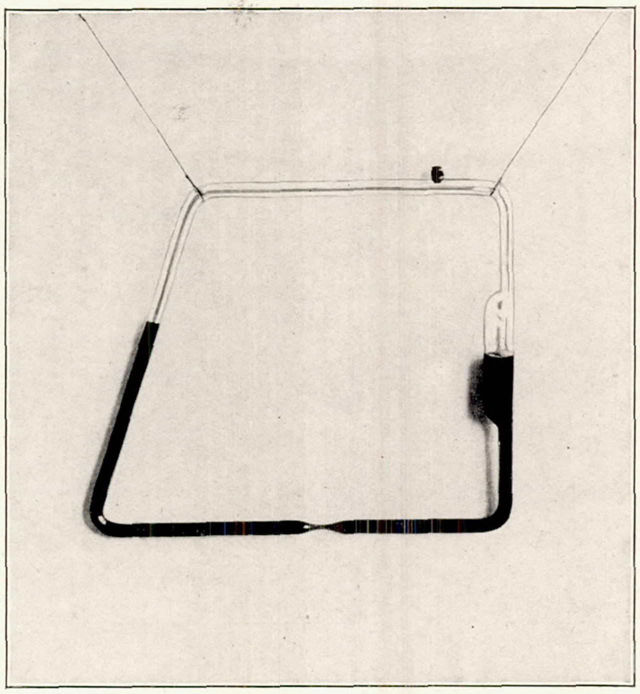


FIG. 11.—INCLINOMETER TUBE.

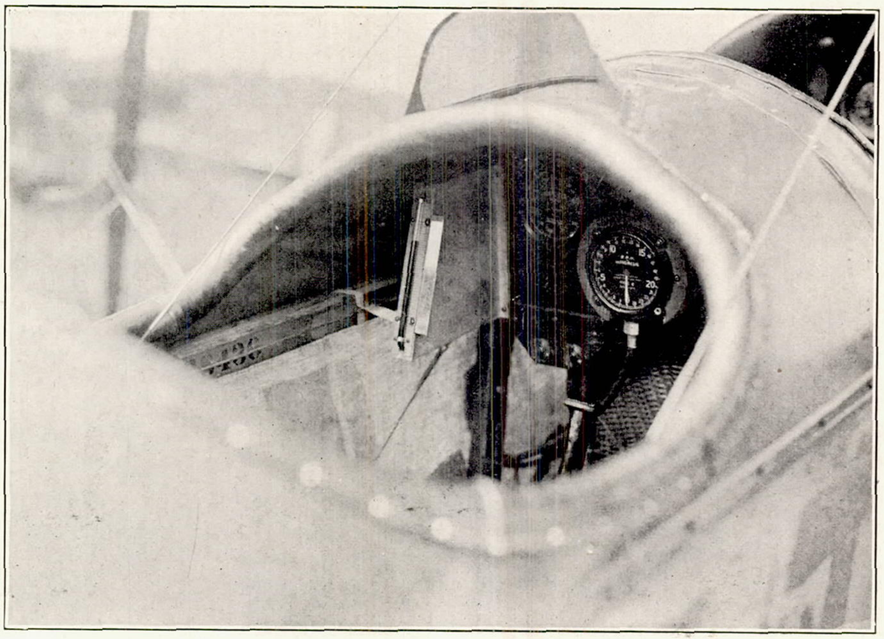


FIG. 13.—COCKPIT AND INSTRUMENT BOARD OF NO. 1.

the velocity of the vertical current and to the L/D ratio, inversely proportional to the speed of flight. If the rising current had a vertical velocity of 11 feet per second, the air speed and L/D being the same as before, no thrust would be required and the machine would soar without engine power. Such currents as this seldom if ever exist, but rising and falling currents of smaller velocities are almost omnipresent. They account for many seemingly wild results in this and other similar work, and the only way to eliminate their effects is to run a great number of tests of the same sort, under all light and weather conditions and over as many different types of terrain as possible, and then average the results.

Figure 13 shows the instrument board in the observer's cockpit of No. 1, with inclinometer, air-speed meter, altimeter, and tachometer installed. The altimeter does not appear in this photograph, being hidden behind the cowling at the right. The arrangement in No. 2 is practically the same.

The tests were carried out at altitudes varying from 1,500 to 4,000 feet. It was not considered safe, in view of the danger of falling into a spin when flying at large angles and of the possibility of a forced landing, to work below the former altitude. The altitude chosen on any particular day depends chiefly on air conditions, the climb being continued far enough to escape the "bumps" frequently found near the ground. Each "run" continued for from 1 to 2 minutes, the pilot being instructed to fly level (using the statoscope to detect changes in altitude) and at a constant air speed during that period. The observer read and recorded the readings of the air-speed meter, the inclinometer and the tachometer every 10 seconds, and noted the altimeter reading and the air temperature at the beginning of each run. The pilot's task was a very difficult one, for he had constantly to watch the statoscope and air-speed meter, in addition to holding the machine steady laterally and watching out for other airplanes. Besides all this, when flying over the speed course to calibrate the meter the pilot had to steer a straight course over the ground between the two observing stations. Test flying is a very highly specialized branch of work, the difficulties of which are not generally appreciated, and there is no type of flying in which a difference between the abilities of pilots thoroughly competent in ordinary flying becomes more quickly apparent. Most of the piloting for the committee has been done by Mr. E. T. Allen and Lieut. H. M. Cronk, but seven other pilots have been used on one or more occasions.

In order to determine the minimum speed in steady flight and to secure data for comparison with wind tunnel tests over the whole range of angles customarily covered by the latter, it was necessary to fly horizontally at an angle at least equal to the angle of maximum lift and as much larger as possible. The procedure in attaining these high angles was to throttle the engine to the lowest speed at which level flight could be maintained, and then open the throttle gradually, drawing the stick back at the same time. The airplane can thus be flown level in a very badly stalled condition, the action of the longitudinal controls being reversed (i. e., if the machine is losing altitude it is necessary to decrease the angle of attack, pushing the stick forward, in order to ascend). Furthermore, the airplane is very unstable laterally at angles in excess of 12° or 13°, and it is prone to fall off into side slips. Most pilots, in trying to fly at extremely high angles for the first time, are unable to keep the machine in equilibrium for more than a few seconds. One of the pilots flying for the committee, after considerable practice, became very skillful in this work and found it possible, given favorable weather conditions, to maintain steady level flight for an indefinite period with the throttle wide open and the machine stalled to an angle of attack of 18° or a little more. The ailerons alone are very ineffective in maintaining lateral stability at large angles, as any raising of one aileron greatly diminishes the drag on that portion of the wing, while drawing down the other aileron correspondingly increases the drag there. The result is that a large yawing moment, nearly if not quite sufficient to overcome the effect of the rolling moment due to the ailerons, is produced and tends to force the machine into a spin. It is necessary constantly to use the rudder in conjunction with the ailerons to a considerably larger extent than is necessary at normal angles.

RESULTS OF THE TESTS FOR LIFT COEFFICENTS.

A number of tests (about 10) were made on each airplane. Some of these have not been plotted up or included in the averages, either because they were not extended over a large enough range of angles or because they contained results which were self-contradictory or because it was found, when an attempt was made to work them up, that essential data were lacking. In selecting tests to be incorporated in the final tabulation no attempt was made to pick those which would check well with each other, and the results were not even compared until the final choice had been made and the computations completed. In order to indicate the degree of consistency obtained among the various factors on successive observations in one typical flight, the angle of attack, as determined by the inclinometer, is plotted against the indicated air speed in figure 14. As already noted, observations on the two instruments were taken every 10 seconds, and each pair of readings is plotted as a separate point. Where two or more readings corresponded to exactly the same point the fact is indicated by the proper number of concentric circles. There are about 50 points represented in figure 14, yet there are only two or three which depart from a smooth curve by more than one-half degree.

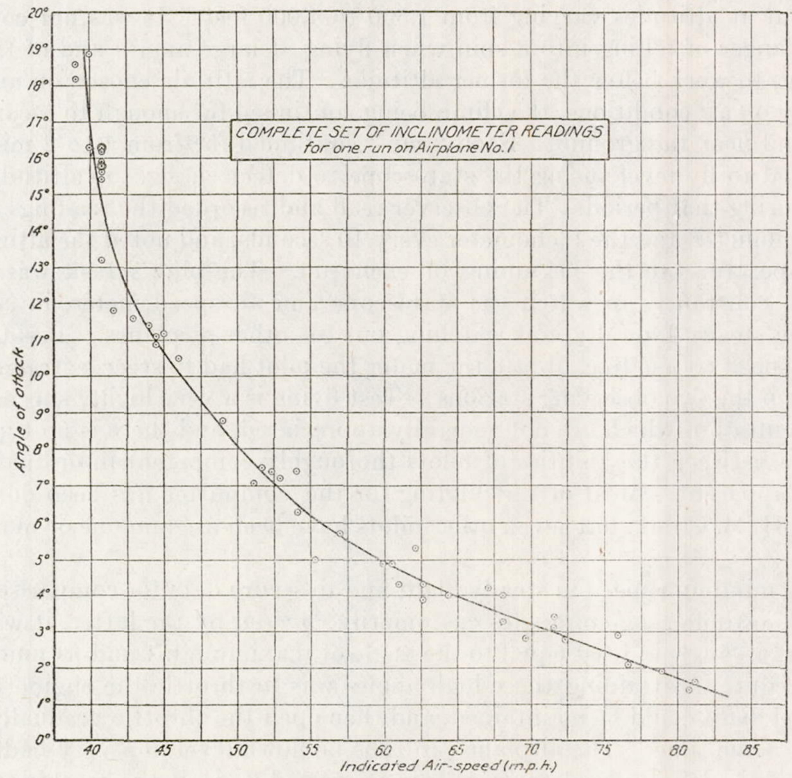


FIGURE 14.

Figure 15 gives the curve of L_c against angle for No. 2, with all the points computed from four tests marked. At angles of attack up to 10° the agreement among the four curves is fully as good as would be expected for a like number of wind-tunnel tests on the same model. Beyond that angle they begin to diverge. but three of the four sets of points stay close together throughout. The very large discrepancy between these three and the fourth at large angles may be explained by the failure of the pilot in the July 30 test to hold the path level. In seeking to fly at the lowest possible speed, he probably allowed the machine to settle or "pancake," so that the true lift was less than the weight of the airplane.

The mean lift curves for No. 1 and No. 2 are brought together in figure 16. The difference between the two is unfortunately not so small as that between the curves for the various tests on a single machine, and the reason for the discrepancy is not apparent. The difference between the two machines certainly is not great enough to account for it, although the reserve tank in the upper wing of No. 1 might affect the lift by a small amount. However, even if the difference between the two lift curves be regarded as wholly due to error in the experiments, the two are nearly enough alike to indicate the general form of the curve and to permit of interesting deductions.

The most important result that can be drawn from such work as this relates to the comparison between free-flight and wind-tunnel results. It has not been possible as yet to have an accurate model of the JN4H made up for wind-tunnel test, but a great deal of work has been done on the JN2[1], and this can be used as a basis of comparison. The JN2 has an Eiffel 36 wing-section, like the JN4H, but it differs from the latter in that its wings are of equal span and in a number of other details. The JN2 has a larger down load on the tail than has the 4H, as will be shown in connection with the discussion of balance, and the actual lift of the wings must therefore be greater. It would then be expected, other things being equal, that the lift coefficients here computed, which ignore the tail load entirely, would be a little smaller for the 2 than for the 4H, but the difference would hardly exceed 3 per cent.

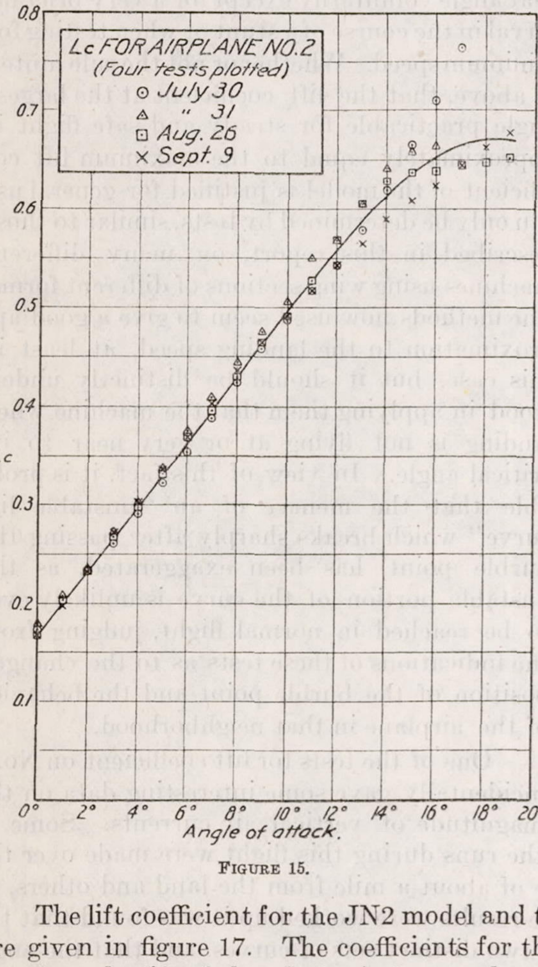


FIGURE 15.

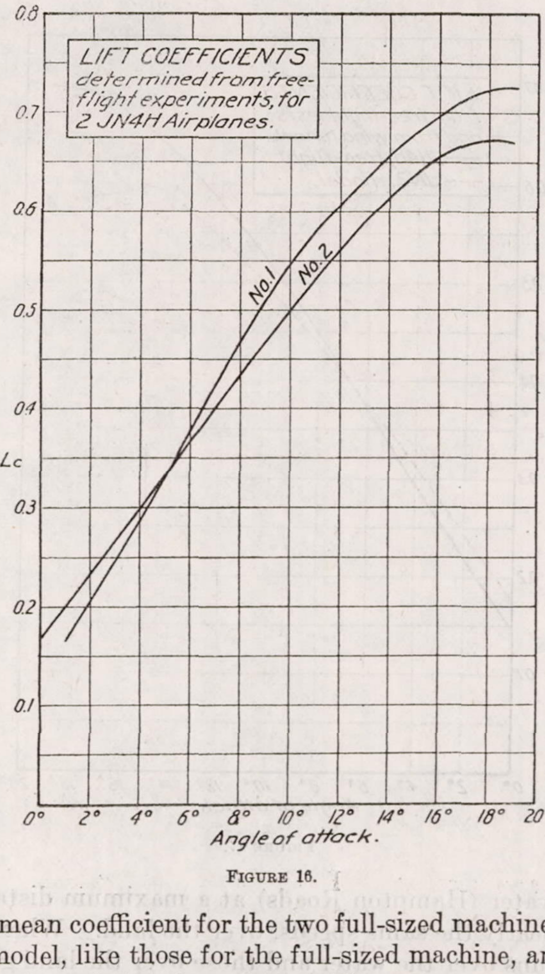


FIGURE 16.

The lift coefficient for the JN2 model and the mean coefficient for the two full-sized machines are given in figure 17. The coefficients for the model, like those for the full-sized machine, are based on the lift of the whole airplane and not on that of the wings alone. The two curves run fairly close together up to 6°, although the lift of the model is distinctly the larger, even when allowance is made for the effect of the difference in tail load just mentioned. The model lift coefficient at angles below 6° is larger than that given by the free-flight tests for either No. 1 or No. 2. At angles in excess of 6° the model lift coefficient begins to drop off rapidly by comparison with the free-flight values. The burble point for the former comes at an angle nearly 4° smaller than that for the latter, and its maximum lift is about 15 per cent less, so that the minimum speed, or, as it is usually called, landing speed, computed from the model test, would be three miles an hour higher than that found by experiment. Actually, however, the model test gives the practicable land-

[1] Third Annual Report, National Advisory Committee for Aeronautics, p. 278 et seq.

ing speed more closely than does the free-flight test, for the customary angle of attack in a good landing is about 12°, an angle at which the lift coefficient is almost exactly equal to the maximum lift coefficient of the model. In order to land the machines which were the subject of these tests at the lowest speed at which they can be flown, the tail skid would have to touch the ground while the wheels were still 16 inches above its surface (assuming the downward slope of the flight path at the instant of making contact to be 2°). As every pilot will recognize, a landing in such an attitude would be distinctly unusual, to say the least. As has already been pointed out, it requires exceptional skill to fly at angles of 15° or more, and it would not be safe for any pilot to attempt it near the ground. It is, therefore, evident that the burble point is of very little practical interest in airplane design, as it is improbable that any pilot ever flies his machine at that angle voluntarily except for a very brief interval in the course of a stunt or when testing for minimum speed. Whether or not the rule hinted at above, that the lift coefficient at the largest angle practicable for steady and safe flight is approximately equal to the maximum lift coefficient of the model is justified for general use can only be determined by tests, similar to those described in this report, on many different machines using wing sections of different forms. The methods now used seem to give a good approximation to the landing speed, at least in this case, but it should be distinctly understood in applying them that the machine when landing is not flying at or very near to its critical angle. In view of this fact, it is probable that the menace of an "unstable lift curve" which breaks sharply after passing the burble point, has been exaggerated, as the unstable portion of the curve is unlikely ever to be reached in normal flight, judging from the indications of these tests as to the changed position of the burble point and the behavior of the airplane in that neighborhood.

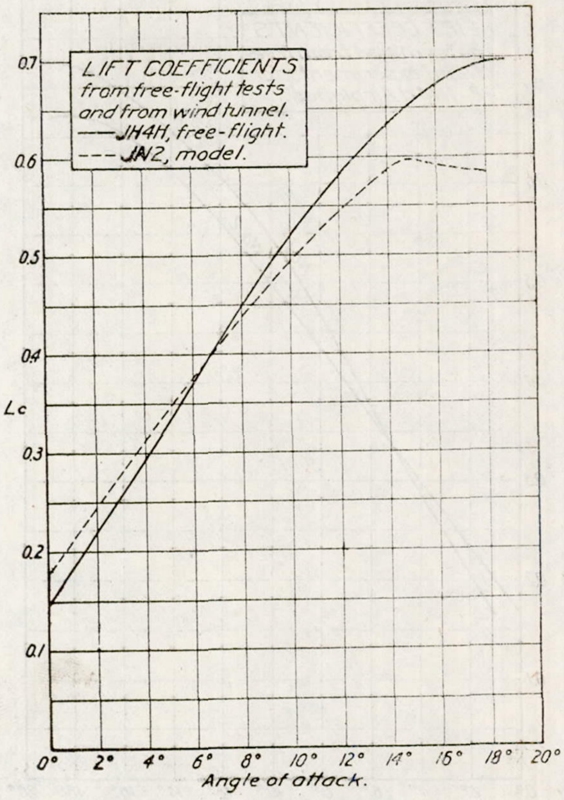


FIGURE 17.

One of the tests for lift coefficient on No. 2 incidentally gave some interesting data on the magnitude of vertical air currents. Some of the runs during this flight were made over the water (Hampton Roads) at a maximum distance of about a mile from the land and others, at nearly the same speeds, over the land. When the results were worked up it was found that the runs over the water and those over the land gave two distinct sets of curves, and that the angle of attack for a speed of 78 miles per hour was greater by 1° on the first set than on the second. This leads to the conclusion that the air was descending over the water or ascending over the land or both, and that the vertical velocity of the air in one place relative to that in the other was 120 feet per minute. This is undoubtedly an exceptional condition, as subsequent tests, although they frequently showed a difference in angle with the kind of country over which the machine was passing, indicated no other vertical velocities as large as that just mentioned. It should be noted that the flight just described took place in the morning, on a sunny day, and that all the observations were taken at a height of 2,700 feet. Since the results obtained on the runs over the land checked well with the other tests on the same machine it is probable that the vertical velocity there was not very large, and that most of the relative movement deduced was due to a downward motion of air over the bay, or at least over that portion of it covered by the flight.

A much disputed question relates to the effect of the slip-stream on the lift of an airplane. Although no attempt at quantitative measurements in inclined flight has as yet been made, the minimum speed attainable has been observed under various conditions of engine operation, and no indication of a marked slip-stream effect on lift has been apparent. Some such effect probably exists, but it is certainly small. The minimum speed with throttle wide open is, to be sure, somewhat less than the minimum speed in gliding, but the difference is not too large to be accounted for by the lesser total lift in the first case, due to the vertical component of the thrust-balancing part of the weight of the machine directly.

RESULTS OF THE TESTS FOR DRAG COEFFICIENTS.

In working up the results of the tests for drag the procedure followed was in general analogous to that just described for lift. The primary curve, corresponding to the plot of inclinometer readings against speed, was one of $\frac{V}{ND}$ against angle or speed (usually the latter). Such a curve for a single flight is given in figure 18, each point representing a single pair of readings (of air-speed meter and tachometer). It will be noted that the points do not lie on the curve with any such exactness as do those in figure 14, and that they separate into little groups. Each group of points includes the readings taken during a run in a straight line and at an approximately constant speed, and each group defines a little curve of its own, the slopes of these short subsidiary curves being considerably greater than that of the mean curve connecting them. This apparent discrepancy is due to the inertia of the airplane, which causes it to delay appreciably in responding to changes of condition. For example, if the engine speed drops slightly from any cause, there is a distinct interval before steady conditions are restored by a decrease in air speed and an increase in angle of attack, and if the engine speed returns to its original value after a few seconds the air speed will hardly have changed perceptibly in the meantime. If, on the other hand, the air speed changes, the engine speed responds almost instantly. If, for example, the air speed increases, the angle of attack of the propeller blades against the air falls off, the resisting torque of the propeller decreases, and there is an unbalanced torque tending to speed up the rate of rotation. Since the moment of inertia of the rotating parts is small, the response to this accelerating torque is, as already noted, very rapid. The result is that N can make considerable momentary changes, producing a corresponding effect in $\frac{V}{ND}$, without appreciably affecting V, but that any change in V is promptly followed by the corresponding change in N, and the points obtained during a short run with the conditions nearly but not quite constant therefore plot as a line nearly parallel to the axis of $\frac{V}{ND}$.

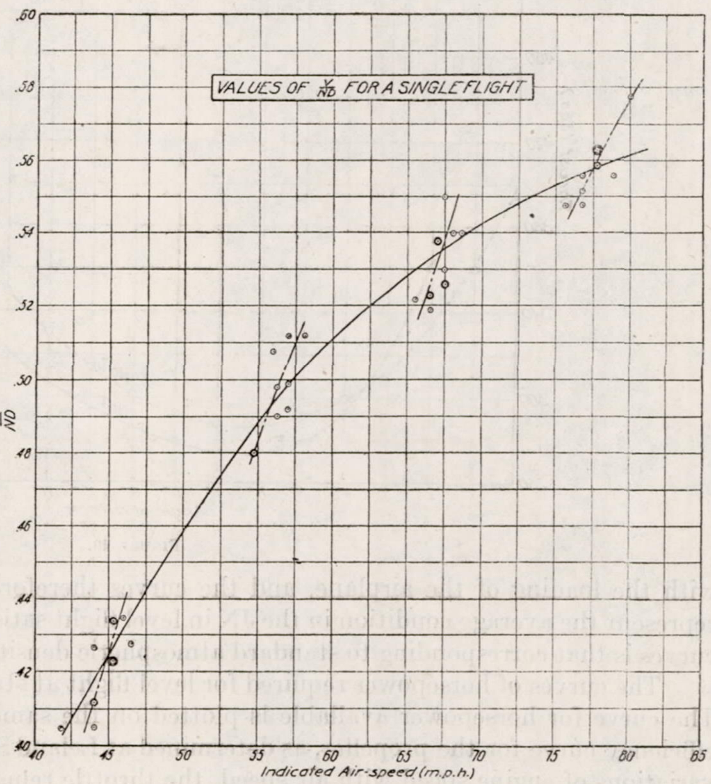


FIGURE 18.

The difference between successive tests was, as would be expected, greater than in the case of the lift coefficient, both because of the very large effect of vertical currents and because of the failure of the pilots in some cases to keep the path level. The extreme results for a given angle, however, seldom varied by more than 10 per cent. The errors in the determination are much greater at very large and at very small angles than at those in the neighborhood of the maximum L/D, partly because there were few tests which extended to very large angles. Even those tests which covered the full range of angles spread out widely at the ends of the curves, although very closely bunched in the intermediate portion. There was, as will be seen a little later, a marked difference between the results for the two machines, exceeding 10 per cent for a considerable range of angles. This difference can be attributed largely to the difference in the propellers, a difference already noted in the first part of the report, and it is probable that, since the propeller used on No. 2 was the more warped, the results given for the drag and L/D on No. 1 are more accurate than are those for No. 2. A test was made with the propellers interchanged, and the results obtained from No. 2 on that occasion checked very well with the mean curve for No. 1.

The mean curves of thrust for the two machines are given in figure 19. These curves call for no special comment, their general form being evident. The thrust for a given angle varies

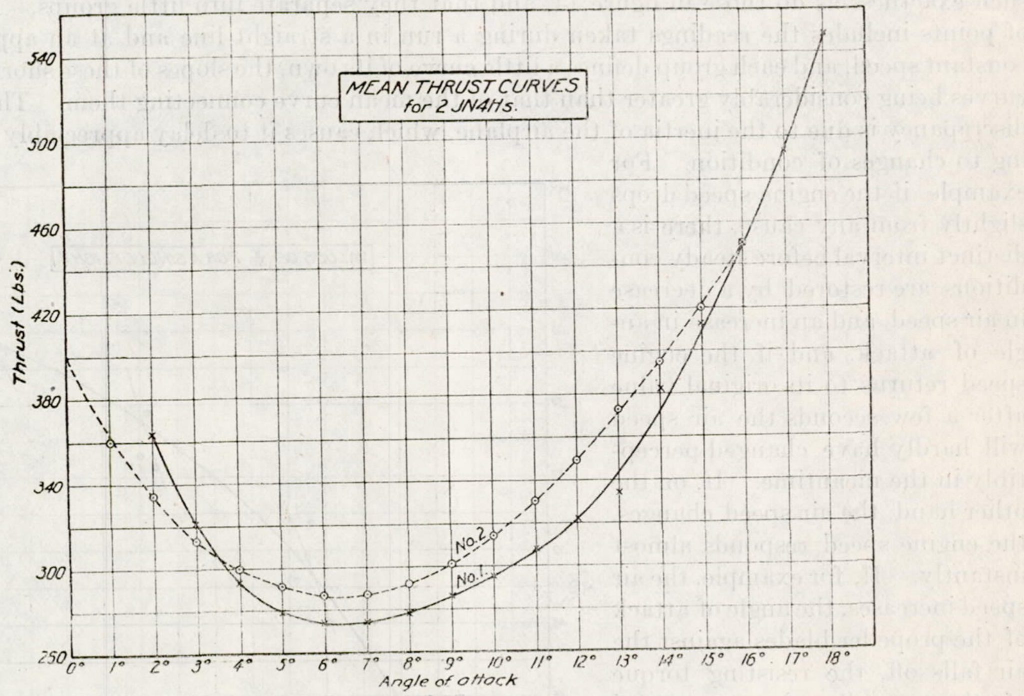


FIGURE 19.

with the loading of the airplane, and the curves therefore are somewhat indefinite, but they represent the average condition in the JN in level flight satisfactorily. The thrust given in these curves is that corresponding to standard atmospheric density.

The curves of horsepower required for level flight at standard density are given in figure 20. The curve for horsepower available is plotted on the same sheet, its form being based on the efficiency curve for the propeller, as determined at Leland Stanford Junior, and on the computed variations of engine speed with air speed, the throttle remaining wide open at all times and the engine torque being assumed constant. In order to make the intersection of the curves check with the maximum speed as determined by test it was necessary to take the engine horsepower as 130 (a value which appears reasonable, as the engines had seen a considerable amount of service and would not turn up beyond 1,530 revolutions per minute in level flight with the propeller normally used on No. 1, or 1,570 revolutions per minute with that used on No. 2). It will be noted that the curves of horsepower available and required have their second intersection at an angle a little smaller than the burble point. This checks very well with the observed fact that, with the throttle wide open and the machine flying level, it was not quite possible to reach the burble point. This is shown by the mean lift curves, which stop just short of the critical angle. This coincidence of computed and observed results at the lower end of the horsepower curve affords additional reason for confidence in the validity of the method employed for using wind-tunnel data on the propeller in conjunction with measurements on the complete airplane in free flight.

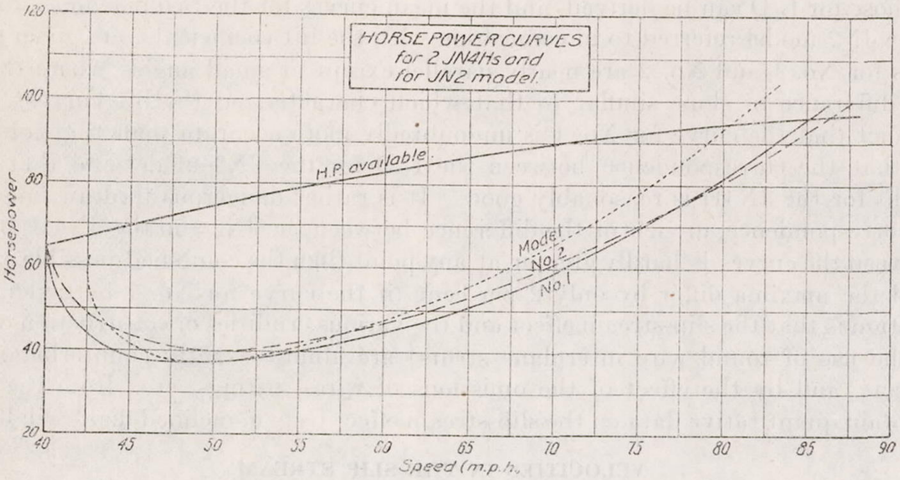


FIGURE 20.

The air speed for best climb is deduced from the horsepower curves to be 56 miles per hour. No thorough tests on climb have been made, but the air speeds adopted by the pilots who have flown these machines, when they desired a maximum rate of ascent, have ranged from 48 to 57 miles per hour, with the most skillful and experienced pilots, in most cases, choosing a speed nearer to 48 than to to 57. It appears, then, that the air speed which would be recommended as a result of the study of the curves of figure 20 is very nearly correct, but probably a little on the high side. This is rather surprising, as the effect of the increased slip-stream velocity with the machine climbing with wide-open throttle would presumably be to raise the speed for minimum horsepower required, and the speed for best climb predicted from these curves would therefore be expected to be a little low. In any case, however, the discrepancy is small, and the climbing speed is so nearly the same for all speeds from 50 to 60 miles per hour that the difference can hardly be detected. The climbing speed for No. 1 is computed from the horsepower curves to be 585 feet a minute.

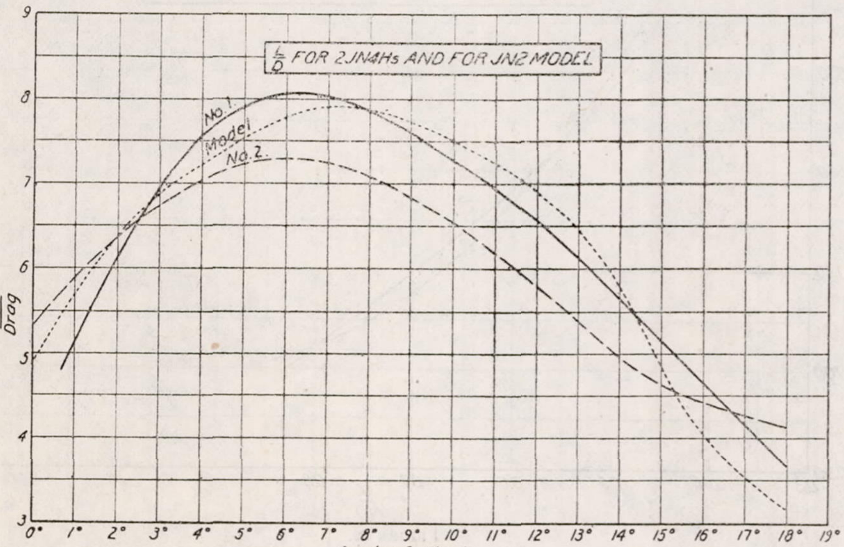


FIGURE 21.

Although, as already noted, no accurate determinations of the rate of climb have been made, such observations as have been taken indicate a maximum rate somewhat less than 585 feet a minute. This is what would be expected, the difference being due to the increased slip-stream effect with open throttle. The curve of horsepower required computed from the JN2 model test, with due allowance for the difference in weight between the JN2 and the JN4H, is also plotted in figure 20. It checks well with the free flight curves except at extreme high and low speeds. From the curves of thrust those for L/D can be derived, and the mean curves for the two machines, together with that for the JN2 model referred to in connection with the lift coefficients, are given in figure 21. The curves for No. 1 and No. 2 are nearly parallel except at small angles, where there appears a marked difference of slope similar to that which characterized the lift curves. Bearing in mind the fact that the curve for No. 1 is undoubtedly more accurate than that for No. 2, it is apparent that the correspondence between the L/D for the JN2 model and that determined in free flight for the JN4H is reasonably good. It is rather dangerous to draw fine conclusions from this correspondence, in view of the difference between the JN2 and the JN4H, but the separation between the curves is hardly greater at any point than the combined possible experimental errors, and the maxima differ by only 2 per cent (if the curve for No. 1 be taken as correct). The indication is that the slip-stream effect and the various crudities of construction on the model (such as the use of round wire interplane struts) are almost exactly counterbalanced by the "scale effect" and by the effect of the omissions of wires, fittings, etc., from the model. In order to obtain quantitative data on the slip-stream effect tests in inclined flight will be necessary.

VELOCITIES IN THE SLIP STREAM.

In order to measure the velocity in the slip stream and compare it with the velocity computed from the results of model tests on the propeller a pitot-venturi head, exactly like the one used for measuring the air speed, was attached to the forward left center section strut. The mouth of the tube was 3.92 feet behind the trailing edge of the propeller, and the axis of the venturi was 2.72 feet radially from the propeller axis. The regular air-speed head and the one in the

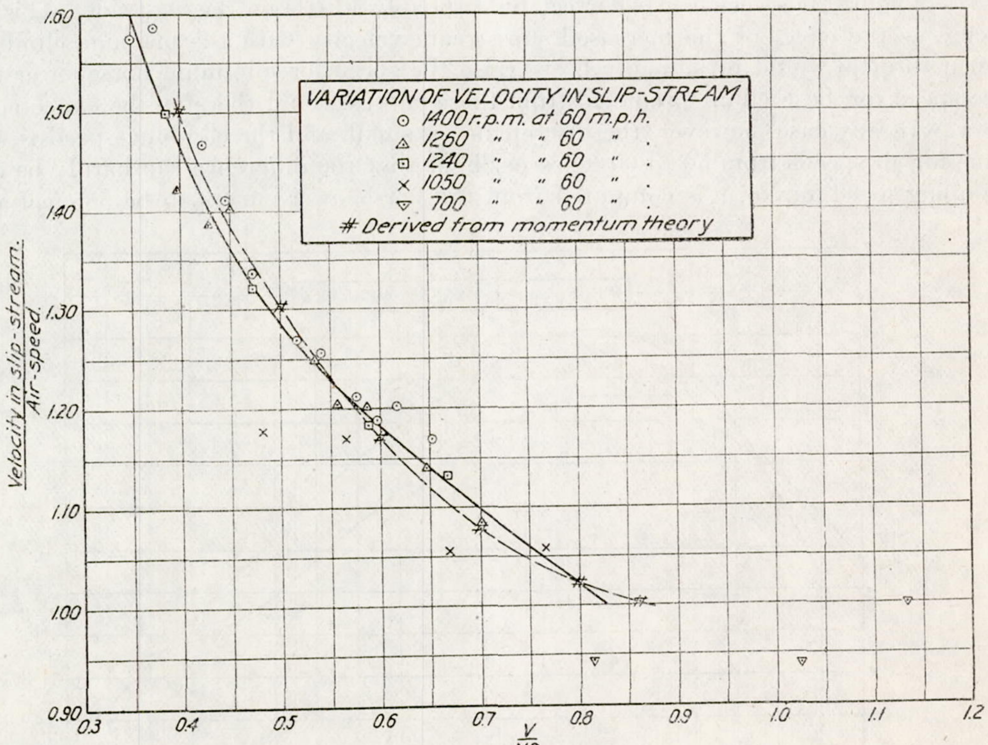


FIGURE 22.

slip stream were both connected to the same meter through the medium of two valves, which made it possible to change readily from one to the other, and to read the air speed or slip-stream velocity, as might be desired. The readings secured in this way are, of course, not highly accurate, as the slip-stream velocity includes a considerable tangential component, the magnitude of this swirl varying with the air speed and engine speed. The air therefore meets the tubes obliquely, and the reading of the meter is probably lower than the true velocity. The error in velocity should not, however, be more than 5 per cent, and the results obtained will at least serve to give an idea of the relation between slip-stream velocity and the factors which control it.

The procedure in these tests was to set the throttle at a fixed position, and to fly the machine at a number of different air speeds without moving the throttle (these flights, of course, were not level). The air speeds used for each throttle setting ranged from 90 to 42 miles per hour, with an occasional dive to 100 miles per hour or a little more. The ratio of slip-stream velocity to air speed for a given propeller depends only on $\frac{V}{ND}$ and these quantities can therefore be plotted against each other. This has been done in figure 22, and it will be noted that nearly all of the points lie close to a smooth curve and that there is no distinct break between the sets of points taken at different throttle openings. The only points which do not fit the curve are those which were taken with the engine throttled down to a very low speed, so low that the propeller was giving no thrust. The slip-stream velocities under this condition were lower than they apparently should have been.

The dotted curve in figure 22 represents the velocity ratio computed from the thrust coefficients by the method described in Report No. 71. This curve checks very well with the other one, and this check indicates that the thrust coefficients as determined in the wind tunnel held for the full-sized machine, and that they are not very materially affected by the presence of the body. Of course, this check is only a rough one. To secure an accurate comparison between the theoretical and actual values it would be necessary to sound the slip-stream thoroughly, measuring the velocities at many points, but previous experiments (by Eiffel and others) indicate that the velocity is nearly constant over a large portion of the propeller disk area, and readings at a single point therefore give some indication of the average condition. It appears that interference between the propeller and the other parts of the airplane can not have a very large effect, as any very notable increase in thrust due to the presence of the body would lead to an increased slip-stream velocity. Experiments at the Royal Aircraft Factory [1] on a pusher biplane, have shown a similarly excellent check between the calculated and measured slip-stream velocities.

The maximum slip-stream velocity with the machine stationary on the ground and the engine turning 1,400 revolutions per minute was about 80 miles per hour. The velocity was very unsteady under the conditions, the meter reading varying by about 6 miles per hour almost instantaneously. This irregularity of flow was no doubt due in part to interference of the ground, but the flow in the slip-stream was in general more irregular, and the velocity fluctuated more rapidly and through a larger range at low speeds than at high.

LONGITUDINAL BALANCE.

The factor on which the longitudinal balance of an airplane primarily depends, and to any variation in which it is always highly sensitive, is the position of the center of gravity of the machine. The first step, then, in any study of balance and of the action of the controls is to determine as accurately as possible the position of the C. G. with regard both to its vertical and its horizontal co-ordinates.

The method used in finding the location of the center of gravity was the usual one of weighing the machine on three pairs of scales, one under each wheel and one under the tail skid, first with the tail skid and wheels on the same level and then with the tail raised. The

[1] Experimental Determination of the Slip-stream Behind the Air-screw of a Pusher: British Advisory Committee for Aeronautics, R. & M. No. 382. 1916.

tail can be raised enough, without overbalancing the machine, to rotate it through an angle of about 15° when the pilot and observer are on board and through 10° when the seats are empty. From the weights thus obtained the center of gravity can be computed with a probable error of less than 0.01 foot in the horizontal co-ordinate and less than 0.03 foot in the vertical.

With a pilot weighing 125 pounds in the front seat and a 165-pound observer in the rear (this being the crew with which most of the tests were conducted), the center of gravity of No. 1 was 1.04 feet behind the leading edge of the lower wing, 2.50 feet behind the leading edge of the upper wing, and 0.28 foot above the thrust line, the axes of reference being taken parallel and perpendicular to the top longeron. The center of gravity of No. 2 was 0.99 foot behind the leading edge of the lower wing, 2.44 feet behind the leading edge of the upper wing, and 0.2 foot above the thrust line. The observer in No. 2 weighed only 125 pounds. If the mean chord be taken as 60 per cent of the way from the lower to the upper chord to allow for the larger area and larger unit lift of the upper wing, the line through the C. G. and perpendicular to the wing chords cuts this mean chord at 39 per cent of its length from its leading edge on No. 1 and 35 per cent on No. 2. This is materially farther back on the wings than the usual location for the C. G.

Since the balance depends on moments about the C. G., a small change of force on the tail planes, acting as it does at a large moment arm, has an important effect, and the angle of the stabilizer is therefore of primary importance. As already noted in the general descriptions of the machines, the stabilizer is supposed to lie flat on the upper longerons. Although the stabilizers were warped the mean chord of the surface was parallel to the top longerons within 0°.2 on both machines.

In order to determine the angle at which the elevator was set at any instant, a sector carrying a scale was fixed to the elevator rocker-arm shaft in the rear cockpit of No. 1, and this sector moved under a pointer fixed to the seat rail. No means of measuring the control position were provided on No. 2, as the arrangement of the elevator-control linkage was different on the two machines, and an entirely new and somewhat more complicated device would have had to be designed. The elevator control wires were adjusted somewhat more tightly than is usual in order to prevent any backlash. The elevator position indicator is shown in position in figure 23.

The force applied to the stick was measured by the instrument illustrated in figure 24. The knob which normally caps the stick was removed, and the slide held between two springs was slipped over the head of the tube. The pilot read the forces directly from the scale. The force indicator was originally fitted with two springs of equal strength, but, as it was found that the force was practically always in one direction, the springs shown in the cut were substituted.

The elevator positions for a variety of air speeds and engine speeds are given by the curves of figure 25. These curves were obtained in the same way as were the points on the slip-stream curve (fig. 22), each one relating to a fixed throttle setting. A fixed throttle setting, rather than a fixed engine power or number of revolutions per minute, is the criterion to which longitudinal balance and stability should be related.

Indicated air-speed (with the speed course correction made) is used directly as the basis for plotting the curves, and variations of air density during the test are entirely neglected. The elevator angles and forces depend primarily on indicated air-speed, since the angle of attack and the flow of air about the machine are functions only of the indicated air-speed and the slope of the flight path. The air density affects the controls in two ways, but both are of minor importance. In the first place, the slope of the flight path for a given throttle setting and indicated air-speed varies with the air density. This factor is insignificant. Secondly, the velocity of the slip-stream and its effect on the controls depend on the true speed and so on the density. This effect, although it is of greater magnitude than the one first mentioned, can safely be neglected except for the large changes of destiny experienced in mounting to great altitudes. All the tests described here were carried out at between 1,500 and 4,000 feet.

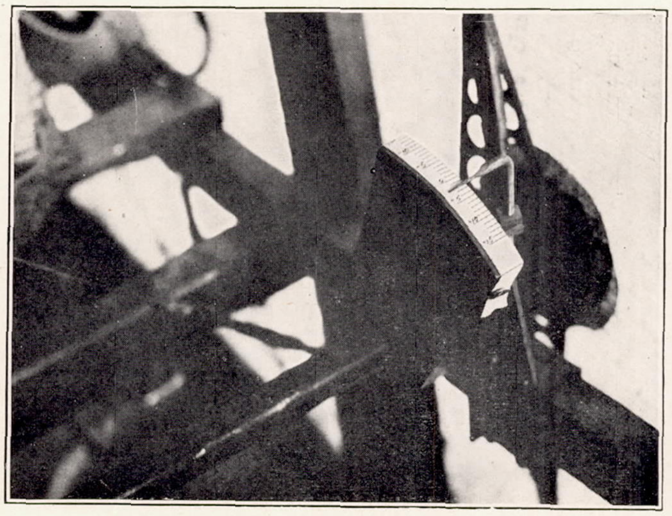


FIG. 23.—ELEVATOR ANGLE INDICATOR.

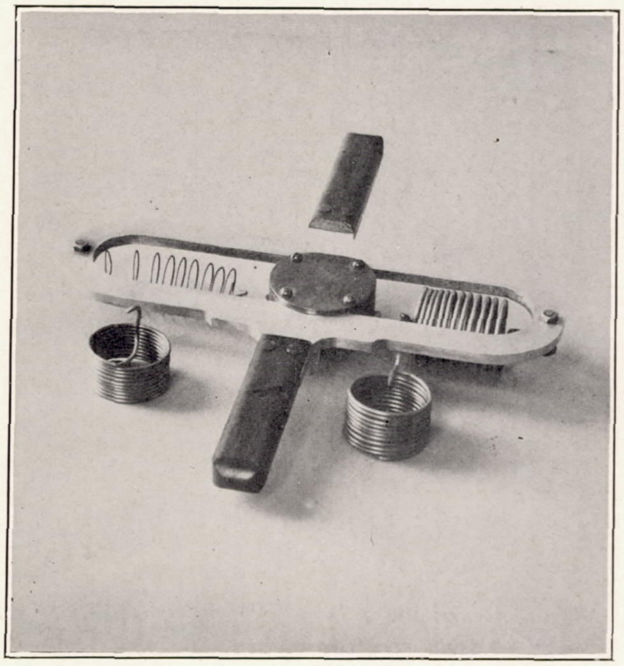


FIG. 24.—ELEVATOR FORCE INDICATOR.

Curve No. 1 relates to flight with wide-open throttle, No. 5 to gliding descent with the engine throttled down to idling speed. The elevator angle is referred to the top longerons as a datum line, and is taken as positive when the trailing edge of the elevator is pulled down. It will be observed that the curves all have the same general form, and that the positive angle of elevator setting for equilibrium at any given speed decreases progressively as the engine speed decreases. This is due to the slip-stream effect on the stabilizer and to the location of the center of gravity above the thrust line, both of these things tending to cause the airplane to nose down to a smaller angle of incidence as the throttle is closed and therefore requiring that the elevator be pulled up in order to maintain the same angle of attack and the same air-speed. Translated into practical terms, this means that, if the stick were locked in position while the

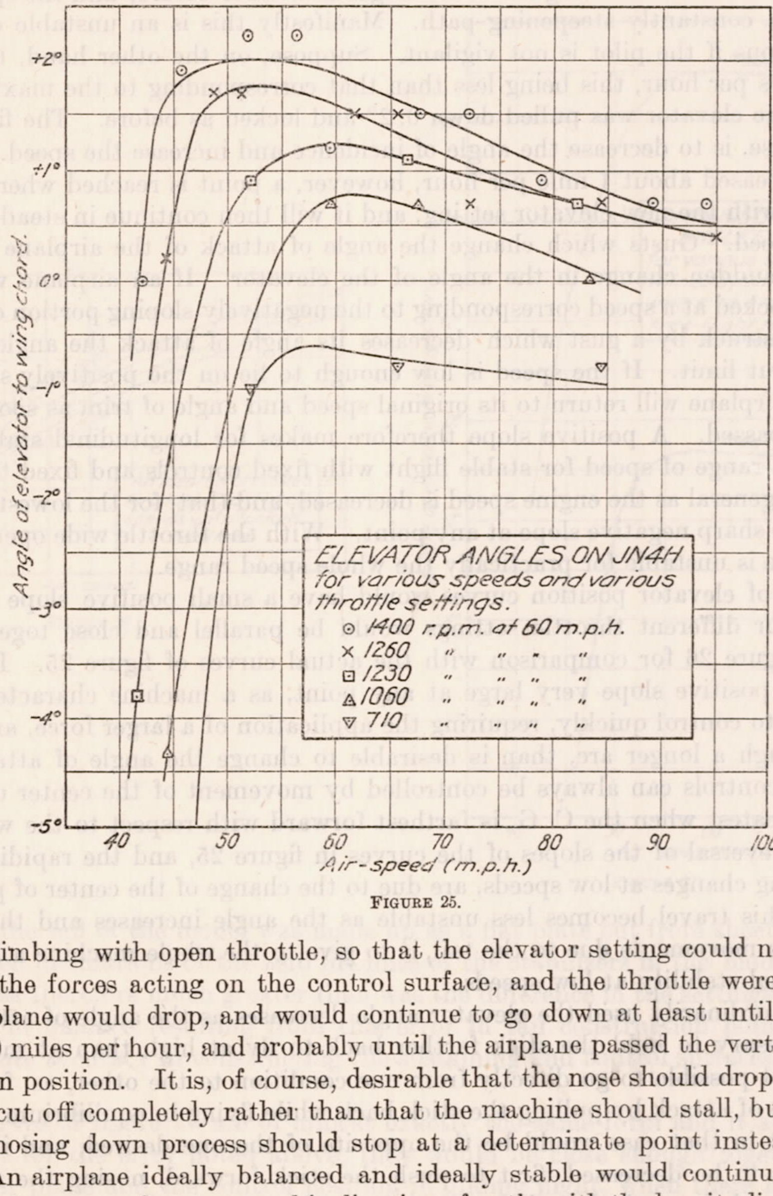


FIGURE 25.

machine was climbing with open throttle, so that the elevator setting could not change, whatever might be the forces acting on the control surface, and the throttle were then closed the nose of the airplane would drop, and would continue to go down at least until the speed of the dive reached 90 miles per hour, and probably until the airplane passed the vertical and attained an up-side-down position. It is, of course, desirable that the nose should drop when the engine is throttled or cut off completely rather than that the machine should stall, but it is also desirable that the nosing down process should stop at a determinate point instead of continuing indefinitely. An airplane ideally balanced and ideally stable would continue at some speed within its normal range and at a normal inclination of path, with the longitudinal control locked whatever might be done to the throttle. The condition of locked control, of course, is only one of several which may occur. Others, even more important, will be discussed later in this section.

It is characteristic of the curves of figure 25 that they have a maximum point, and that their slopes at high and low air-speeds are accordingly of opposite sign. The effect of this change of slope can best be illustrated by two concrete examples. If an airplane is flying with the throttle setting corresponding to curve No. 3, and at a speed of 65 miles per hour, and if the stick is then suddenly pushed forward by an amount sufficient to increase the elevator angle by $0^\circ.2$ and locked in this new position, the primary effect will be to nose the airplane down, decreasing the angle of incidence and increasing the speed, since the pulling down of the elevator sets up an unbalanced upward force on the tail, and this gives rise to a diving moment about the center of gravity. By the time the speed has increased to 80 miles per hour the proper elevator setting for equilibrium is $0^\circ.7$, but the surface is locked at $1^\circ.2$. There is, therefore, still an unbalanced diving moment, larger now than before, and the speed continues to increase with a constantly steepening path. Manifestly this is an unstable condition, and it may be dangerous if the pilot is not vigilant. Suppose, on the other hand, that the initial speed was 50 miles per hour, this being less than that corresponding to the maximum elevator angle, and that the elevator was pulled down $0.\ 2^\circ$ and locked as before. The first effect, just as in the other case, is to decrease the angle of incidence and increase the speed. By the time the speed has increased about 1 mile per hour, however, a point is reached where the machine is in equilibrium with the new elevator setting, and it will then continue in steady flight at this slightly higher speed. Gusts which change the angle of attack of the airplane have just the same effect as a sudden change in the angle of the elevator. If an airplane which is flying with the control locked at a speed corresponding to the negatively sloping portion of the elevator position curve is struck by a gust which decreases its angle of attack the angle will continue to decrease without limit. If the speed is low enough to lie on the positively sloping portion of the curve the airplane will return to its original speed and angle of trim as soon as the effect of the gust has passed. A positive slope therefore makes for longitudinal stability. It will be noted that the range of speed for stable flight with fixed controls and fixed throttle setting becomes wider in general as the engine speed is decreased, and that, for the lowest curve (engine idling), there is no sharp negative slope at any point. With the throttle wide open, on the other hand, the machine is unstable for practically the whole speed range.

An ideal set of elevator position curves would have a small positive slope at all points, and the curves for different throttle settings would be parallel and close together. Such a set is shown in figure 26 for comparison with the actual curves of figure 25. It is not desirable to have the positive slope very large at any point, as a machine characterized by such curves is difficult to control quickly, requiring the application of a larger force, and the moving of the stick through a longer arc, than is desirable to change the angle of attack. The stability with fixed controls can always be controlled by movement of the center of gravity, the stability being greatest when the C. G. is farthest forward with respect to the wings.

The sudden reversal of the slopes of the curves in figure 25, and the rapidity with which the elevator setting changes at low speeds, are due to the change of the center of pressure travel on the wings. This travel becomes less unstable as the angle increases and the effect, when combined with the movements due to the tail, is to give to the whole machine a high degree of statical longitudinal stability at low speeds.

At all speeds ordinarily used the elevator angle decreases as the angle of attack decreases, so that it is necessary to hold the stick farther back to fly at high than at moderate speed. Of course, it is not possible to go directly from one condition to the other, as, for instance, to decrease the angle of attack by pulling the stick back while flying in equilibrium at a moderate speed. The effect in that case would be the opposite of the one desired, and it is necessary, when the angle is to be decreased, first to push the stick forward, nosing the machine down until the desired angle is reached, and then to pull it a little farther back than its original position in order to keep the machine in the attitude thus assumed.

For the sake of comparison the curve of elevator angles for a JN2 has been computed from tests made at the wind tunnel of the Massachusetts Institute of Technology [1] and is given in figure 27 together with a reproduction of the curve for the JN4H with the engine idling. In computing the curve for the model the center of gravity was assumed to be in the same position with regard to the mean chord of the wings as in JN4H No. 1. The differences between the JN2 and the JN4H are not of a nature which would be expected materially to affect the balance and stability, except that the stabilizer on the former is set at $-3°$ to the wing chord, while that on the latter is at $-2°.3$. This accounts for a part, but only a part, of the relative displacement of the two curves. It will be noted that the model test would have led to a prediction of tail-heaviness, the opposite of the condition existing. This difference can be attributed

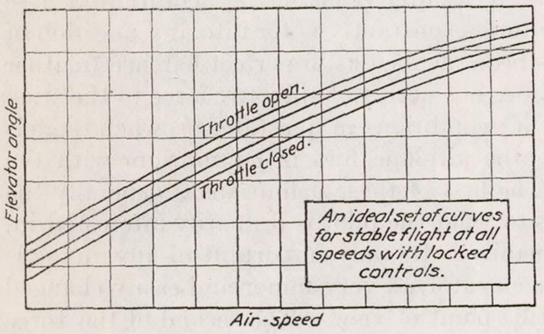


FIGURE 26.

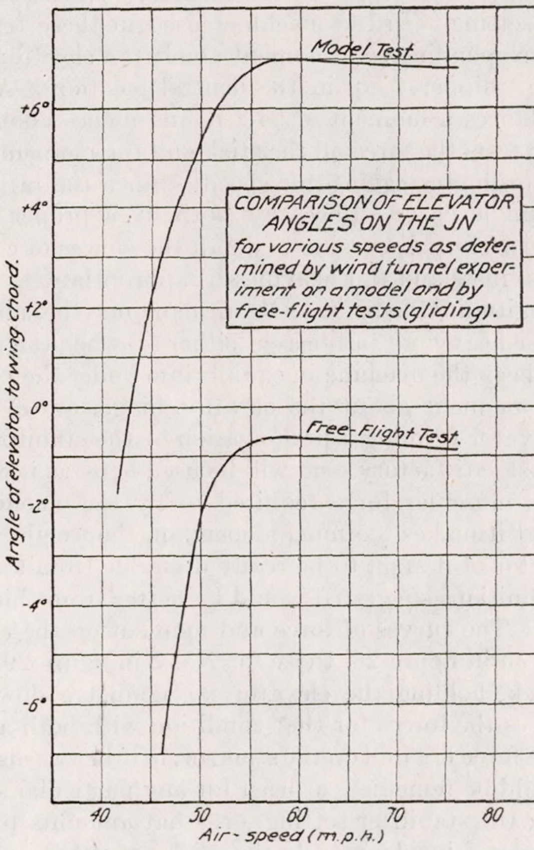


FIGURE 27.

to the fact that the tail of the model was made up as a flat plate cut from sheet metal and the difference between inclinations of the zero lift lines of the stabilizers in the model and the full-sized machine was therefore much greater than was the difference in the settings of their chords. The large error in balance resulting from this error in tail construction points again to the necessity of minute accuracy in constructing the sustaining and control surfaces of wind tunnel models.

The two curves of figure 27 are of almost exactly the same form and it appears probable that, were it not for the error noted above, they would be close enough together so that the balance of the air plane and the control position in gliding flight, when there is no slip-stream effect, could be closely predicted from the model test. The present experiments and others of a similar nature on many different types of machines will provide the necessary data for

[1] Bulletin Airplane Engineering Dept. U. S. A., June 1918, p. 89

correcting the wind tunnel results for slip-stream effect and so for predicting the balance of an airplane at full power before it is built.

The discussion so far has been confined to the case of stability with locked controls. This of course, is rather an uncommon case at present as very few machines, especially of nonmilitary type, are fitted with means for locking the stick in position. The provision of a device for this purpose is highly desirable from some standpoints, and may become the usual thing at some future date, but there are other cases which, as already noted, are of more importance at present.

If the elevator is left free and uncontrolled it will take up a position in which there is a small moment about the elevator hinge, due to the air forces acting on the surface, tending to decrease the angle. This corresponds to an upward force on the elevator and is required to balance the weight of the member, which produces a moment tending to increase the angle of setting. In the machines used in these tests a force of 8½ pounds at the top of the stick, corresponding to a moment about the elevator hinge of 206 pound-inches, was required to hold the "flippers" up in the neutral position. A force of 1 pound at the upper end of the stick balances a moment of 24.2 pound-inches about the elevator hinge. In plotting the results of the tests the force on the stick and the moment about the elevator hinge have both been plotted as ordinates against air speed. Since the ratio between the forces and the moments is fixed a single curve suffices for both by a proper adjustment of scales.

Before discussing in detail the curves of control force, a digression on the definition of nose heaviness and tail heaviness is appropriate, as these terms constantly enter into any question of longitudinal balance. An airplane may be, and has been, defined as in perfect balance (neither nose heavy nor tail heavy) either (*a*) when the pilot does not need to apply any force to the stick to keep the machine in equilibrium under the particular conditions in question, (*b*) when there is no moment about the elevator hinge, or (*c*) when the airplane flies in equilibrium with the elevator forming a prolongation of the stabilizer. The first of these definitions is generally the most satisfactory, and will be used here, as it relates to what the pilot is primarily interested in, the muscular force required to fly the machine steadily. Its only important disadvantage is that it makes too much depend on the weight of the elevators, a very minor and easily changed factor of design, to be really desirable from a scientific point of view. The second of the three definitions suggested would be better from this standpoint.

The curves of force and moment on the elevators of No. 1 for various throttle settings are given in figure 28, those for No. 2 in figure 29. The positive sign corresponds to a pull on the stick, holding the elevator up against a downward force. The curve marked "level flight" gives the forces for that condition with both air speed and throttle setting varing. In all cases the force is a pull on the stick, or, in other words, the airplane is nose heavy. This nose heaviness could be remedied, at least for any particular speed, or reduced to any desired extent by changing the stabilizer setting, or, what amounts to the same thing, by rigging the wings at a larger angle of incidence. If the stick on either one of the machines used in these tests is released, it will move forward from the equilibrium position and the machine will go into a dive with the throttle wide open. Releasing the stick during gliding descent also throws the airplane into a dive, the speed and steepness of which rapidly increase, apparently without limit.

With free controls, just as with the controls locked, stability is indicated by the slope of a curve, but it is the curve of control forces in this case instead of that of control positions. When the slope of the curve of forces is negative, as it is at low speeds in figures 28 and 29, the machine is stable with free controls, provided that the line of zero force on the stick intersects the curve of forces, as any change of speed would set up moments which would cause the elevators to move in the proper direction to restore the machine to its original attitude. When, on the other hand, the slope is positive the equilibrium is unstable and can only be restored, once it is upset, by the intervention of the pilot. It is evident from the curves that with free controls, just as with the controls locked, the statical longitudinal stability is greatest at low speeds of flight, that the machine becomes unstable at speeds in the neighborhood of the maximum attainable, and that the stability is greater in gliding than with the throttle open.

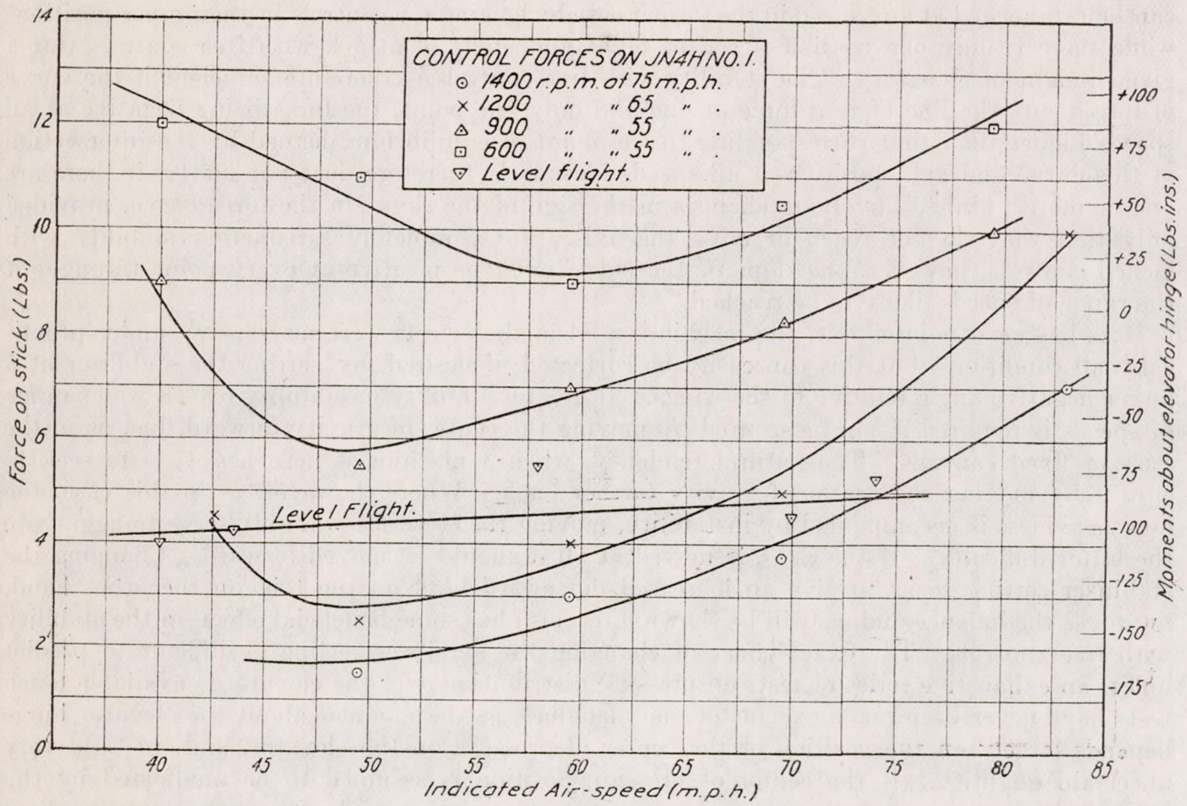


FIGURE 28.

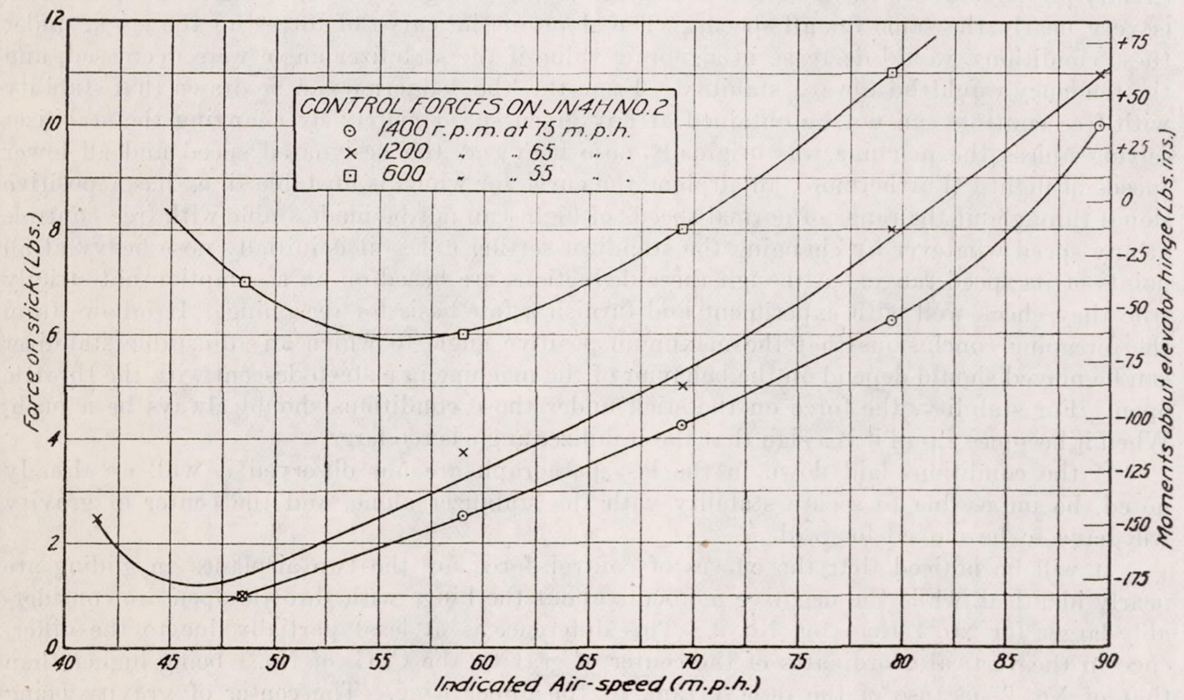


FIGURE 29.

The chief difference between statical stability with locked and free controls is that equilibrium can be established at any speed in the former case by locking the controls in the proper position while there is only one possible speed of flight and angle of attack with free controls (for a given weight of elevator). The stability with free controls is therefore sufficient if the curve of forces cuts the line of zero force at one and only one point, the force being negative at all speeds higher than that corresponding to the point of equilibrium defined by the intersection of this curve and axis, positive at all speeds lower. It therefore does not matter if there are one or more "kinks," involving changes in the sign of the slope, in the force curve, provided only that they do not reach or cross the axis. For completely satisfactory stability with locked controls, however, the slope of the curve must be positive at every point throughout the range of speeds likely to be reached.

As has been pointed out, the machines used in these tests were nose heavy under practically all conditions, but this can easily be corrected, if desired, by setting the stabilizer at a larger negative angle relative to the wings. If greater stability or stability over a wider range of speeds is required it can be secured by moving the center of gravity forward, just as in the case of fixed controls. The natural tendency, when a machine is nose heavy, is to seek to cure it by moving the center of gravity farther back. Where, however, as in this case, the nose heaviness is accompanied by instability, moving the C. G. aft will only serve to aggravate the latter difficulty. If the C. G. is moved at all it should be moved forward. Changing the stabilizer setting so as to give an increased downward force on the tail, on the other hand, improves the balance and, as will be shown later, also has some beneficial effect on the stability with free controls. The exact effect of changing the stabilizer setting is difficult to predict unless an exhaustive series of tests on pressure distribution over the elevator is available (such tests have never been made except for one machine), as the moment about the elevator hinge depends largely on the position of the center of pressure on the elevator, and this is a very uncertain quantity. If the center of pressure position is assumed to be unaffected by the changes in elevator angle to secure equilibrium at a given speed with a changed stabilizer setting, the alteration in moment about the hinge, due to the different stabilizer angle, is almost exactly proportional to the square of the speed, as the change in elevator angle for equilibrium is very nearly the same for all speeds. The slope of the curve of forces on the stick, under these conditions, would decrease in algebraic value if the stabilizer angle were decreased, and the tendency would be toward stability. From this the deduction can be drawn that stability with free controls can not be obtained at any given speed merely by changing the stabilizer setting unless the machine was originally nose heavy at the designated speed and all lower speeds of flight. Furthermore, an airplane the curve for which is unstable (i. e., has a positive slope) throughout the range of normal speeds of flight can not be made stable with free controls at any speed whatever by changing the stabilizer setting unless it is initially nose heavy at all points of its speed range. Although these deductions are based on an assumption not strictly true they check well with experiment and furnish a fair basis for reasoning. It follows from the foregoing conclusions that the maximum positive angle to which an adjustable stabilizer can be moved should depend on the behavior of the machine in a steep descent with the throttle open. For stability, the force on the stick under those conditions should always be a push. When it becomes a pull it is a sign that the stabilizer angle is too large.

If the conditions laid down in the last paragraph are not observed it will, as already noted, be impossible to secure stability with the stabilizer alone, and the center of gravity will have to be moved forward.

It will be noticed that the curves of control force for the two airplanes in gliding are nearly identical, while the negative moments about the hinge with throttle open are considerably larger for No. 1 than for No. 2. This difference is at least partially due to the difference in the vertical coordinates of the center of gravity, the C. G. of No. 1 being higher than that of No. 2 because of the reserve tank in the upper wing. The center of gravity being farther above the thrust line in No. 1, the thrust on that machine produces a stalling moment about the C. G., and this has the effect of making the machine less nose heavy than it would otherwise be.

It is desirable that the pilot of an airplane should be able to release the controls at any time without causing the machine to go into a steep dive or to stall badly. In order to fulfill this requirement the center of gravity should be materially farther forward with respect to the wings than it was in the particular airplanes which were the subjects of these tests, and the stabilizer should be set at such an angle to the wings that the machine will be in equilibrium with the controls free and the engine throttled at a speed well within its normal range (60 miles per hour would be a good figure for an airplane of the type and performance of the JN4H). Exact recommendations as to the position of the C. G. can not be made without further tests, but it is probable that 28 per cent of the way back from the leading edge on the mean chord of the wings will be found a satisfactory location. The negative angle of the stabilizer with respect to the wings should be larger in these machines than inthose in which the stabilizer section is symmetrical about a horizontal plane. A stabilizer with a flat lower and a cambered upper surface, such as that ont he JN4H, has its zero lift line at an angle of from 2° to 4° to its chord, and it is the zero lift line which should be considered in choosing the setting.

In order to put to the test these theories as to the cause and cure of instability and poor balance, airplane No. 1 was rerigged with the stagger reduced by 3 inches, and with the rear of the stabilizer blocked up so that its chord was at a negative angle of 1°.6 to the top longerons, or 4° to the wings. The reduction of the stagger by moving the upper wing backward has practically the same effect as has moving the center of gravity forward.

Although the tests with this new arrangement have not as yet been carried far enough to make it possible to plot a set of curves, it was very apparent that the nose heaviness of the machine was much diminished and that the stability, both with free and fixed controls, was improved. The machine was still unstable at high speeds, but much less so than before. It was dived to a speed of 115 miles per hour with the throttle half closed, and the pull on the stick at this speed was only 10 pounds. There was no difficulty in taking off or landing, and the performance of the machine was not modified in any other respect. It is believed, as a result of these tests, that it will be found possible by further changes of the same nature to secure complete statical stability of the JN4H at all speeds without incurring any counterbalancing disadvantages.

Longitudinal balance of the De Haviland.

In order to have data on another airplane for purposes of comparison, and also to secure definite information on the effect of an adjustable stabilizer, the experiments which have been described above were repeated on the De Haviland 4 with Liberty engine. The method pursued in the first series of tests on this machine was identical with that already described, and the curves of control position, force, and moment for various throttle settings are given in figures 30 and 31. The force required at the top of the stick to balance the weight of the elevator was $3\frac{3}{4}$ pounds, and a force of 1 pound on the stick corresponded to a moment of 24.6 pound-inches about the elevator hinge. The "gearing" of the control was therefore practically identical with that in the JN. The scale of abscissæ may not be strictly accurate, as the air-speed meter on this machine was never calibrated on the speed course, but it probably would not be in error by more than three or four miles an hour at any point.

It appears from these curves that the DH4 possesses statical longitudinal stability both with fixed controls and with free controls, and that the trimming speed for any given condition increases as the engine speed decreases. If, for example, the elevator is locked at +3° with the throttle open the machine will fly at 82 miles per hour, and will automatically return to that speed if any disturbance causes a momentary deviation from it. If the engine is then throttled down to the idling condition, leaving the control still locked at +3°, the nose will drop and the steepness of the flight path will increase until the speed of 114 miles per hour is attained. The airplane will then continue to descend steadily at this speed on a flight path of constant slope. There will be no tendency, as in the other airplanes which have been discussed, to dive more and more steeply without limit.

Much the same statements can be applied to flight with free controls, except that in this case there is only one trimming speed for a given stabilizer angle and throttle setting. Here, again, the trimming speed increases as the throttle is closed.

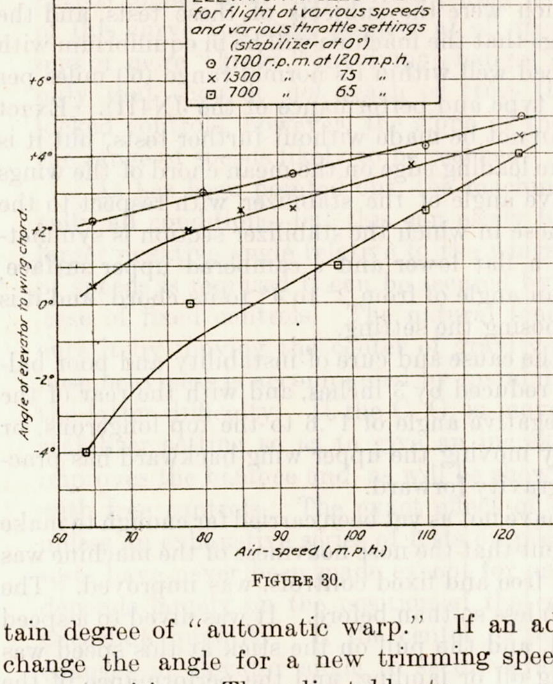


FIGURE 30.

It is obvious that the airplane of the future must have a high degree of inherent stability, so that it can be flown "hands off" for considerable periods in calm air. Since it is not desirable that the machine be limited to a single air speed for a given throttle setting, some means must be provided for changing the trimming speed. This can be done either by a device for locking the controls in any desired position or by making it possible for the pilot to adjust the stabilizer angle while in flight. The first of these alternatives has the advantage that it is easy and quick to operate, as the stick can be made with a lock instantaneously operable by the pressure of a finger. The locking should apply only to the fore-and-aft motion, the stick being left free to move from side to side in order that the pilot may correct disturbances of transverse equilibrium without releasing the lock, and, also, so that the ailerons may be free to move when struck by gusts, so giving a certain degree of "automatic warp." If an adjustable stabilizer is provided, it takes longer to change the angle for a new trimming speed than it does to move the stick and lock it in a new position. The adjustable stabilizer has, however, the very great advantage that the stick is left entirely free for control, and it can therefore be used to reduce the strain on the pilot even when the air is too rough or when the machine is too near the ground to permit of releasing or locking the stick.

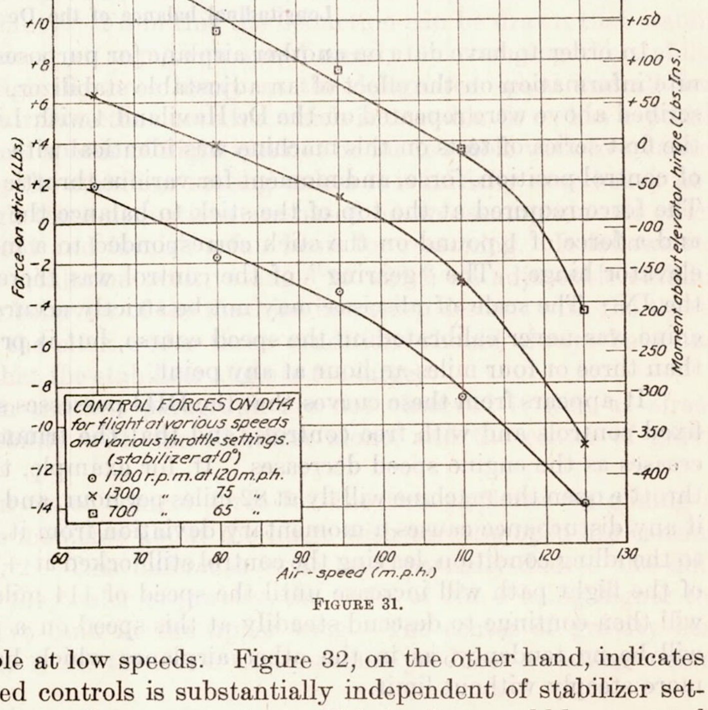


FIGURE 31.

The effect of the adjustment of the stabilizer is shown by figures 32 and 33, which give the curves of control forces and moments for level flight with three different stabilizer settings. Figure 33, giving the control forces required and the trimming speeds with free controls for the several settings, is the more important of the two. It appears from the curves there given that the statical longitudinal stability with free controls diminishes rapidly as the stabilizer angle is increased, and that, when the neutral line of the stabilizer is set at $+1° 30'$ to the wing chord, the machine is statically unstable at low speeds. Figure 32, on the other hand, indicates that the degree of stability with locked controls is substantially independent of stabilizer setting, the three curves being very nearly parallel to each other. This is what would be expected from model tests and from theoretical considerations, some of which were developed in the preceding section of this report.

The trimming speed increases as the stabilizer angle increases, slowly at first and then very rapidly. A change of angle from $-1° 30'$ to $0°$ only raises the trimming speed with free controls from 71 to 86 miles per hour, but only about $0° 40'$ further change in angle is required to increase the trimming speed from 86 to 120 miles per hour. Since so small a change of angle has so large an effect it is necessary, in order to gain the full benefit of an adjustable stabilizer, that the adjustment be through a screw or other slow-motion device with a minimum of backlash, so that the angle can be regulated with great exactness. The backlash on the DH4 tested was about $0° 15'$.

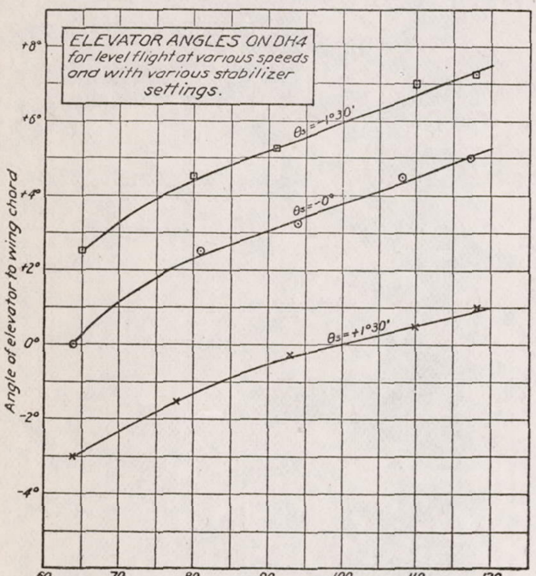


FIGURE 32.

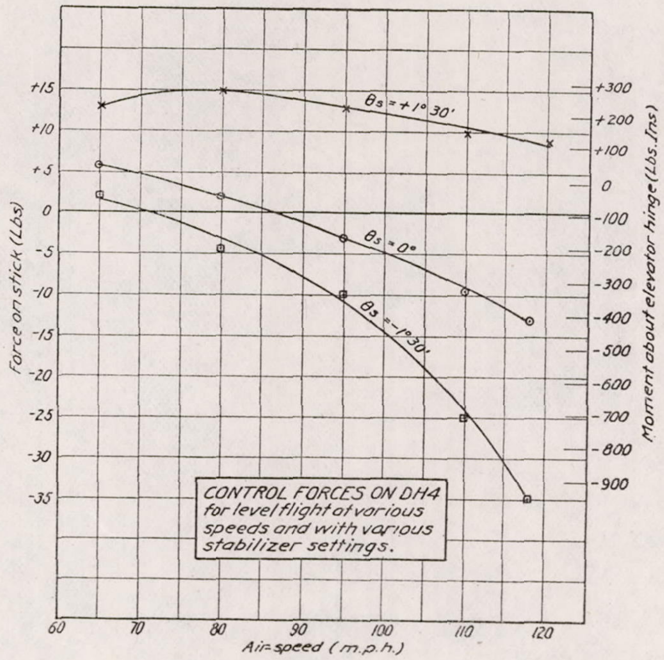


FIGURE 33.

The provision of an adjustable stabilizer on the DH4, and the range of angles chosen for the adjustment, were largely due to the distance between the center of gravity and the observer's cockpit and the gasoline tank, a small change of weight in the rear cockpit having a large effect on the balance of the machine. For the conditions existing when these tests were carried out (170-pound observer, no heavy instruments, guns, photographic apparatus, or other equipment in the rear cockpit, and gas tank two-thirds full) the maximum positive adjustment of the stabilizer would never be required.

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