TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No. 1

NOTES ON LONGITUDINAL STABILITY AND BALANCE.

by

E. P. Warner, Chief Physicist,
Aerodynamical Laboratory, N.A.C.A.
Langley Field, Va.

FILE COPY
To be returned to
the files of the National
Advisory Committee
for Aeronautics.

Washington,
April, 1920.

NOTES ON LONGITUDINAL STABILITY AND BALANCE.

By

Edward P. Warner.

More or less complete studies of longitudinal stability have now been made on five airplanes, - the JN4H, DH4, VE7, USAC-11 and Martin Transport. In addition to these tests, numerous modifications have been made in the design of the JN4H and the effect on stability and balance investigated.

The tests on the DH4 and on the JN4H as normally used are described and discussed in Report No. 70 of the National Advisory Committee for Aeronautics, and the methods of making the tests and interpreting the results are also taken up in some detail in that report. The conclusions drawn may, however, be summarized here.

The balance of an airplane, and its degree of nose-heaviness or tail-heaviness at any speed and throttle setting, can manifestly be determined by measuring the force which the pilot must apply at the upper end of the stick in steady flight. This force can always be modified in either direction and in any desired degree by changing the stabilizer setting, and this means of correction should be chosen in preference to moving the C.G. relative to the wings unless there is special reason for adopting the latter plan. The balance, as expressed by the force required on the stick,

is much affected by the weight and chord of the elevators. The JN4H, for example, is very nose-heavy when normally rigged, but this is not because the C.G. is too far forward (it is, on the contrary, too far back) but because the static moment of the elevators about the hinges, due to their own weight, is abnormally large, and a large pull (about 8½ lbs.) on the stick is required to hold the flippers up, even when there is no downward air load on them. Machines with adjustable stabilizers can, of course, be made to balance at any speed by adjustment of the surface.

The stability with free controls can best be determined by measuring the force on the stick at a fixed throttle setting and a number of different air-speeds and plotting the forces as ordinates (a pull on the stick being taken as positive) against the air-speeds as abscissae. The necessary and sufficient condition for stability with free controls at any speed is then that the curve of forces shall have a negative slope at that speed, and the steeper the negative slope the greater the stability. The machine cannot, of course, be flown with free controls at any speed except the one at which the curve crosses the horizontal axis, but this axis can easily be shifted vertically if desired by attaching a counterweight, spring, or elastic to the stick in such a way as to change the "effective weight" of the elevators, and so the pull on the stick due to that weight. The actual measurement of the forces at several different speeds and the plotting of a curve is far more accurate and satisfactory as a means of determining longitudinal stability than is the customary method of recording the pilot's impressions on the subject, as it practically eliminates the per-

sonal equation, and gives a definite quantitative result in place of such vague phrases as: "Stability very good"; "Stability poor"; "Stick pushes strongly against the hand at low speed".

DISCUSSION OF EXPERIMENTS.

The force curves for the five machines which have so far been studied, with data taken at three or four different throttle settings for each machine, are plotted in Figs. 1 to 5. The stabilizer on the DH4 was set with its center line parallel to the chord of the wings. There was no means of determining the stabilizer setting on the Martin Transport while in flight, but it was adjusted to trim at 100 m.p.h. with the throttles open, and this setting was maintained throughout the tests.

There is no very consistent rule for the variation of stability either with throttle setting or with air-speed, although the general tendency is to be more stable when gliding than with open throttle. The Martin and Curtiss are more stable at low air-speeds than at high, while just the reverse is the case with the DH4 and LePere. The Vought is extraordinary in that it possesses the same degree of stability, and just about the ideal degree, at all engine speeds and all air-speeds. It will be noted that the JN stabilizer is flat on the lower surface, that of the Vought slightly convex, while those of the DH4 and LePere are nearly symmetrical. It appears then, that all of these machines except the Martin follow the rule that a convex camber of the lower surface of the stabilizer is favorable to stability at high speeds, and that, in order to secure the same degree of stability under all conditions of flight and to keep the force on the stick comfortably small at all times,

the camber of the lower surface should be from one-quarter to one-half that of the upper. The fact that the Martin forms an apparent exception to this rule should not be regarded too seriously, as the friction in the controls on that machine was so great that the force readings cannot be depended on to be accurate within two or three pounds. Further tests on the JN have shown that the stability at high speeds is much improved when the stabilizer or tail-plane is inverted.

The degree of stability in an airplane with an adjustable stabilizer or tail-plane depends largely on the setting of that member and such a machine will, from this cause alone, be more stable when gliding than with throttle open. The curves for the Martin for example, would be much more stable (larger negative slope) if the stabilizer or tail-plane had been set to trim at 100 m.p.h. while gliding, rather than while operating at full power.

If there is instability in an unpleasantly large degree, it may be corrected by: (a) moving the center of gravity farther forward; (b) setting the stabilizer or tail-plane at a larger negative angle to the wings; or, (c) using a larger stabilizer or tail-plane. These conclusions are not only the result of theory, but they have also been checked by actual tests on the JN4H, in the course of which tests the stagger was decreased (this being equivalent to a forward movement of the center of gravity relative to the wings), the C. G. was moved both horizontally and vertically by the attachment of weights at various points, and the stabilizer or tail-plane angle was altered several times. In order that the machine may not be made excessively nose-heavy or tail-heavy it is usually necessary to combine (a) with either (b) or (c). The effect of in-

creasing the size of the stabilizer or tail-plane can be secured by any means which steepens the lift curve of that surface and so increases its stabilizing efficiency. In particular, this object may be accomplished by increasing the aspect ratio of the stabilizer or tail-plane or by using a more efficient section or a section more efficiently presented. For example, there is, under all ordinary conditions of flight, a downward load on the stabilizer or tail-plane, and a section flat on the lower surface, like that employed on the JN, is therefore working at a negative angle of attack, a condition in which the lift curve has a materially smaller slope than it has for positive angles. It might, therefore, be expected that the stabilizing effect of the tail planes of the JN would be improved by inverting the section, making the upper surface flat and the lower one cambered, and this has been found to be the case. It has already been shown, however, that the section of the tail should usually be controlled by the consideration of securing the same degree of stability at all speeds.

If the elevator were weightless, or if its weight were balanced, and if there were no moment about the elevator hinge when there is no force on the elevator, stability with free controls at the trimming speed (the speed at which the machine would fly if no restraint of any sort were placed upon the stick) could be satisfactorily investigated in the wind tunnel by removing the elevators from the model and testing it for longitudinal stability with only the stabilizer or tail-plane in position, and a test of this sort furnishes a fairly satisfactory approximation to the truth under the conditions actually existing. Unfortunately, however, neither of the conditions stated above are, in general, observed, and the problem of

analysis of the tail forces, their distribution between the fixed and movable portions and their effect on stability becomes one of great complexity, usually soluble only by direct experiment on full-sized machines in free flight.

For a section, symmetrical about its center line, the angle of attack at which the pitching moment about the leading edge is zero is of course identical with the angle of zero lift. For unsymmetrical sections, such as are very commonly used in stabilizers and elevators, the moment about the leading edge disappears when there is a considerable negative lift, and, conversely there is a moment tending to raise the trailing edge of the elevator when the net lift of that member is zero. It is then evident, if the assumption of a weightless elevator be abandoned and if the interference between stabilizer and elevator be neglected for the moment, that, with the controls free, there will have to be a larger upward force on the elevator, in order to balance the moment about its hinge due to its own weight, if the surface is flat above and cambered below than if the more usual reverse disposition is adopted. Since any upward force on the elevator requires a counter-balancing addition to the downward force on the stabilizer, this is a point, although not a very important one, in favor of the tail-surfaces flat below and cambered above. For a similar reason, any decrease in the weight of the elevator or in the distance from its center of gravity to the hinge is very beneficial. The design of control and stabilizing surfaces offers, both from the structural and the aerodynamic standpoints, a fruitful field for experimental and theoretical research, and there is no point at which such research is more needed.

Machines properly balanced with open throttle are all nose-heavy when gliding, and, conversely, those which are properly bal-

anced when gliding are tail-heavy with full power. This is due to the effect of the slip-stream on the controls, and it is interesting to note that this effect exists in a marked degree even on the Martin, where only a small part of the tail-surface lies inside of the slip-streams. The most obvious means of counteracting this slip-stream effect is to raise the thrust-line, thereby giving rise to a diving moment when the engine is on full which will counterbalance the stalling moment due to the downward blast of the slip-stream on the stabilizer. The change in elevation of the thrust-line which would be required for complete balancing would, however, be too great to be practicable on machines of ordinary type. In a JN4, for example, the thrust-line would have to be raised a little more than a foot with respect to the center of gravity in order that the force curves with open and closed throttle might be identical. It is probable that one reason for the unusually small separation of the several force curves in the Vought is the relatively low position of the C.G. in that machine, although the C.G. is not low enough, relative to the thrust-line, to balance the slip-stream effect very completely. In flying boats, where the C.G. is far below the thrust-line, it is reported by pilots that the moment due to eccentricity of the thrust is more than sufficient to balance that due to the slip-stream effect, and the boats therefore tend to stall when the throttle is closed and dive when it is opened. This, of course, is more objectionable than the opposite tendency, but the ideal condition would be half-way between, one in which the air-speed with free controls remains constant at a speed slightly in excess of the speed of minimum required power. Progress towards this ideal condition can be made by tilting the engine down at the front, as on the JN4A, or, on a single-engined machine, by increasing the

aspect ratio of the tail. Tilting the engine-bed causes the angle at which the air strikes the stabilizer to be diminished at the same time that the speed is increased. Here, again, the effect is rather small if the change is kept within reasonable limits. Tilting the engine-bed on the JN 2° had a distinct effect on the spacing between the force curves with open and closed throttle, but the effect was not sufficient to bring the curves to coincidence. Increasing the aspect ratio of the tail is helpful in that it increases the proportion of the stabilizer which is outside of the slip-stream.

In a twin-engined machine, the effect of the slip-stream on the control forces can be reduced either by "toeing in" the engines so that their slip-streams will travel outwards and escape the stabilizer, by setting the engines farther apart, or by having the engines rotate in opposite directions, the upper propeller blade moving away from the center of the machine in both cases, so that the tangential component in the slip-stream, or the race rotation, will be upward in that part of the slip-stream (the part nearest the center of the machine) which impinges on the stabilizer and will tend to counteract the downward direction taken by the slip-stream as a whole and due to the downwash of the wings. The first of these three remedies causes some loss of efficiency, although that loss need not be very pronounced, the second involves constructional difficulties and increases the stresses in landing, and the third makes trouble for the engine manufacturer, requiring the making and stocking as spares of an additional series of camshafts. In view of the ease with which an adjustable stabilizer can be incorporated on these large machines, it is not probable that any of the devices mentioned above will come into common use. There

is, however, no reason why the tail surfaces on single engined machines of small and moderate size should not have a somewhat higher aspect ratio than is the case on many such airplanes at the present time, - materially higher, for example, than on the JN. Much, if not most, of the extraordinary controllability, maneuverability, stability, and general facility of handling of the Vought may be ascribed to the section and plan form of its tail surfaces. By judicious choice of the section and by increasing the aspect ratio of the stabilizer, its efficiency may be so much increased that the area can be considerably reduced. We may then achieve, at the same time, a reduction in total weight, a reduction in the forces on the stick and in the control leads, an increase in aerodynamic efficiency, and a great improvement in stability.

The position of the center of gravity with respect to the wings is, as already mentioned, a very important factor in determining the longitudinal stability of an airplane, a forward movement of the C. G. increasing the stability. The C. G. on the Vought, the stability and balance of which may be considered as ideal, is 30% of the way back on the mean chord. That on the DH4 with the load carried during the tests was 29% of the way back, and the machine was stable except at very low speeds. On the JN4H, with normal rigging and a heavy observer, the C. G. was about 38% of the way back on the mean chord and the machine was markedly unstable. Subsequent changes have reduced the C. G. position coefficient to 32%, under which condition the instability still persists, although it is much reduced in magnitude. The locations of the center of gravity on the LePere and Martin were not determined. It is probable that the C. G. position coefficient on the JN would

reduced to about 28% to secure a satisfactory average of stability. The C.G. must be farther forward on the JN than on the Vought in order that stability may be satisfactory. This is due to the greater efficiency of the tail surfaces on the Vought.

Summarized, the conclusions to be drawn from the results of these experiments and from the theoretical analysis are:

1. That tail surfaces should be of large aspect ratio.

2. That the stabilizer or tail-plane should be larger than the elevator, and that the elevator should be as light as it can safely be made, its center of gravity being kept as near as possible to the hinge.

3. That the tail should be cambered both above and below, the upper camber usually being greater than the lower.

4. That the center of gravity should be from 28% to 30% back of the mean chord.

5. That the thrust-line should be as high as it can conveniently be placed.

Although no scale for indicating the elevator angle at any instant was fitted to any of the three machines tested in Dayton, some idea of that angle in normal flight could be gained in the case of the LePere by observing the position of the balanced portion of the elevator with relation to the adjacent edge of the stabilizer, and, in the case of the Vought, by recording the position of the stick in the front cockpit (by measuring the distance from the head of the stick to the instrument board) and determining after landing the elevator angle corresponding to the observed stick position.

Stability with fixed or locked controls is deduced from the slope of a curve of elevator angle against speed, the method of analyzing this curve being discussed in full in Report No. 70

where it was shown also that the DH4 had a stable curve of elevator angles at all speeds, while that of the JN was stable at low speeds and unstable at high. While it was impossible to make any exact measurements in the cases of the Vought and LePere, it was evident that the first of these machines would possess a small, but amply sufficient degree of stability with locked, as with free, controls. The LePere would be substantially neutral with locked controls and open throttle, stable with closed throttle, as the position of the stick for straight flight with open throttle is, as nearly as could be detected, the same for all air-speeds.

On the Vought, the angle of the elevator to stabilizer, with open throttle, ranged from $+ 1^{\circ}$ at low speeds to $+ 3^{\circ}$ at high. In gliding, the elevator was pulled up to a negative angle. On the LePere, on the other hand, the elevator was in line with the stabilizer with throttle open and set about -4° to the fixed surface when the throttle was closed. These figures have an interesting bearing on the tail-heaviness of the LePere.

Tail-heaviness ordinarily means that there is an upward air force on the elevator, and that the moment of this force about the hinge is more than sufficient to balance that of the weight of the elevator. Naturally, such a machine requires a positive elevator angle for equilibrium. The LePere, on the other hand, although it is extremely tail-heavy, carries the elevator at a zero or negative angle for equilibrium having the trailing edge of the elevator pulled up considerably higher in normal flight than does the nose-heavy JN. This, also, is in spite of the fact that the angle of zero lift for the JN tail surfaces would be smaller than for the symmetrically-cambered tail of the LePere. To take another instance,

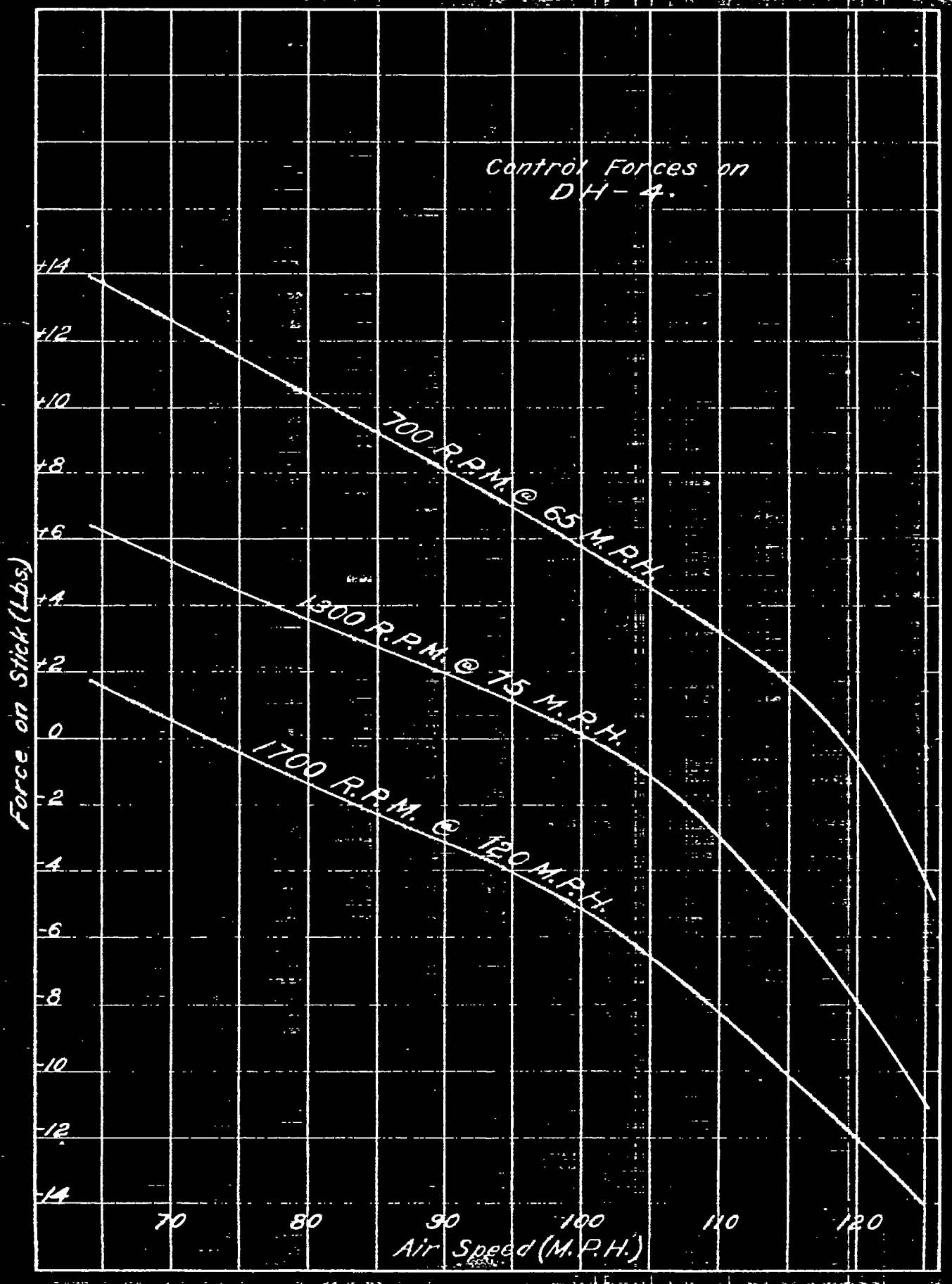
the DH4, with a tail having nearly the same section as that of the Le Pere, is nose-heavy at all speeds if the stabilizer be so adjusted that the elevator angles are equal to those on the LePere. With the stabilizer adjusted for proper balance, the elevator has to be pulled down to a positive angle of from 2° to 4°, whereas on the Le Pere it has to be pulled up to a negative angle to the wings and the machine is still tail-heavy. The stick forces required to balance the weights of the elevators are substantially equal (within 1 lb.) on the DH4 and LePere.

The conclusion is that the measurements of forces and angles on the LePere, if interpreted in the ordinary way, lead to diametrically opposite conclusions, and that the two sets of data can only be reconciled by taking account of the balancing portion of the elevator hitherto ignored.

Since the center of pressure of a flat plate or symmetrically cambered surface approaches the leading edge as the angle approaches zero, it is evident that, if such a surface be hinged anywhere back of the leading edge, the curve of C.P. travel will cross the line of the hinges at least twice during the range of angles normally used. Such a surface is used on the LePere, and, when it is observed that the balancing portions are in a position where they carry a much larger unit pressure than any other part of the elevator, it appears highly probable that the elevator is overbalanced under some conditions. If this be the case, it would fully account for the seeming anomaly in the control forces, as the effect of tail-heaviness may be produced by a down load with the center of pressure forward of the hinge, quite as well as by an up load

applied behind the hinge.

In view of the difficulty experienced with the balance of the LePere fighter and of the considerations just stated, I strongly recommend that the effect of eliminating the balancing part of the elevator and adding that area to the stabilizer be tried.


Control Forces on
DH-4.
700 R.P.M. @ 65 M.P.H.
1300 R.P.M. @ 75 M.P.H.
1700 R.P.M. @ 120 M.P.H.
Force on Stick (Lbs)
+14
+12
+10
+8
+6
+4
+2
0
-2
-4
-6
-8
-10
-12
-14
70
80
90
100
110
120
Air Speed (M.P.H.)

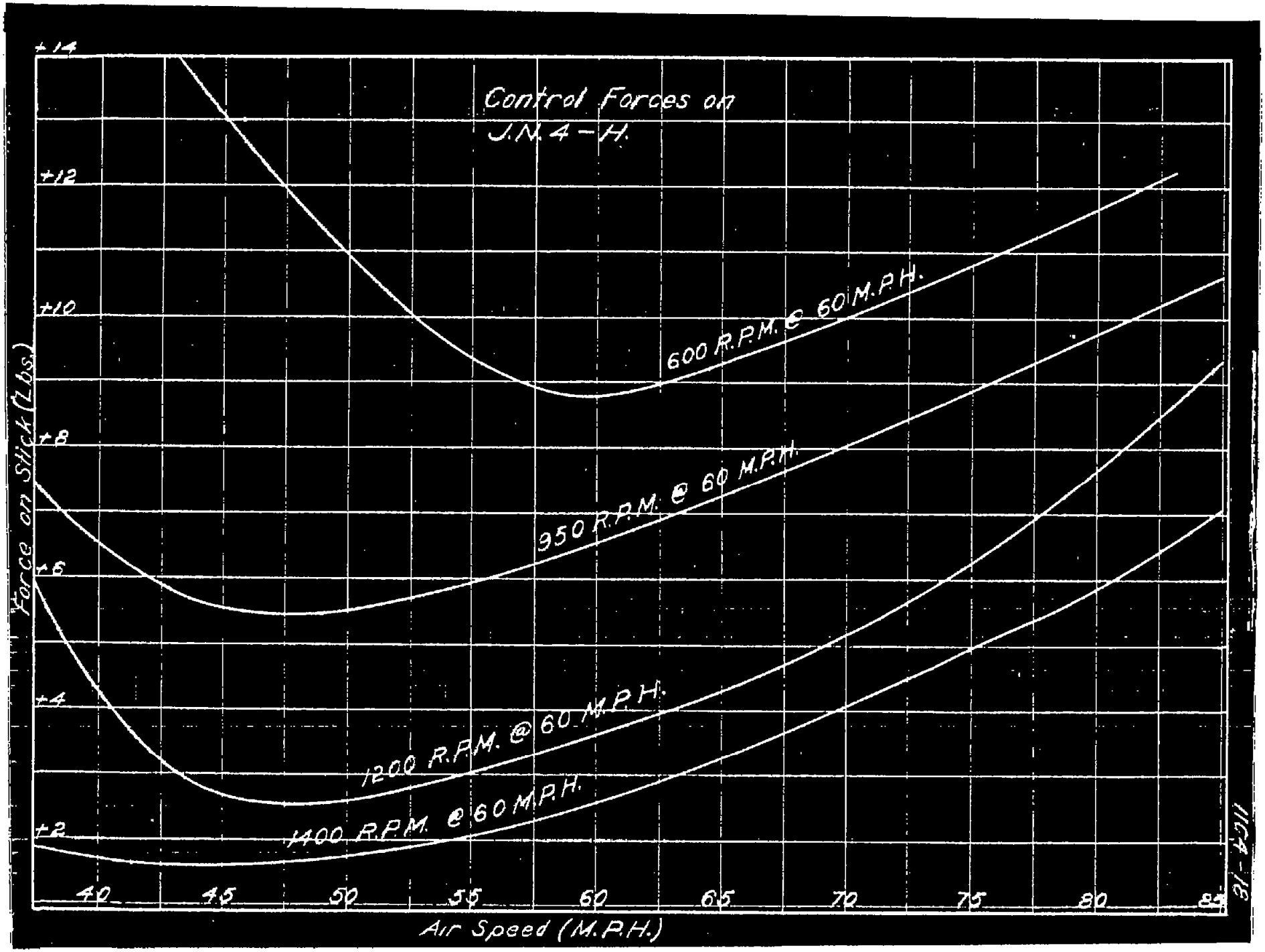
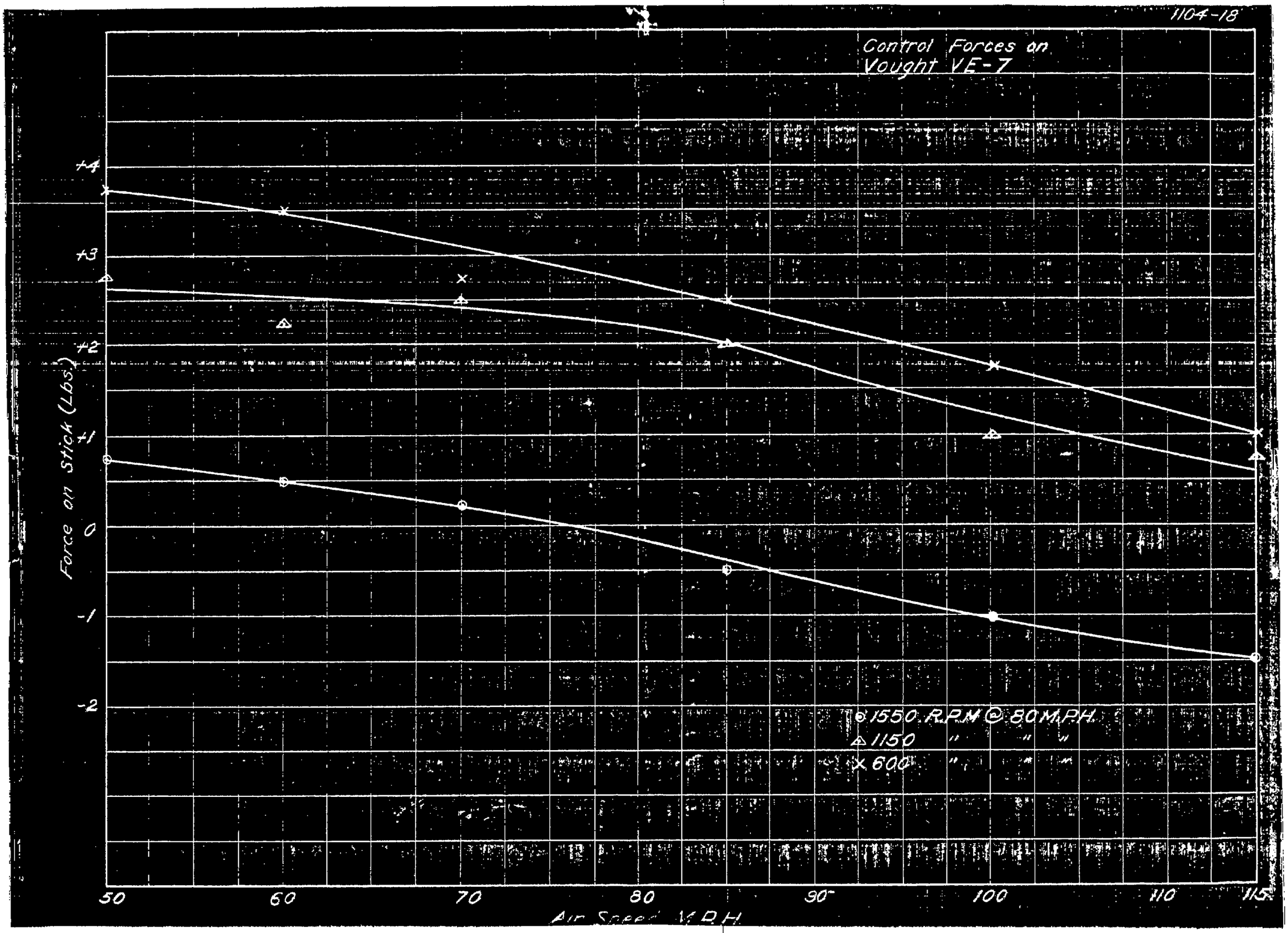
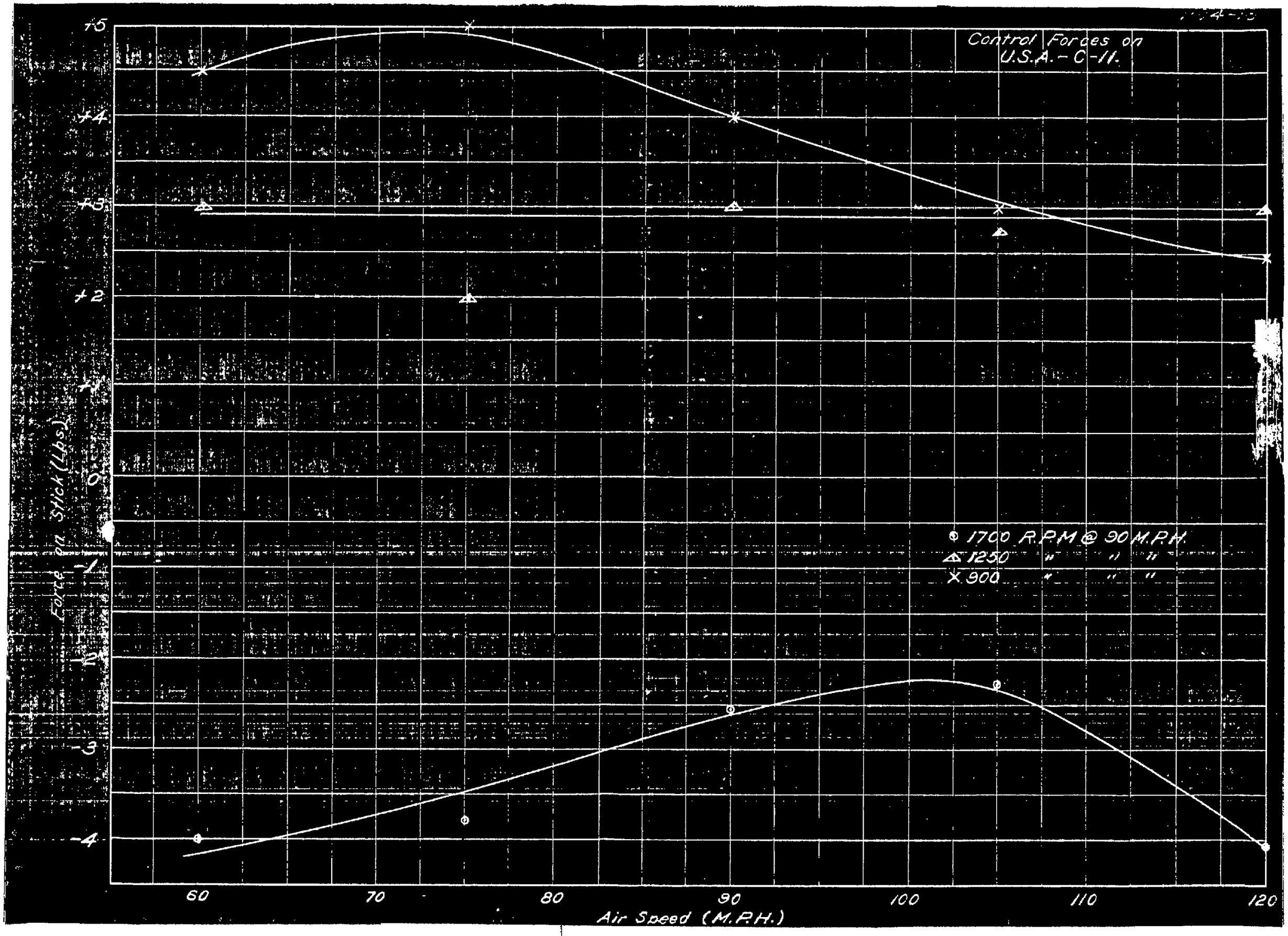
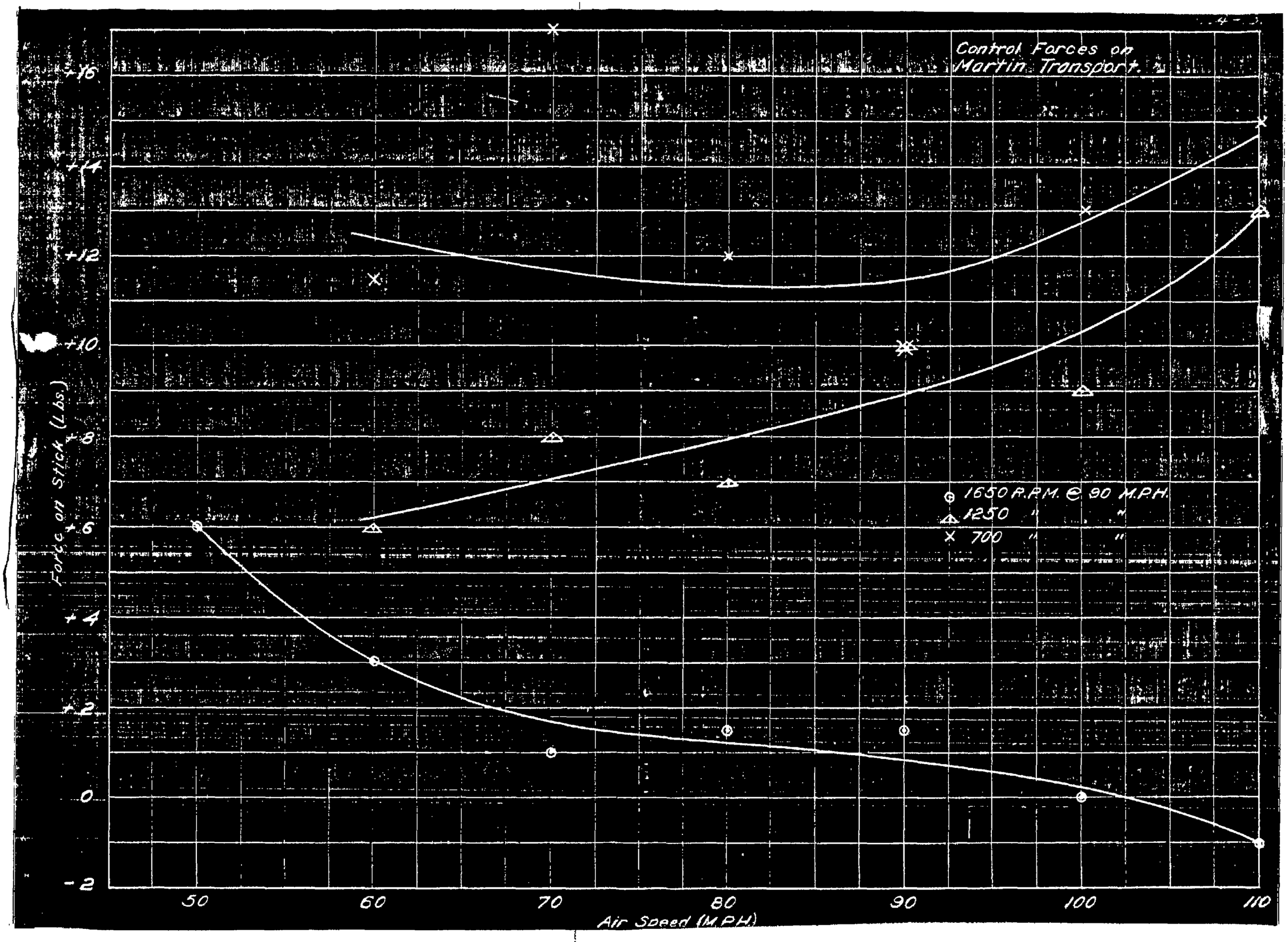

Control Forces on
J.N.4-H.
+14
+12
+10
+8
+6
+4
+2
Force on Stick (Lbs.)
600 R.P.M. @ 60 M.P.H.
950 R.P.M. @ 60 M.P.H.
1200 R.P.M. @ 60 M.P.H.
1400 R.P.M. @ 60 M.P.H.
40
45
50
55
60
65
70
75
80
85
Air Speed (M.P.H.)

FIG. 4-16


Control Forces on
Vought VE-7
+4
+3
+2
+1
0
-1
-2
Force on Stick (Lbs.)
1550 R.P.M @ 80 M.P.H.
1150 " " "
600 " " "
50
60
70
80
90
100
110
115
Air Speed M.P.H.


Control Forces on
U.S.A.-C-11.
+5
+4
+3
+2
+1
0
-1
-2
-3
-4
Force on Stick (Lbs.)
1700 R.P.M. @ 90 M.P.H.
1250 " " "
X 900 " " "
60
70
80
90
100
110
120
Air Speed (M.P.H.)


Control Forces on Martin Transport.
Force on Stick (Lbs.)
+16
+14
+12
+10
+8
+6
+4
+2
0
-2
50
60
70
80
90
100
110
Air Speed (M.P.H.)
1650 R.P.M. @ 90 M.P.H.
1250 " "
X 700 " "