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ADVISORY COMMITTEE FOR AERONAUTICS.

REPORTS AND MEMORANDA, No. 632.

THE LONGITUDINAL CONTROL OF "X" AEROPLANES.

By H. GLAUERT, OF THE ROYAL AIRCRAFT ESTABLISHMENT.

PRESENTED BY THE CONTROLLER, TECHNICAL DEPARTMENT, AIRCRAFT PRODUCTION.

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THE LONGITUDINAL CONTROL OF "X" AEROPLANES.

By H. Glauert, of the R.A.E.

Presented by Controller, Technical Dept., Aircraft Production.
January, 1919.

Summary.—(a) *Reasons for enquiry.*—The behaviour of the original type of "X" aeroplane was found to be very unsatisfactory when looping or diving at high speed. It was desired to find the cause of the unpleasant characteristics and to test such modifications as would render the aeroplane more suitable for flying. The Report of the Accidents Committee on the same aeroplanes is contained in R. & M. 629.

(b) *Range of investigation.*—An original type of "X" aeroplane and three modified types have been tested, the experiments consisting of the measurement of the force on the control column at all speeds up to 100 m.p.h., both with engine on and gliding. Each type was tested with different tail-settings.

(c) *Results and conclusions.*—The best type of modification was obtained by cutting down the chord of the wings from 6 ft. 4 ins. to 6 ft. The wing section was then of an ordinary type instead of the high lift type previously used. The top plane was also given a certain amount of back stagger, and the elevator chord was considerably reduced.

1. *Nature of investigation.*—The behaviour of the original type of "X" aeroplane was very unsatisfactory at high speeds, as it was very difficult for the pilot to pull the aeroplane out of a steep dive. In addition the aeroplane frequently showed a tendency to hang on its back at the top of a loop. The reports received from different pilots showed a certain divergence of opinion. All were agreed that it was very difficult to pull the aeroplane out of a dive at 100 m.p.h. with engine on, and that this difficulty disappeared as soon as the engine was switched off. As regards the behaviour in a loop the reports differed considerably. Some pilots found no difficulty in performing this manœuvre, but others found that the aeroplane hung on the top of the loop and began to glide on its back. This behaviour appeared to be independent of the position of the throttle and the elevator control seemed to be incapable of restoring the aeroplane to its proper position. In each case, however, recovery was effected by altering the position of the throttle.

Examination of these reports led to the conclusion that the "X" was very unstable longitudinally and had a stable trimming attitude on its back. Preliminary calculations showed that the pull on the control column at high speeds was very considerable and that this would account for the difficulty experienced in pulling the aeroplane out of a steep dive. No appreciable difference was found in the control forces on full throttle or gliding, and the greater ease of pulling out of a dive with the engine switched off appeared to be due to the increase of incidence and decrease of forward speed when the thrust of the airscrew was reduced. In the same way, any change in the position of the throttle when the aeroplane was gliding on its back would provide an impulsive rotation which would enable the pilot to restore the aeroplane to a level keel.

It was decided to test the control forces of an "X" aeroplane to determine their magnitude and to obtain such modifications to the type as would obviate or reduce the difficulties experienced on a dive or loop.

2. *Range of investigation.*—Four different types of the "X" aeroplane have been tested, varying in wing section, stagger and size of elevators. Each type was also tested with different tail settings so as to obtain the best arrangement in each case. Full details of the aeroplanes are given in Table 1, the principal characteristics being as follows :—

(1) X. 9 (original) was first tested as a standard "X" aeroplane with high lift wing section and large elevators.

(2) X. 9 (modified) differed from the standard type, having 4° back stagger and smaller elevators.

(3) X. 10 was fitted with a normal wing section in place of the standard high lift type. This was carried out by cutting off the front 4 ins. of the standard wing section. Small chord elevators were fitted and the top plane was back staggered about 1½°.

(4) X. 11 was identical with X. 10 except that the back stagger was increased to 4½°. This aeroplane was also fitted with an adjustable spring on the lever of the control column.

The different types of wing arrangement are shown in figures 1 to 4, and the position of the centre of gravity of the aeroplane with full load is also shown in each case.

3. *Method of experiment.*—The method of experiment was to fly the aeroplane steadily at various speeds, both with engine on and gliding, and to note for each speed the force required on the control column and the position in which the elevators were held. In the experiments with engine on, the engine was on full throttle at speeds below 90 m.p.h. and throttled to 1,800 r.p.m. approximately for higher speeds. The force was measured by means of a spring and dial on the top of the control column and the elevator angle by means of a sliding rod and scale at the side of the pilot's cockpit. X. 9 and X. 10 were tested with different tail settings, and X. 11 with the adjustable spring in three different positions. The modified X. 9 was tested both with and without a passenger. The results of all the tests are given in Tables 2 to 6, and Figs. 5 to 13. The force on the control column and the elevator angle are plotted against the inverse square of the indicated airspeed ($10^4/V_i^2$) which gives approximately a measure of the attitude of the aeroplane. A scale of airspeed is also given on each figure.

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4. *Original X. 9* (*Table* 2, *Fig.* 5).—X. 9 in its original form was an early "X" aeroplane and the form of the force curve is typical of an aeroplane which is longitudinally unstable owing to its centre of gravity being too far back (*cf.* Report R. & M. 470, Fig. 11, tail setting 2°·5). The results with engine on and gliding show no difference above 50 m.p.h., the elevator angles are small, the aeroplane is in unstable trim at 50 m.p.h. and there are indications that the aeroplane would have a stable trimming speed in the neighbourhood of or beyond the critical angle, engine on. The pull increases rapidly with speed and would reach a maximum at or near the terminal velocity of the aeroplane. The results of report R. & M. 470 indicate that the aeroplane would have another stable trimming attitude at a negative angle of incidence, *i.e.*, on its back, and this fact has been established by the behaviour of "X" aeroplanes on various occasions.

From the results shown in Fig. 11 of report R. & M. 470 it was anticipated that it would be possible to improve the behaviour of the aeroplane by reducing the tail-setting and by fitting an elastic to exert a forward force (*i.e.*, a push) on the control column. By altering the tail setting about 4° it was hoped to make the unstable trimming attitude occur beyond the attitude of no lift. The aeroplane would then be out of trim and tail heavy in all normal flying attitudes, but the addition of the elastic would bring the trim back to reasonable speed without involving large forces at high speed. These modifications were therefore made, the tail-setting being reduced from 2°·6 to − 0°·8 and an elastic fitted to exert a force of 8 lbs. The effect of the change of tail-setting was only half the expected amount, so that a pull was still required at high speeds and the elastic was stronger than necessary. The change was a considerable improvement, and by reducing the pull of the elastic to 4 lbs., the force required on the controls would not have exceeded 8 lbs. for a speed up to 90 m.p.h. This simple modification reduced the forces on the standard type to half their original values.

5. *Modified X. 9* (*Tables* 3, 4, *Figs.* 5-8).—After modification X. 9 differed from the standard type in two ways; the top plane had been moved back about 10 inches and the chord of the elevators reduced from 30 to 17 inches. The first modification should be equivalent to moving the centre of gravity forwards and so make the aeroplane less unstable longitudinally. The second modification should reduce the force on the control column by reducing the moment about the hinge of the elevators. In this condition the aeroplane was tested both with and without passenger and with two tail-settings in each case. This modified type was no improvement on the standard form; the forces were slightly greater and the aeroplane is no more stable. This effect must be ascribed to the change of the centre of pressure due to the change in stagger of the wings. The effect of the change of tail-setting was very small.

6. *X.* 10 (*Table* 5, *Figs.* 10, 11).—X. 10 had a normal type of wing section, a small amount of back stagger, and small chord elevators. This type was the most satisfactory of those tested. With a tail-setting of $-2°$ the forces only varied from a pull of 5 lbs. at low speed gliding to a push of 4 lbs. at 100 m.p.h. with engine on. The aeroplane was just stable longitudinally. The reduction of the wing chord was equivalent to moving the centre of gravity forwards 4 ins. and also increased the relative area of the tail plane. Both these changes serve to improve the longitudinal stability of the aeroplane.

7. *X.* 11 (*Table* 6, *Figs.* 12, 13).—X. 11 was fitted with an adjustable spring on the lever of the control column which could take up part of the force on the pilot's hand. The effect of moving this control from one end of its range of movement to the other end was to change the force on the control column 7 lbs. Otherwise the aeroplane differed from X. 10 only in the stagger, which was 3° more negative. The results obtained showed that the aeroplane was slightly unstable, so that the movement of the centre of pressure due to the change of stagger was greater than the corresponding equivalent change in the position of the centre of gravity.

8. *Analysis of results.*—The measurements obtained do not lend themselves to accurate analysis as the elevator angles are only obtained to the nearest degree and the determination of the force is very difficult on an unstable aeroplane. An attempt has, however, been made to obtain some idea of the characteristics of the tail planes. The lift of the tail plane is

$$k_L'\rho S'V^2$$

where k'_L may be written in the form $A\alpha' + B\eta$.

Also the moment about the hinge of the elevators is

$$k_\eta \rho c_\eta S_\eta V^2$$

where $$k_\eta = C\alpha' + D\eta$$

In these formulæ S' is the area of the whole tail plane, S_η that of the elevators and c_η the chord of the elevators.

At constant attitude or constant airspeed we deduce the equations

$$\frac{A}{B} = -\frac{\Delta\eta}{\Delta\alpha_t}$$

$$C' = C - \frac{A}{B}D = \frac{\lambda}{51\, c_\eta S_\eta}\,\frac{\Delta F}{\Delta\alpha_t}\,\frac{10^4}{V_i^2}$$

where α_t is the tail-setting, F the force on the control column, and λ the hinge moment corresponding to 1 lb. pull on the control column.

The data available were analysed on these lines, ignoring observations which appeared to be largely in error. For the large elevators (43 per cent.) on the original X. 9 the value deduced for C′ was 0·0022. For the smaller elevators (31 per cent.) the following results were obtained.

Aeroplane.	A/B.		C′.	
	Engine on.	Gliding.	Engine on.	Gliding.
X. 9. With passenger ...	1·31	1·56	0·0055	0·0052
Without passenger ...	1·65	1·48	0·0053	0·0025
X. 10	1·68	1·77	0·0128	0·0071
Mean	1·57		0·0064	

These values are compared with the corresponding constants of a series of tail planes and elevators tested on R.E. 8 (Report R. & M. 409) in Fig. 29. The values found for C′ fit in reasonably with the previous experiments, but the value of A/B is less satisfactory. This value depends on the elevator angles and these measurements are the least satisfactory part of the experiment.

9. *Conclusions.*—The series of results obtained shows the difficulty of correcting the instability of an aeroplane by merely moving back the top plane, as the change in position of the centre of pressure may at times neutralise the effective movement of the centre of gravity. Considerable improvement can, however, be obtained by decreasing the tail-setting and adding an elastic to the control column to bring the aeroplane back into trim at a reasonable speed. This form of modification can easily be applied and will overcome the difficulty of the large pull which may be required when diving an unstable aeroplane.

TABLE 1.

DETAILS OF AEROPLANES.

Aeroplane.	Original X. 9.	Modified X. 9.	X. 10.	X. 11.
Wing section	High lift	High lift	Normal	Normal
Area, sq. ft.	429	429	407	407
Chord, ins.	76	76	72	72
Rudder chord, ins. ...	30	30	22	22
Elevator area, sq. ft. ...	26	16	16	16
,, chord, ins. ...	30	17	17	17
Angle of wing chord to engine bearers ...	4°·1	4°·1	6°·2	6°·1
Stagger, degs.	3°·7	−4°·0	−1°·6	4°·7
,, ins.	−0·6	−10·2	−9·8	13·6
Elevator hinge moment for 1 lb. on control column (lbs/ft.) ...	1·8	1·5	1·5	1·5

The following measurements were the same for all the aeroplanes :—

Span of main planes	36 ft.
Gap	6 ft.
Tail plane, span...	12 ft.
,, chord	3 ft.
,, area	35 sq. ft.

The measurement of the stagger is given in two ways—(1) the angle between the line joining the leading edges of the wings and the normal to the chord, (2) the distance the leading edge of the top plane projects in front of that of the bottom plane, when the engine bearers are horizontal

TABLE 2.

EXPERIMENTS ON ORIGINAL X. 9.

Condition.	Air-speed (m.p.h.).	Engine on.				Gliding.			
		Pull on Control Column (lbs.).		Elevator Angle (degs.).		Pull on Control Column (lbs.).		Elevator Angle (degs.).	
Tail-setting, + 2°·6.	35	−6	−5	5½	4	—	—	—	—
	40	−4	−7	3½	4	0	—	3	—
	50	0	0	2	3	—	0	—	3
	60	6	3	½	2	5	4	½	2
	70	10	9	0	−½	—	10	—	−½
	80	15½	16	−½	−½	15	—	0	—
	90	21	—	−1½	—	20	18	−½	−½
	100	—	—	—	—	20	—	−1½	—
	103	—	—	—	—	—	35	—	−1½
	105	—	—	—	—	27	—	−1½	—
Tail-setting −0°·8, elastic on control column.	35	1		—		—		—	
	40	1		—		—		—	
	45	3		—		—		—	
	50	5		—		—		—	
	55	6		—		—		—	
	60	7		—		—		—	
	70	9		—		—		—	
	80	10		—		—		—	
	100	15		—					

Table 3.

EXPERIMENTS ON MODIFIED X. 9 WITH PASSENGER.

Condition.	Air-speed (m.p.h.).	Engine on.		Gliding.	
		Pull on Control Column (lbs.).	Elevator Angle (degs.).	Pull on Control Column (lbs.).	Elevator Angle (degs.).
Tail-setting + 2°·3.	40	3 4 5	4 4 4	4	5
	50	7 8½ 9	1½ 1½ 1½	7	½
	60	12 13 13	½ ½ ½	12	−1½
	70	16 16½ 16	−2 −2 −1½	17	−2
	80	— 20 20	— −2 −2	21	−2½
	90	— 25 26	— −2 −2	27	−3
	100	— 36 34	— −2 −2	33	−3½
Tail-setting + 0°·7.	40	4	5	2	4
	50	6	4	7	3
	60	10	3	10	2
	70	12	1	15	− ½
	80	18	1	21	−1½
	90	22	1	27	−5½
	100	27	− ½	—	—

Table 4.

EXPERIMENTS ON MODIFIED X. 9 WITHOUT PASSENGER.

Condition.	Air-speed (m.p.h.).	Engine on.		Gliding.	
		Pull on Control Column (lbs.).	Elevator Angle (degs.).	Pull on Control Column (lbs.).	Elevator Angle (degs.).
Tail-setting − 2°·0.	40	3 1	1½ 1½	0 3	1½ 2½
	50	7 4	½ ½	5 5	½ 1½
	60	10 10	½ −1	10	1½
	70	15 15	−1½ −2	12	−2½
	80	19 18	−1½ −2	15	2½
	90	22 20	−3 −2	18	−2½
	100	23	−3	24	−4
Tail-setting − 0°·3.	40	0	6½	2	5½
	50	3	4½	5	3
	60	7	3½	7	2
	70	9	1½	10	1½
	80	11	1	12	1½
	90	15	1	15	1½
	100	18	1	20	0

REPORT N° 632.

FIG: I.

ORIGINAL AEROPLANE X.9.

WING ARRANGEMENT AND CENTRE OF GRAVITY

THE CHAIN LINES ——·——·—— GIVE THE DIRECTION OF THE ENGINE BEARERS AND LINES AT RIGHT ANGLES TO THEM.

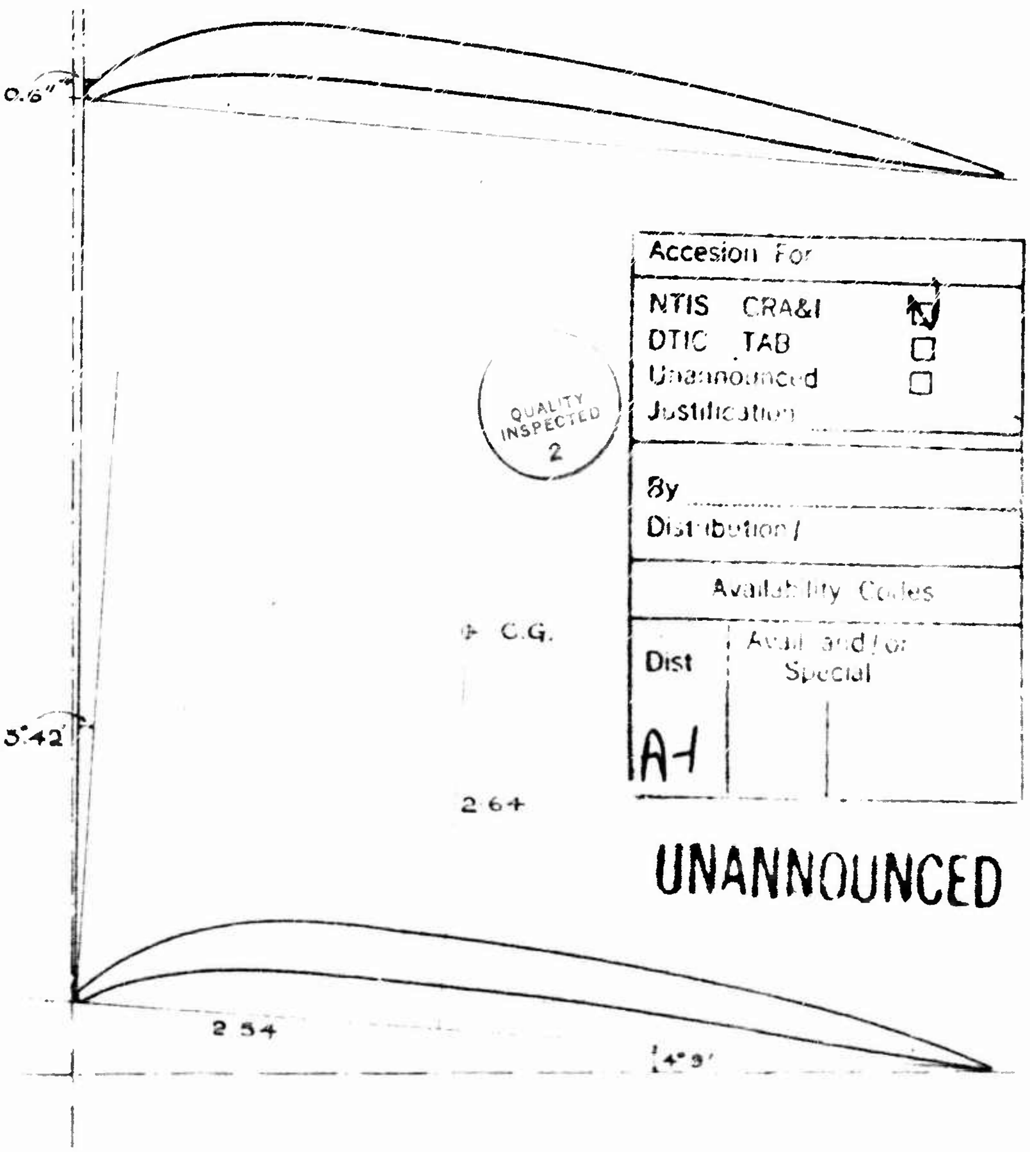

FIG: 2.

MODIFIED AEROPLANE X.9.

WING ARRANGEMENT AND CENTRE OF GRAVITY

THE CHAIN LINES —·—·— GIVE THE DIRECTION OF THE ENGINE BEARERS AND LINES AT RIGHT ANGLES TO THEM

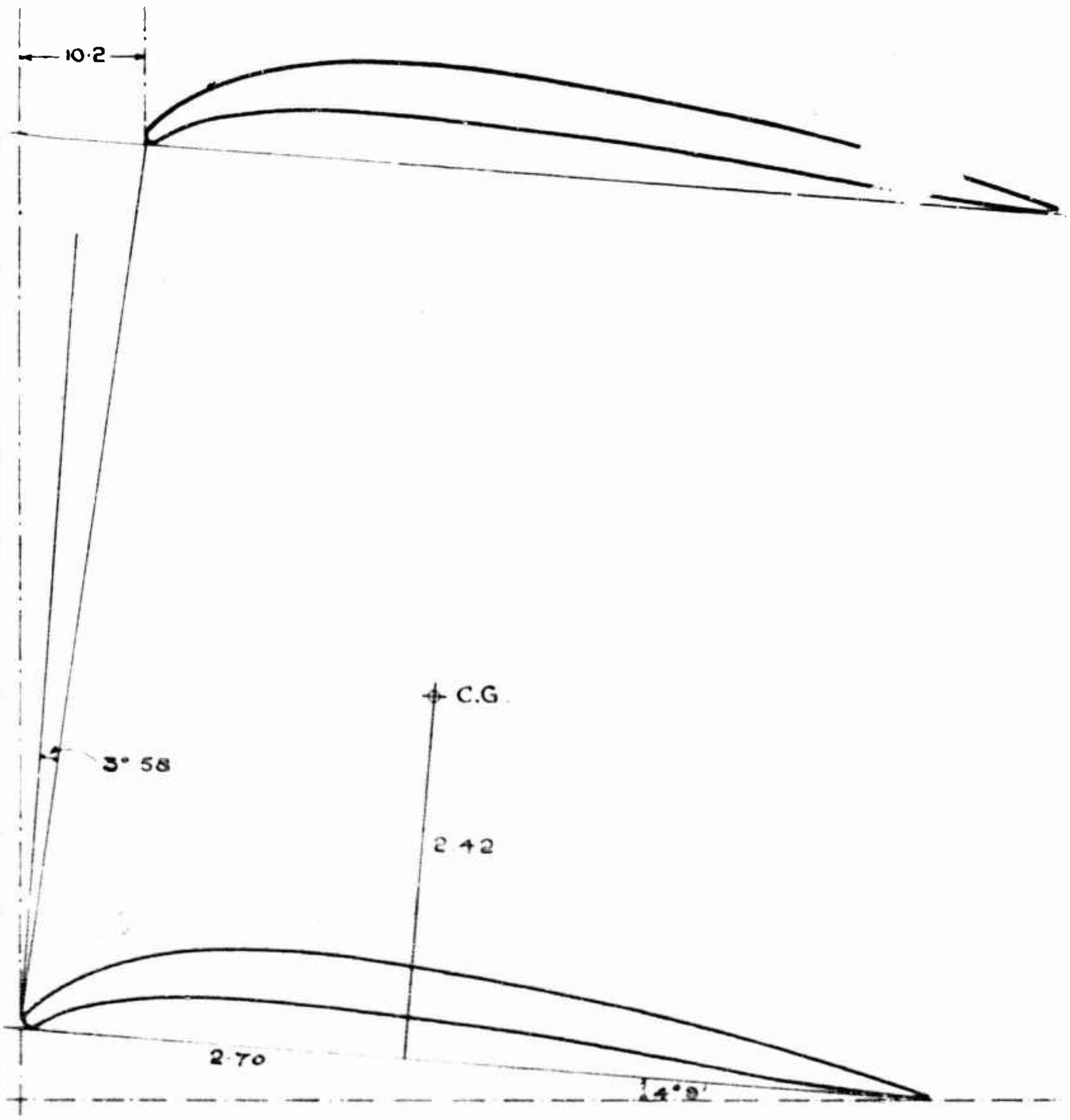

FIG: 3.

AEROPLANE X.10.

WING ARRANGEMENT AND CENTRE OF GRAVITY

THE CHAIN LINES —·—·— GIVE THE DIRECTION OF THE ENGINE BEARERS AND LINES AT RIGHT ANGLES TO THEM.

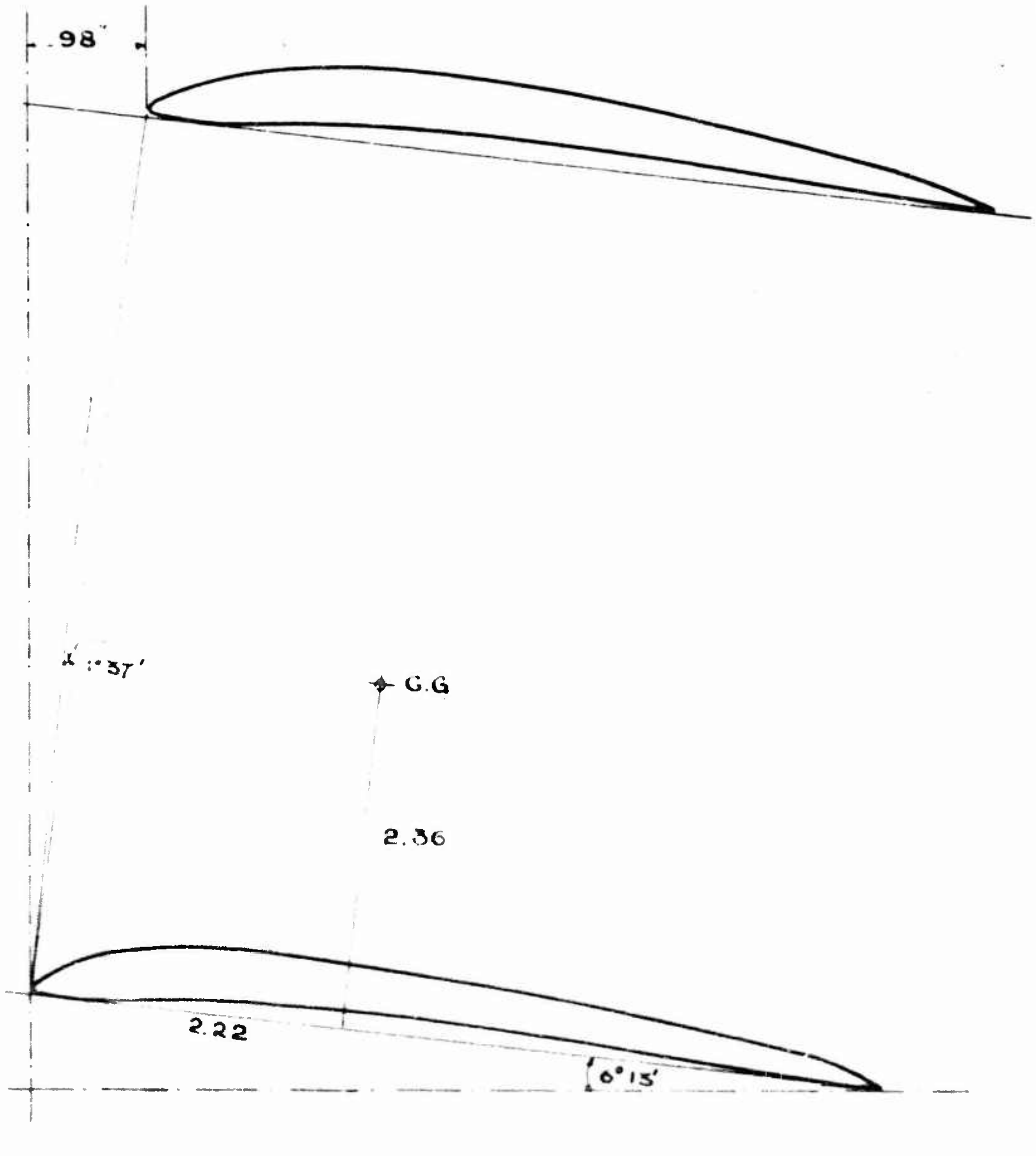

FIG. 4.

AEROPLANE X.11.

WING ARRANGEMENT AND CENTRE OF GRAVITY

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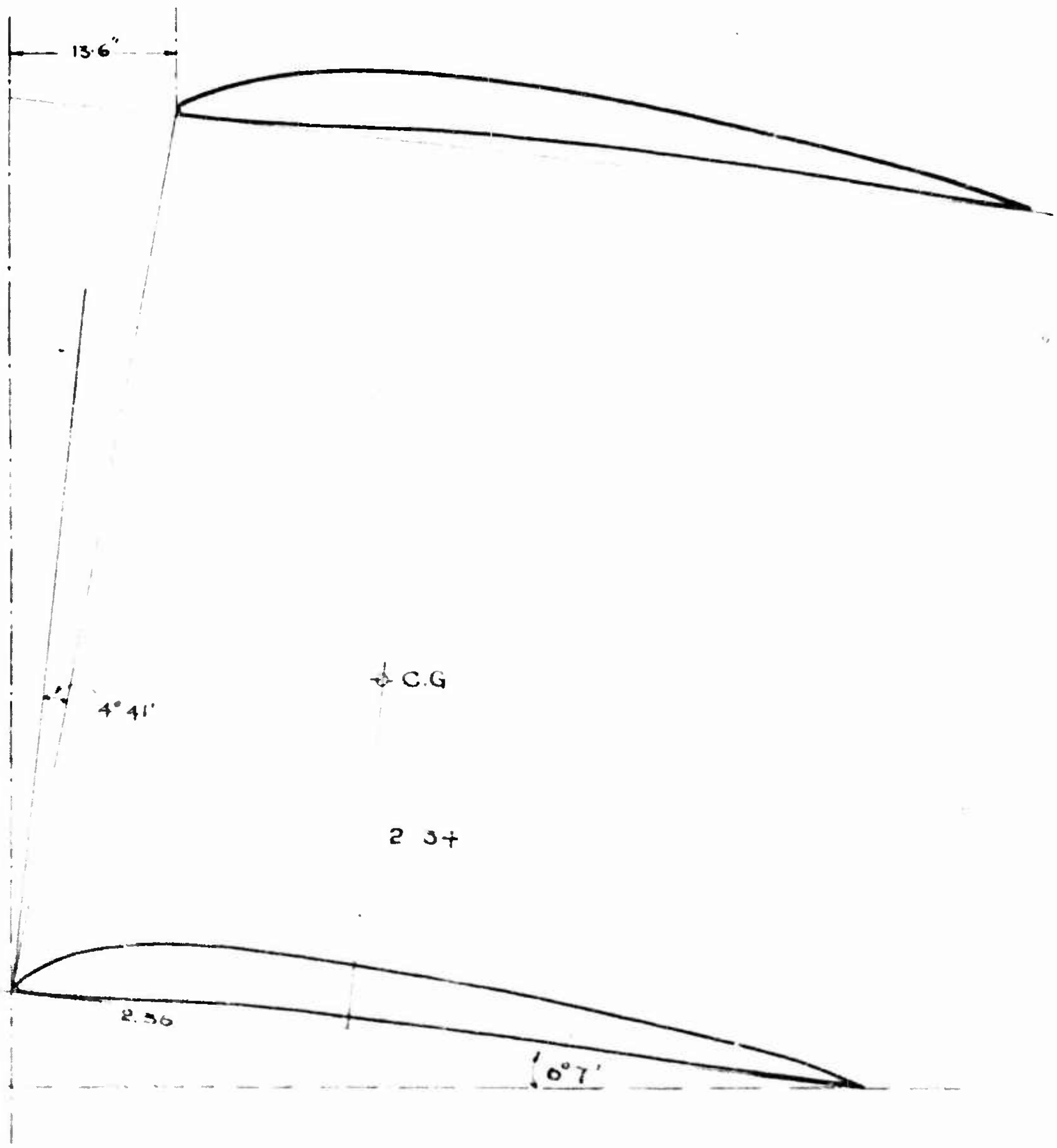


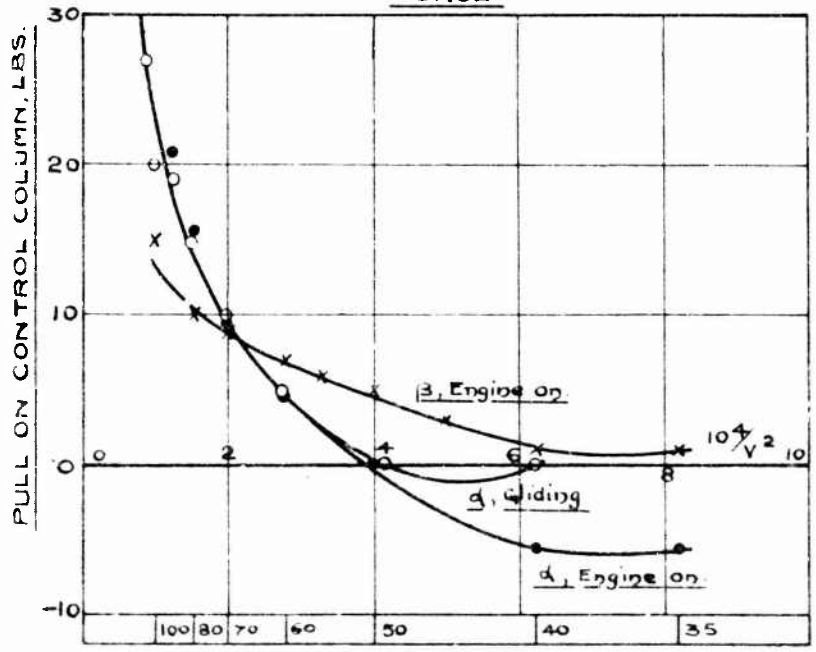
FIG: 5

ORIGINAL AEROPLANE X.9.

(α) TAILSETTING + 2°.6

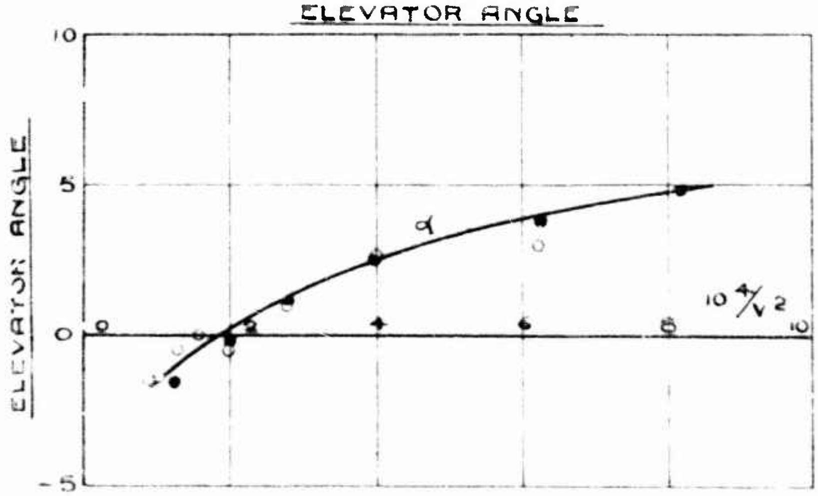
(β) TAIL SETTING − 0°.8 AND ELASTIC ON CONTROL COLUMN.

FORCE



SCALE OF AIRSPEED M.P.H.

ELEVATOR ANGLE



REPORT N° 632.

FIG: 6.

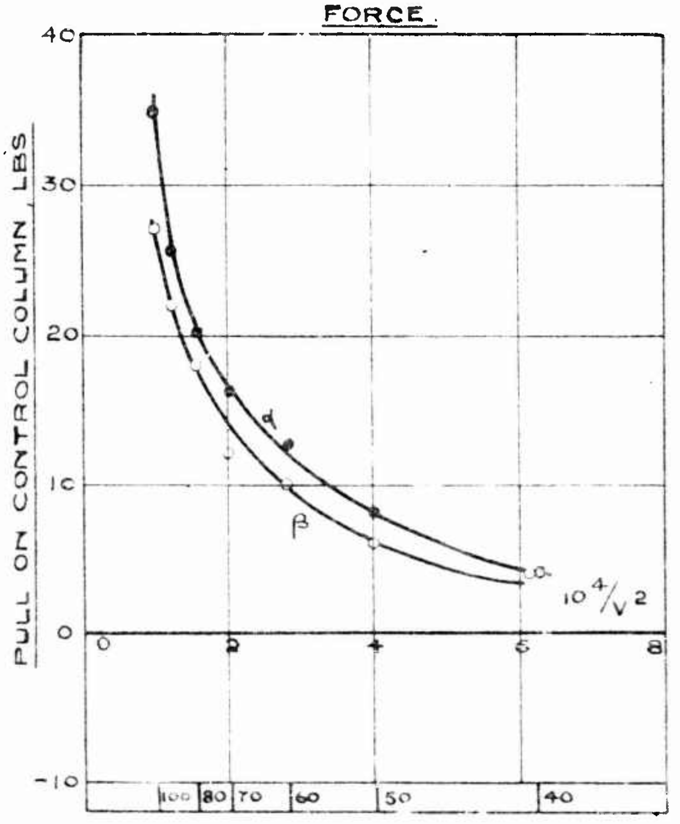
MODIFIED AEROPLANE X.9.

EXPERIMENTS WITH PASSENGER, ENGINE ON

(α) TAIL SETTING + 2°.3

(β) TAIL SETTING + 0°.7

FORCE.



SCALE OF AIRSPEED M.P.H.

ELEVATOR ANGLE

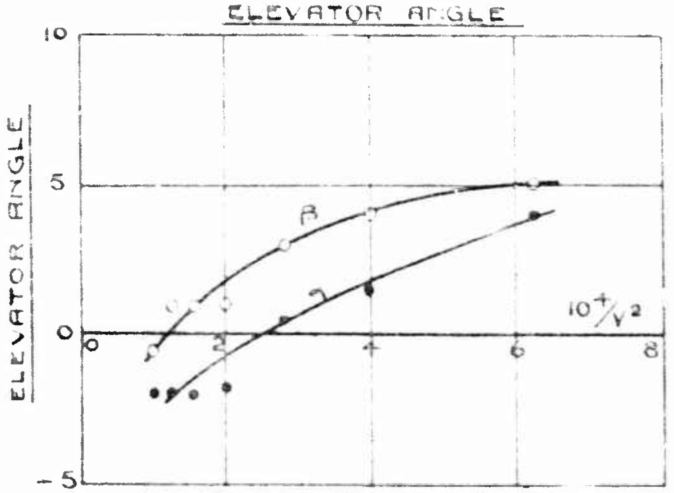


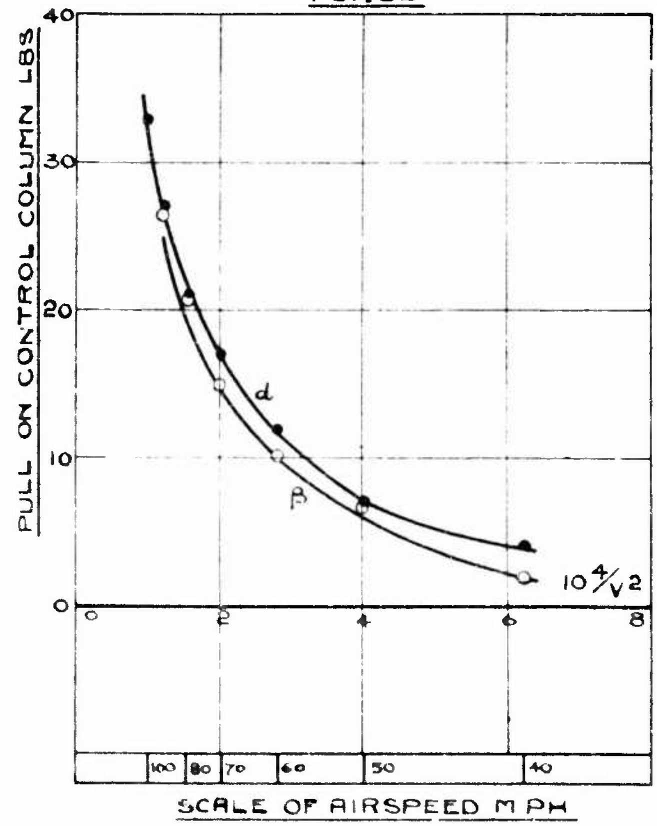
FIG: 7.

MODIFIED AEROPLANE X.9.

EXPERIMENTS WITH PASSENGER, GLIDING.

(α) TAIL SETTING + 2°.3
(β) TAIL SETTING + 0°.7

FORCE



ELEVATOR ANGLE

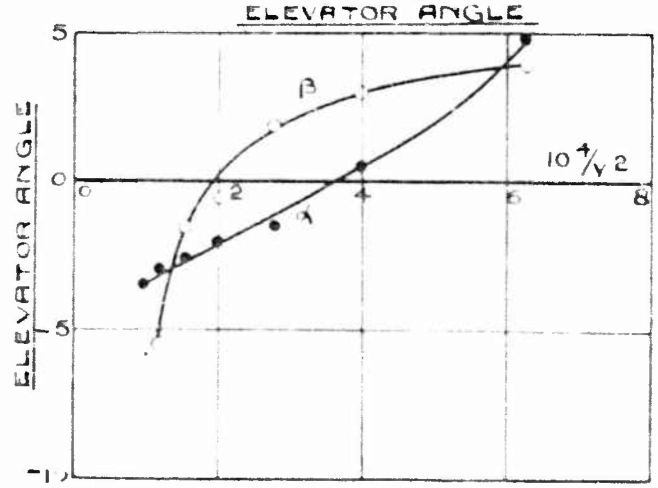


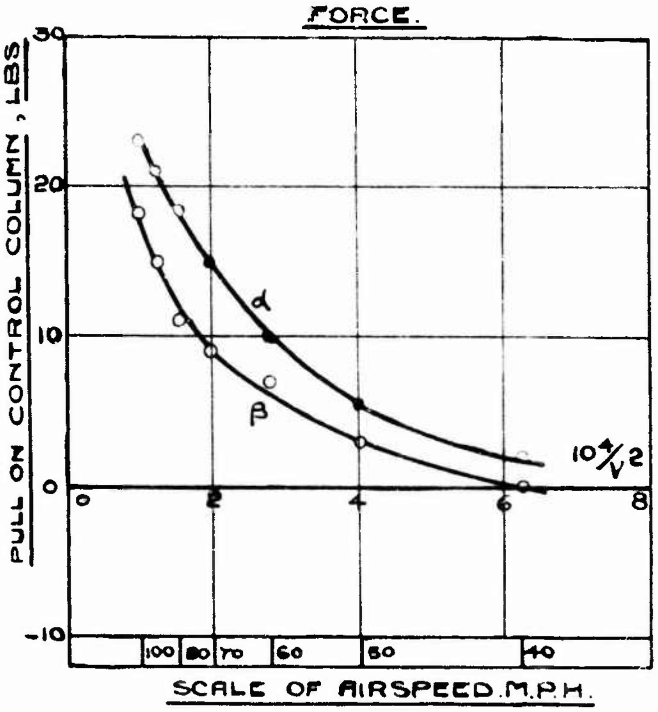
FIG: 8

MODIFIED AEROPLANE X.9.

EXPERIMENTS WITHOUT PASSENGER, ENGINE ON

(α) TAIL SETTING +2°·0

(β) TAIL SETTING −0°·3



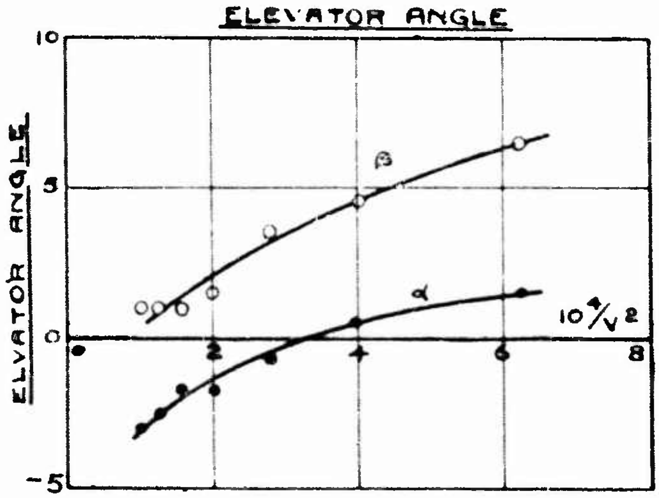


FIG: 9.

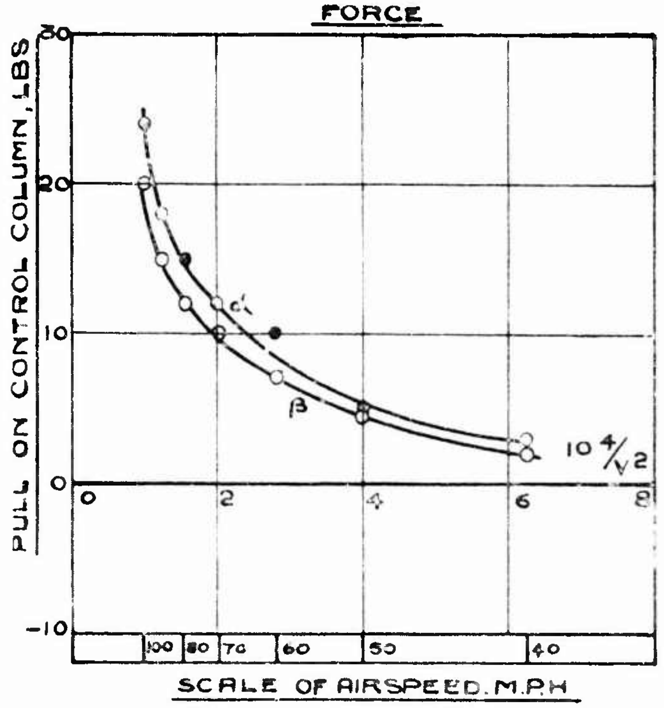
MODIFIED AEROPLANE X9.

EXPERIMENTS WITHOUT PASSENGER, GLIDING

(α) TAIL SETTING + 2°0

(β) TAIL SETTING − 0°8

FORCE



ELEVATOR ANGLE

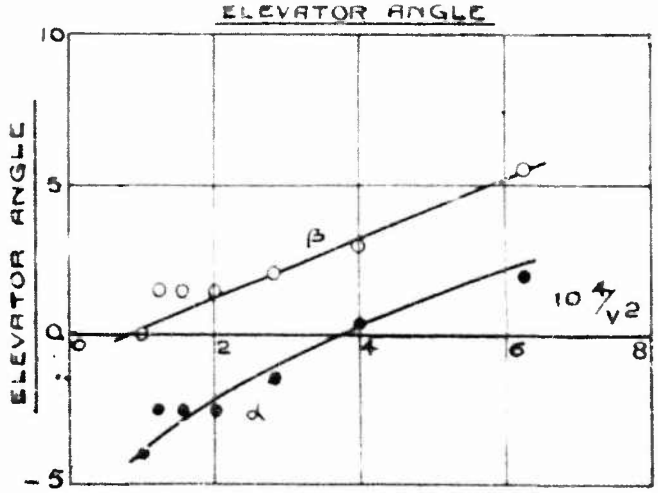
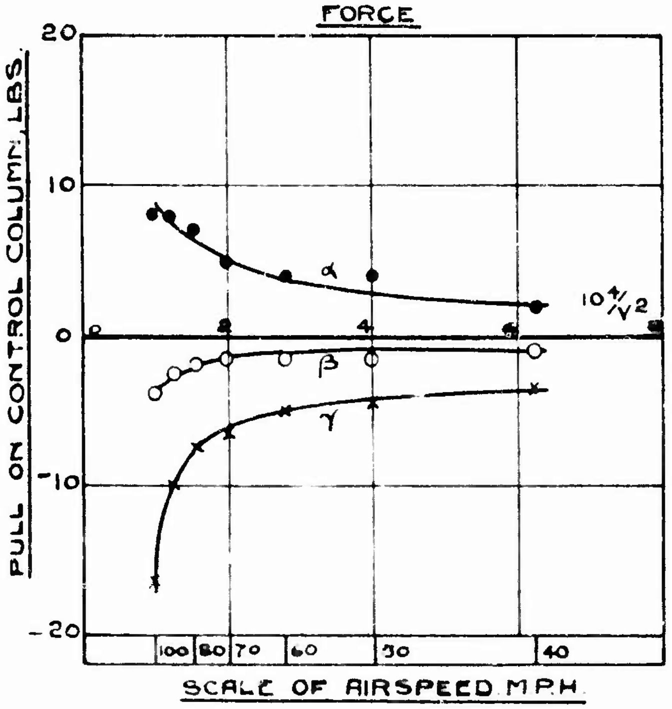


FIG: 10.

AEROPLANE X.10.

EXPERIMENTS WITH ENGINE ON

(α) TAIL SETTING −1°.0
(β) TAIL SETTING −2°.1
(γ) TAIL SETTING −4°.0



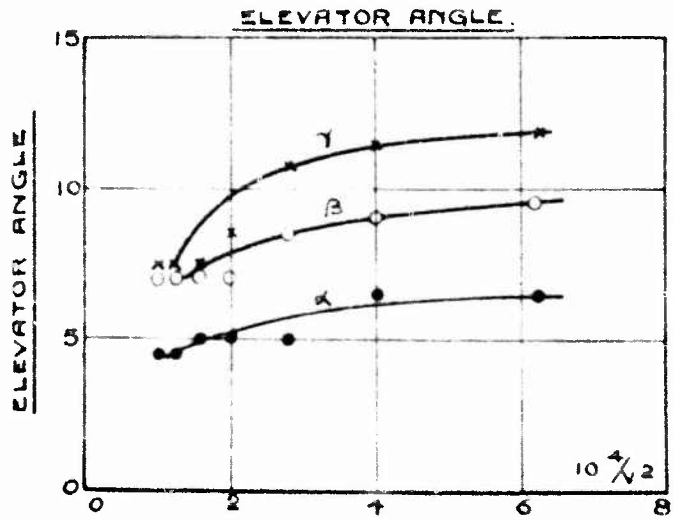


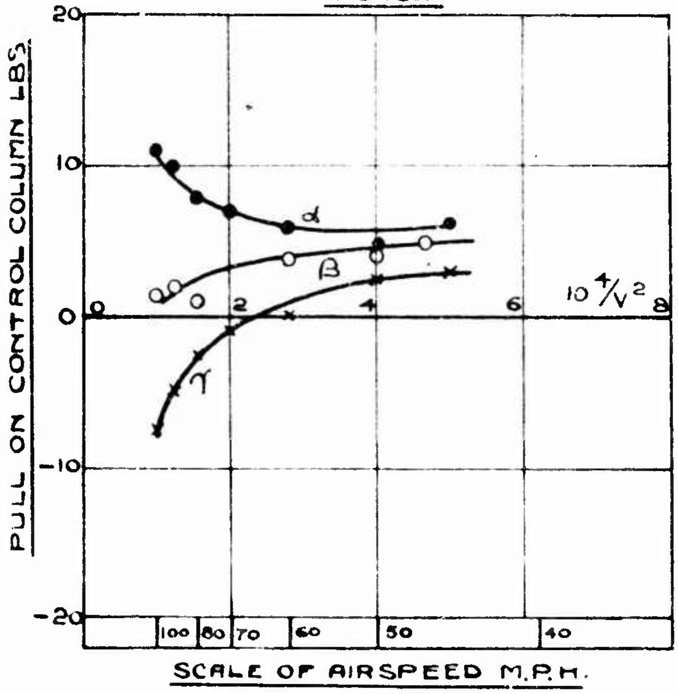
FIG: 11.

AEROPLANE X.10.

EXPERIMENTS GLIDING.

(α) TAIL SETTING −1°.0
(β) " " −2°.1
(γ) " " −4°.0

FORCE



ELEVATOR ANGLE.

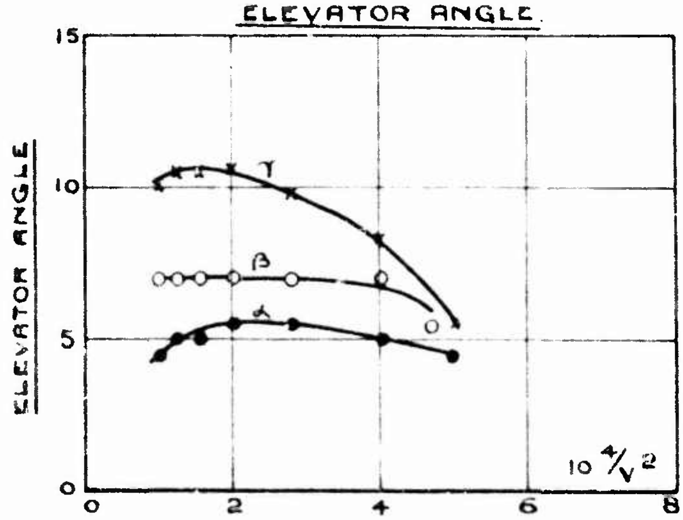


FIG: 12.

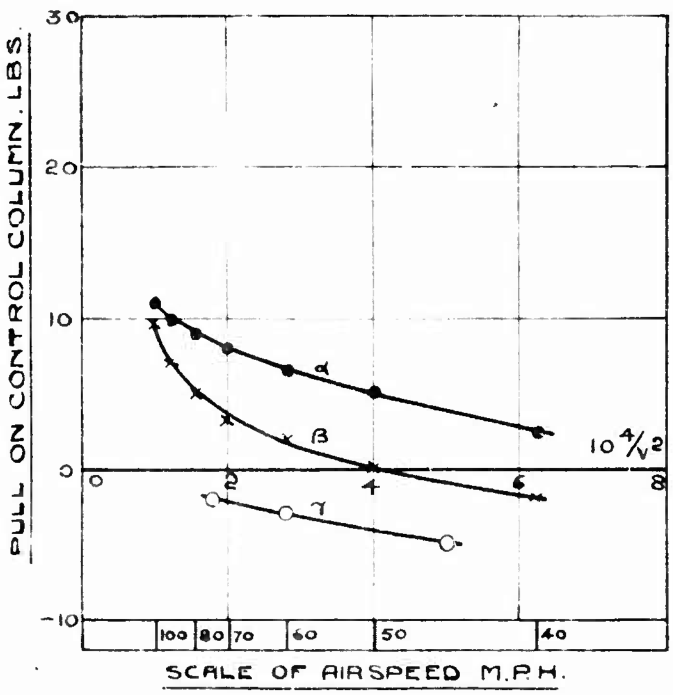
AEROPLANE X.11.

EXPERIMENTS WITH ENGINE ON

TAIL SETTING −0°·9

(α) SPRING CONTROL FORWARD
(β) " " CENTRAL.
(γ) " " BACK.

FORCE



ELEVATOR ANGLE

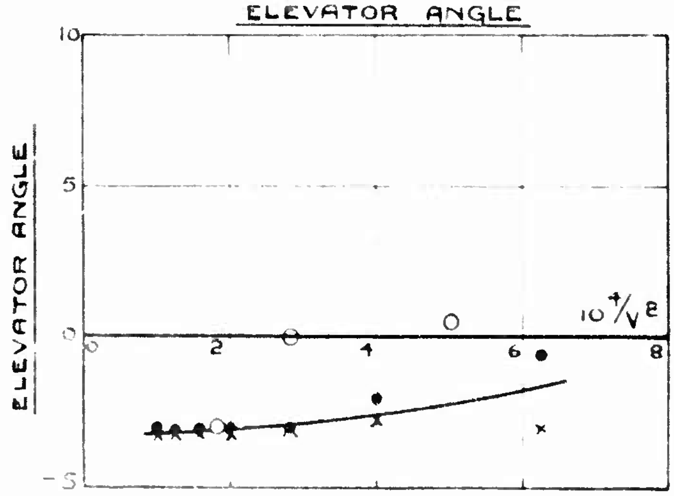


FIG: 13.

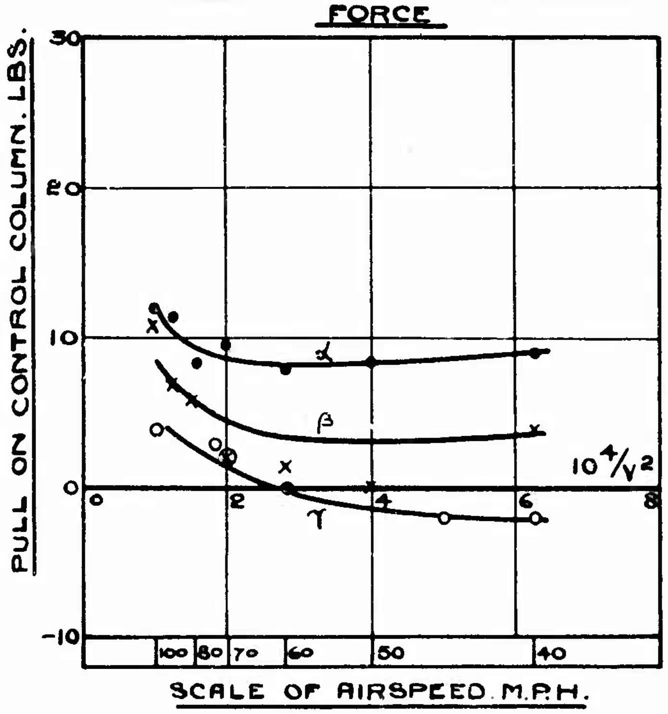
AEROPLANE X.II.

EXPERIMENTS GLIDING

TAIL SETTING – 0°·9

(α) SPRING CONTROL FORWARD
(β) " " CENTRAL
(γ) " " BACK.

FORCE



ELEVATOR ANGLE

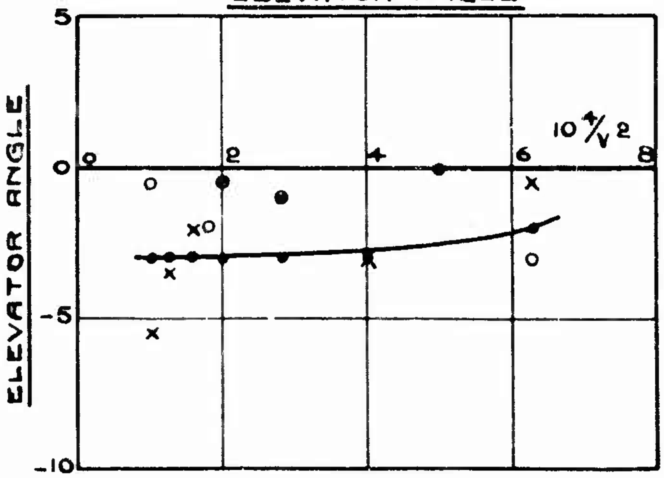


FIG: 14

TAIL PLANE CHARACTERISTICS

$$\begin{cases} k'_L = A\alpha' + B\eta \\ k_\eta = C\alpha' + D\eta \\ C' = C - \frac{A}{B} D \end{cases}$$

× R.E. 8 TYPE
△ B.E. 2C TYPE
○ X. TYPE

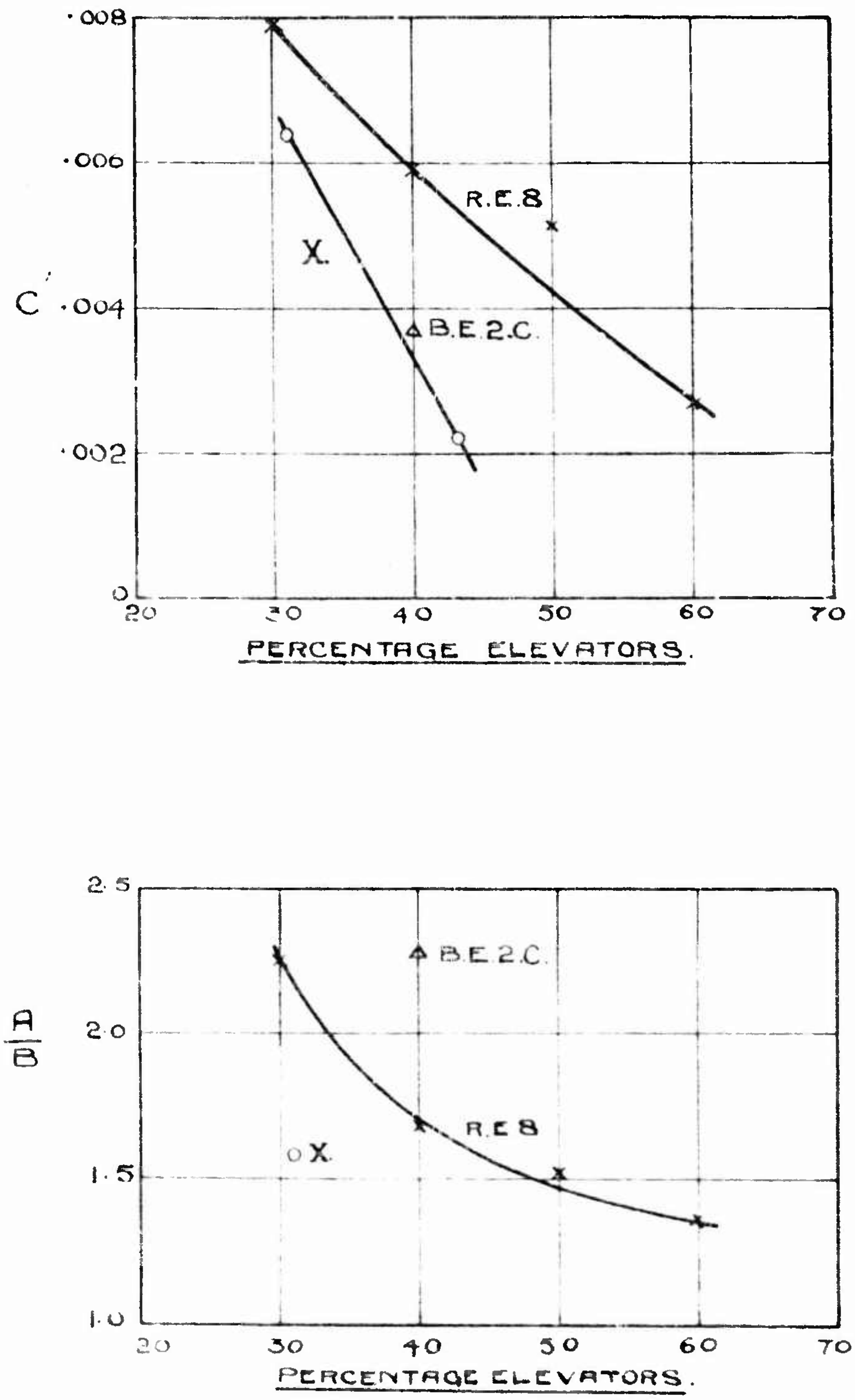


Table 5.

EXPERIMENTS ON X. 10.

Condition.	Air-speed (m.p.h.).	Engine on.		Gliding.	
		Pull on Control Column (lbs.).	Elevator Angle (degs.).	Pull on Control Column (lbs.).	Elevator Angle (degs.).
Tail-setting − 1°·0.	40	2	6½	—	—
	45	—	—	6	4½
	50	4	6½	4½	5
	60	4	5	6	5½
	70	5	5	7	5½
	80	7	5	8	5
	90	8	4½	10	5
	100	8	4½	11	4½
Tail-setting − 2°·1.	40	−1	9½	—	—
	46	—	—	5	5½
	50	−1½	9	4	7
	60	−1½	8½	4	7
	70	−1½	7	2½	7
	80	−2	7	1	7
	90	−2½	7	2	7
	100	−4	7	1½	7
Tail-setting − 4°·0.	40	−3 −4	12 12	— —	— —
	45	— —	— —	— 2½	— 5½
	50	4 5	11½ 11½	3 2	7½ 9
	60	5 5	11 10½	0 0	9 10½
	70	7 6	9 8	−1 −1	10½ 10½
	80	7½ 7½	8 7	−2 −3	10½ 10½
	90	10 10	8 7	−5 5	10½ 10½
	100	18 15	8 7	−7 8	9½ 10½

TABLE 6.

EXPERIMENTS ON X. 11.

Condition.	Air-speed (m.p.h.).	Engine on.		Gliding.	
		Pull on Control Column (lbs.).	Elevator Angle (degs.).	Pull on Control Column (lbs.).	Elevator Angle (degs.).
Spring forward	40	2½	−½	9	−2
	50	5	−2	8½	−3
	60	6½	−3	8	−3
	70	8	−3	9½	−3
	80	9 9	−3	8½	−3
	90	10	−3	11½	−3
	100	11	−3	12	−3
Spring central...	40	−2	−3	4 4	−½ −½
	50	0 0 ½	−2 −3 −3	0	−3
	60	2 2 2	−3 −3 −3	1½	−1
	70	4 3½ 2½	−3 −4 −3	2	−½
	80	5½ 5 4½	−3 −4 −3	6	−2
	90	7 6½ 7½	−3 −4 −3	7	−3½
	100	10 9 10	−4 −4 −3	11	−5½
Spring back ...	40	—	—	−2	−3
	45	−5	½	2	0
	60	−3	0	0	1
	70	—		2	−½
	75	−2	..	3	½
	100	—		4	½

Calibration of the spring showed that moving it back is equivalent to a pull of 4 lbs. and moving it forward to a push of 3 lbs.

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