NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 169

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THE EFFECT OF AIRFOIL THICKNESS AND PLAN FORM ON LATERAL CONTROL

By H. I. HOOT

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AERONAUTICAL SYMBOLS.

1. FUNDAMENTAL AND DERIVED UNITS.

	Symbol.	Metric.		English.	
		Unit.	Symbol.	Unit.	Symbol.
Length	l	meter	m.	foot (or mile)	ft. (or mi.).
Time	t	second	sec.	second (or hour)	sec. (or hr.).
Force	F	weight of one kilogram	kg.	weight of one pound	lb.
Power	P	kg.m/sec		horsepower	HP
Speed		m/sec	m. p. s.	mi/hr	M. P. H.

2. GENERAL SYMBOLS, ETC.

Weight, $W = mg$.

Standard acceleration of gravity, $g = 9.806\text{m/sec.}^2 = 32.172\text{ft/sec.}^2$

Mass, $m = \frac{W}{g}$

Density (mass per unit volume), ρ

Standard density of dry air, 0.1247 (kg.-m.-sec.) at 15.6°C. and 760 mm. = 0.00237 (lb.-ft.-sec.)

Specific weight of "standard" air, 1.223 kg/m.^{3} = 0.07635 lb/ft.^{3}

Moment of inertia, mk^2 (indicate axis of the radius of gyration, k, by proper subscript).

Area, S; wing area, S_w, etc.

Gap, G

Span, b; chord length, c.

Aspect ratio $= b/c$

Distance from $c.\ g.$ to elevator hinge, f.

Coefficient of viscosity, μ.

3. AERODYNAMICAL SYMBOLS.

True airspeed, V

Dynamic (or impact) pressure, $q = \frac{1}{2}\rho V^2$

Lift, L; absolute coefficient $C_L = \frac{L}{qS}$

Drag, D; absolute coefficient $C_D = \frac{D}{qS}$.

Cross-wind force, C; absolute coefficient $C_C = \frac{C}{qS}$.

Resultant force, R

(Note that these coefficients are twice as large as the old coefficients L_c, D_c.)

Angle of setting of wings (relative to thrust line), i_w

Angle of stabilizer setting with reference to thrust line i_t

Dihedral angle, γ

Reynolds Number $= \rho\frac{Vl}{\mu}$, where l is a linear dimension.

e. g., for a model airfoil 3 in. chord, 100 mi/hr., normal pressure, 0°C: 255,000 and at 15.6°C, 230,000;

or for a model of 10 cm. chord, 40 m/sec., corresponding numbers are 299,000 and 270,000.

Center of pressure coefficient (ratio of distance of C. P. from leading edge to chord length), C_p.

Angle of stabilizer setting with reference to lower wing. $(i_t - i_w) = \beta$

Angle of attack, α

Angle of downwash, ϵ

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THE EFFECT OF AIRFOIL THICKNESS AND PLAN FORM ON LATERAL CONTROL.

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SUMMARY.

Tests for the purpose of determining the effectiveness of ailerons were made on six model airfoils in the No. 1 wind tunnel of the National Advisory Committee for Aeronautics. The method consisted in measuring the rolling moments and aileron moments in the ordinary way. In addition to this the wing was allowed to spin freely about an axis in the direction of the air flow and the angular velocity measured.

The results show that the thickness of the air foil has very little effect on either the rolling moment or the hinge moment, but that the tapering in plan form somewhat decreases the rolling moment and hinge moment, although the resulting efficiency is somewhat higher for the tapered wings. The airfoil tapered in plan form, however, shows practically no falling off in the rolling moment at the critical angle of attack, whereas the wings of rectangular plan form show a marked dropping off in the rolling moment at this point. This indicates that it is possible to obtain good lateral control with small ailerons at low speeds if the plan form is tapered. The rotational speed of the different airfoils is practically the same for all of the sections tested.

INTRODUCTION.

Many tests have been made to investigate the effectiveness of ailerons, but most of them have been made on a single-wing section and this usually of a thin type. In view of the increasing use of the thicker types of section and the use of wings tapering in plan form, it was thought that it would be of considerable interest to find the effectiveness of similar ailerons on various wing sections. The following references deal with the subject of ailerons and lateral control:

(1) An Investigation of the Aerodynamic Properties of Wing Ailerons. R. & M. No. 550, No. 615, and No. 651.

(2) On a Method of Measuring Rolling Moments and Aileron Hinge Moments on a Model Biplane. R. & M. No. 512.

(3) Distribution of Load Over Wing Tips and Ailerons. N. A. C. A. No. 161.

(4) Measurement of Control Moments on an Airplane in Flight. Zeitschrift für Flugtechnik und Motorluftschiffahrt, Vol. X, Nos. 21 and 22, 1919.

(5) The Control of a Laterally Stable and Laterally Unstable Airplane. R. & M. No. 209.

(6) Lateral Control of an Aeroplane. R. & M. No. 413 and No. 441.

(7) Experiments on an Aerofoil with Flaps Extending Along the Whole Length. R. & M. No. 319.

(8) Experiments on Models of Aeroplane Wings at the National Physical Laboratory. R. & M. No. 110.
Section IV, Experiments on an Aerofoil Having a Hinged Rear Portion.
Section V, Experiments on an Aerofoil Having a Hinged Rear Portion when Forming the Upper Member of a Biplane Combination.

(9) Experiments on Models of Aeroplane Wings. R. & M. No. 152.
Section II, Aerofoils with Flaps.

(10) Lateral Stability. R. & M. No. 133.

(11) Bulletin of the Aerodynamic Institute of Koutchino, No. I, 1912.

DESCRIPTION OF APPARATUS AND MODELS.

The tests were all made in the N. A. C. A. No. 1 wind tunnel at an air velocity of 30 m./sec. (67.3 miles/hour) on two series of airfoils, all having the same area and fitted with ailerons of the same area. The first series had a rectangular plan form (fig. 1) with various air-foil thicknesses, while the second series had the same section but varied in plan form. All of the sections used were derived from a master section No. 64, and full dimensions of these models are given in Table I and Table II.

A device (fig. 2) was designed to measure the angular velocity of an airfoil about an axis parallel to the air flow. This apparatus consisted simply of a horizontal spindle mounted in ball bearings and supported in the center of the tunnel by wires. The model airfoil was attached to the upstream end of the spindle in such a way that the angle of attack could be easily varied. At the other end of the spindle was attached an electric speed indicator.

The hinge moment and rolling moment were measured by a balance mounted on the roof of the tunnel and connected to the airfoil by a fine wire. This balance (fig. 3) was operated automatically and saved a great deal of time in making the readings. The principle of this balance has been given in N. A. C. A. Technical Note No. 30.

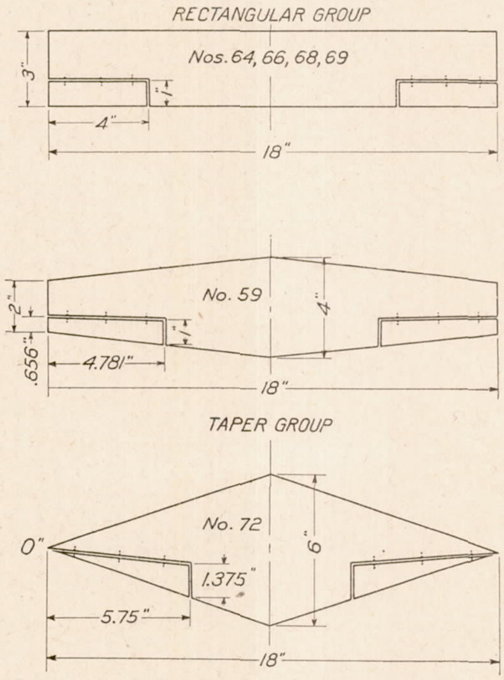

FIG. 1—Plan of airfoils.

An apparatus (fig. 4) was used to support the airfoil in order to measure the rolling and aileron hinge moment. At a point 17.78 cm. (7″) to the center line and 2.54 cm. (1″) from the leading edge the wire extended from the airfoil up to the balance. For the aileron hinge moments this wire was fastened to the trailing edge of the aileron and extended down through the tunnel to a counterweight below. The moment was measured on one aileron, but, as in the other tests, the opposite aileron always had the proper angle. In order to reproduce the same air flow as in other tests the hinge crack was covered with thin paper to prevent air flowing through.

PRECISION.

The models used in this investigation were cut from laminated maple stock and finished to within 0.125 mm. (0.005″) of the given dimensions. In nearly all cases the rolling moment could be checked with a precision of ± 3 per cent, but the aileron moment is not precise to better than ± 10 per cent. The wire used in measuring the forces introduced a force in all the readings for the ailerons due to a wire drag of 16.5 grams at a point of attachment of the wire to the ailerons. This force was corrected according to methods used in R. & M. No. 512. Due to the fact that some of the models were not quite symmetrically mounted in the tunnel, an initial rolling moment was produced at a zero angle of attack in some cases.

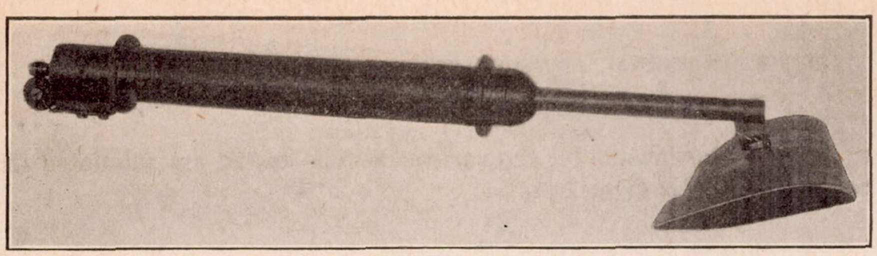

FIG. 2.—Spindle for revolving airfoils.

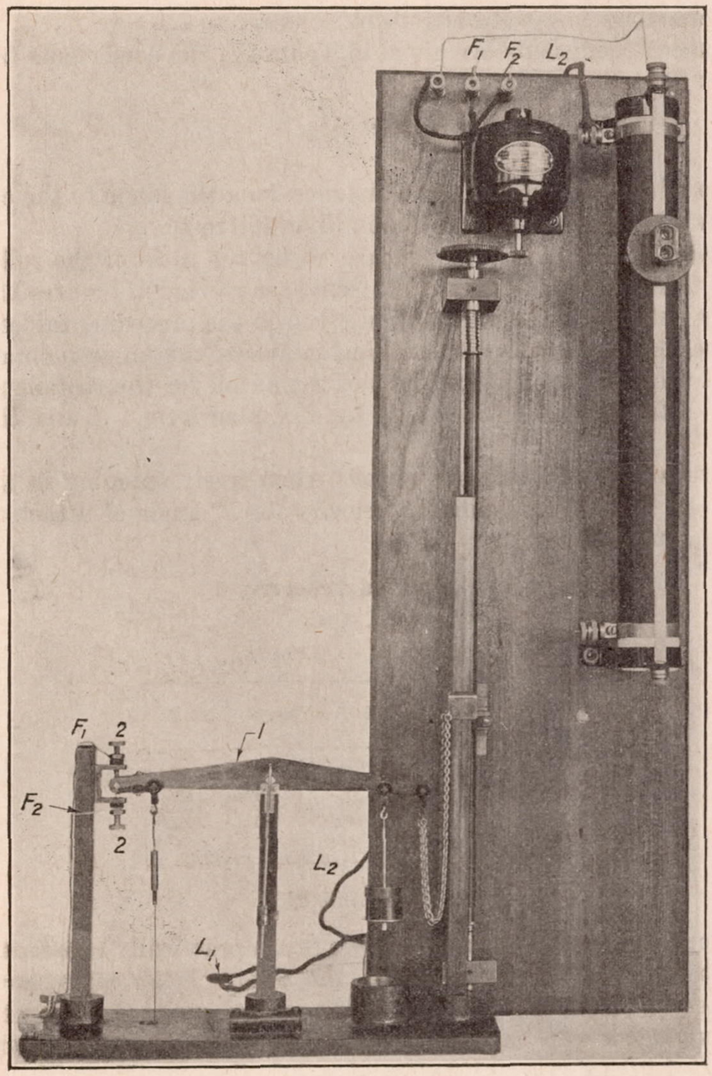

FIG. 3.—Semi-automatic balance.

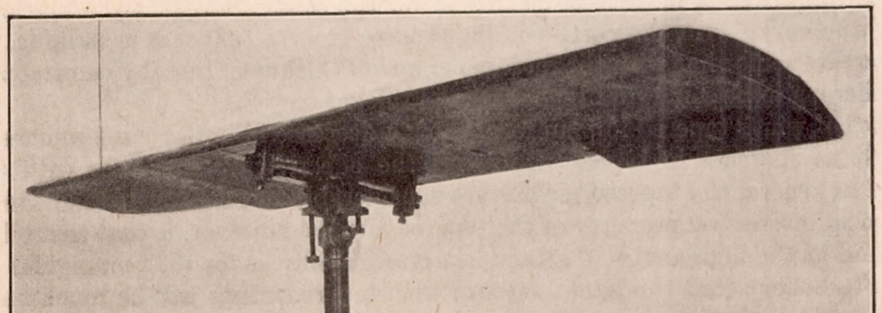

FIG. 4.—Apparatus for supporting airfoils.

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RESULTS.

The rolling moment coefficients for the various airfoils tested are tabulated in Table III. The absolute coefficient used is given by:

$$C_{RM}=\frac{L}{q\,b c^2}$$

where the symbols have the usual meaning. The rolling moment coefficients are also plotted against lift coefficients for a few of the airfoils in Figures 5 to 7.

The hinge moment coefficients are given in Table IV, the coefficients being defined by the following equation:

$$C_H=\frac{H}{q\,h A}$$

where A is the area of the aileron and h the distance from the hinge to the center of area. The coefficients for a few of the airfoils are plotted in Figures 8 to 10.

The effectiveness of the ailerons are measured by the ratio of the rolling moment to the hinge moment and these values for the airfoils tested are plotted in Figures 11 to 13.

To graphically summarize the information given in the preceding tables and charts, curves are given in Figures 14 to 17, where the rolling moment, the hinge moment, and the aileron effectiveness are plotted against the thickness of the airfoil for the rectangular plan form and against the degree of taper for the wings with tapered plan form. L and H are given in gram-centimeters.

The angular velocity of the various airfoils when freely spinning in the wind tunnel are plotted in Figures 18 to 21. The spinning velocity for 5° angle of attack for the various airfoils tested is given in table below:

SPINNING VELOCITY.

(R. P. M.)

5° ANGLE OF ATTACK.

Aileron angle.	No. 64.	No. 66.	No. 59.	No. 72.
5	95	67	—	60
10	165	140	150	130
15	—	205	200	200
20	250	250	256	257
30	320	—	—	—

CONCLUSIONS.

The rolling moments for the rectangular wings are practically constant for all thicknesses of airfoil. At high angles of attack, however, the airfoils in all cases show a sharp decrease in the rolling moments, the thicker sections falling off perhaps sooner than the thin ones. The reason for this phenomenon can be made clear by reference to Figure 22 where the lift curves are plotted for an airfoil having a +20°, 0° and −20° aileron. The rolling moment with positive and negative ailerons will be proportional to the difference between the upper and lower curves. This difference is plotted in Figure 23 on the same scale as the other airfoils. The similarity of the curve with the corresponding curves from actual test is striking. The hinge moments decrease somewhat with the increase of airfoil thickness, thereby causing the effectiveness of the ailerons to be somewhat higher for the thicker sections.

The series of wings tapered in plan form show a decrease in both rolling moment and hinge moment with an increase in taper. However, the effectiveness increases with the increase in taper, and in general the tapered airfoils are considerably more efficient than the rectangular ones. The most interesting property of the tapered airfoils, however, is that the rolling moment does not fall off at the high angles of attack nearly as rapidly as for the rectangular ones. This fact leads us to believe that the lateral control with tapered wings will be much more effective at low flying speed than with the ordinary type of wing.

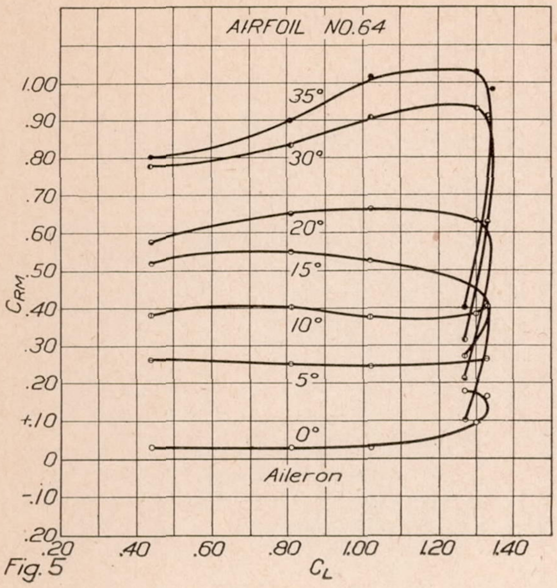


Fig. 5

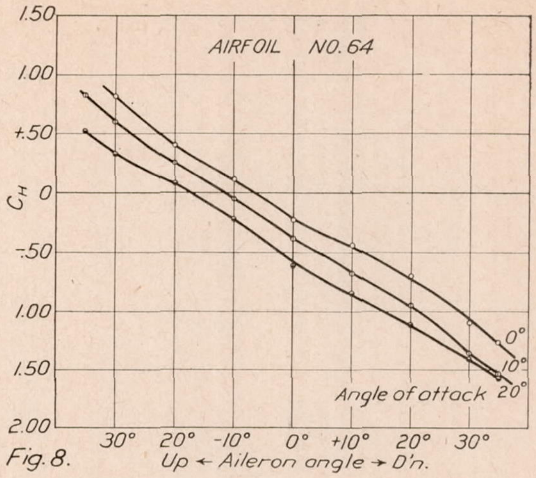


Fig. 8.

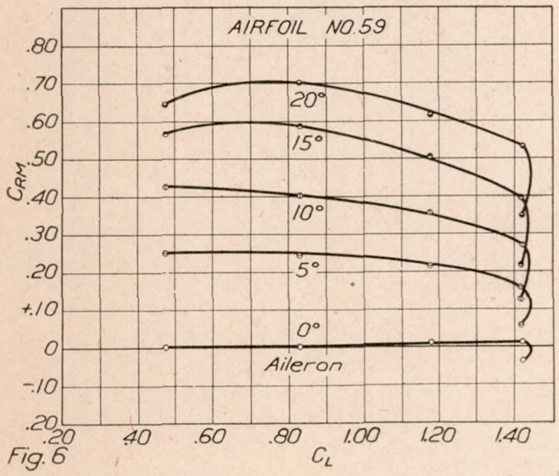


Fig. 6

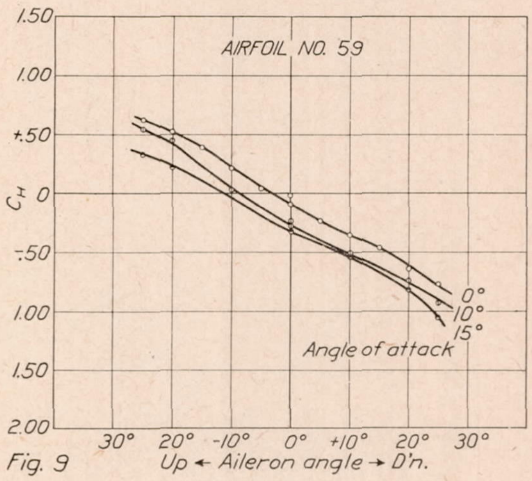


Fig. 9

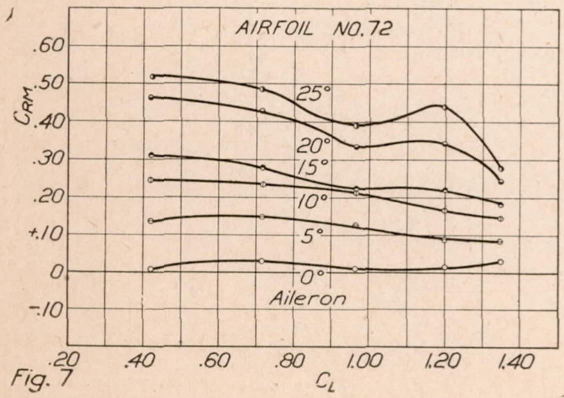


Fig. 7

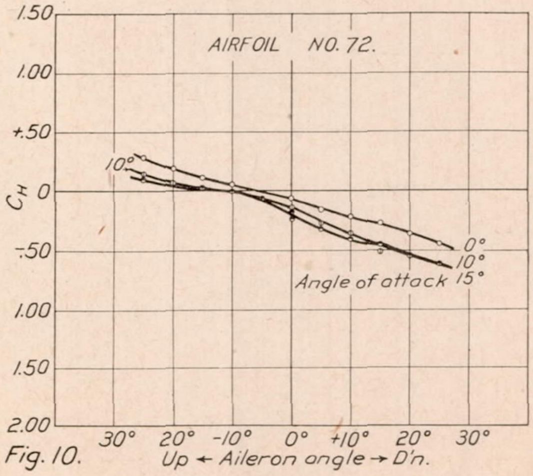


Fig. 10.

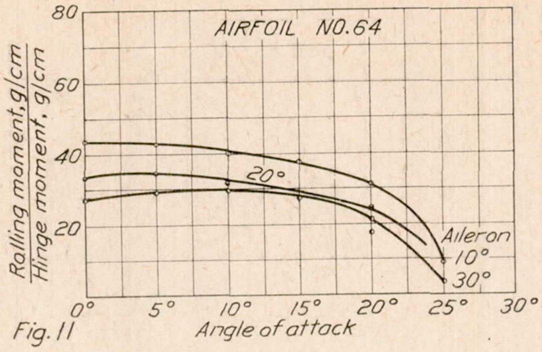


Fig. 11

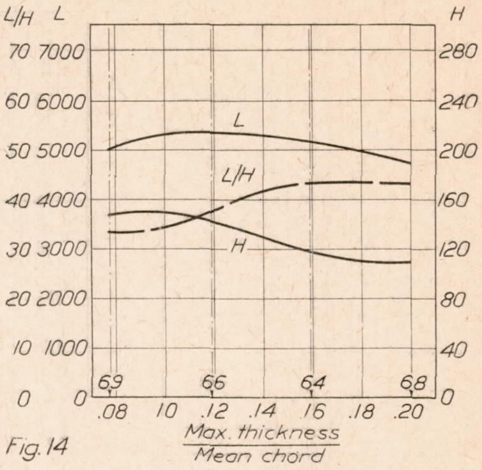


Fig. 14

Series A, rectangular airfoils.
Angle of attack=0°; aileron angle=10°.

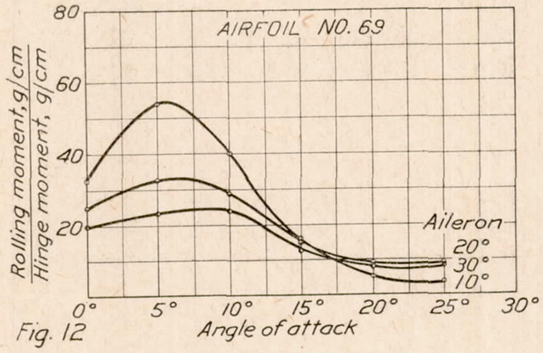


Fig. 12

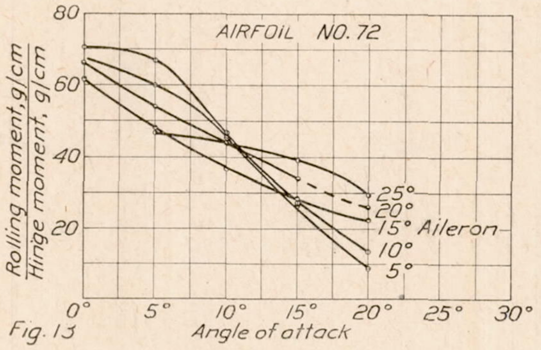


Fig. 13

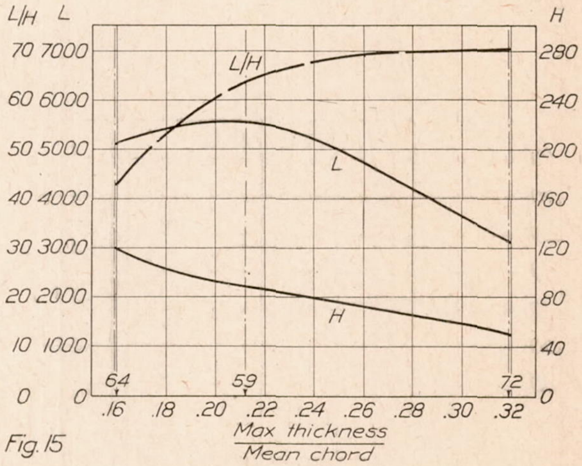


Fig. 15

Series B, tapered airfoils.
Angle of attack=0°; aileron angle=10°

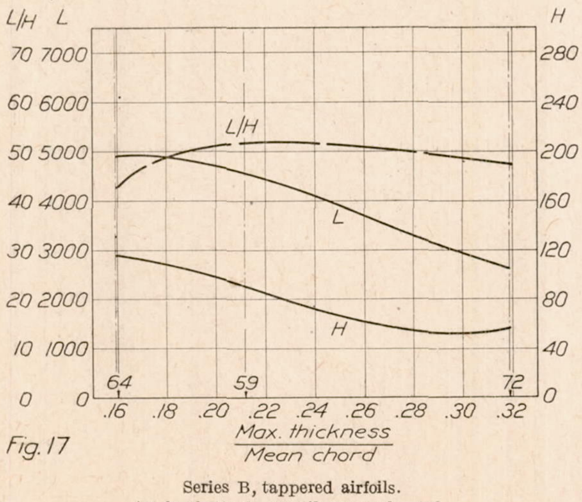


Fig. 17

Series B, tappered airfoils.
Angle of attack=10; aileron angle=10°

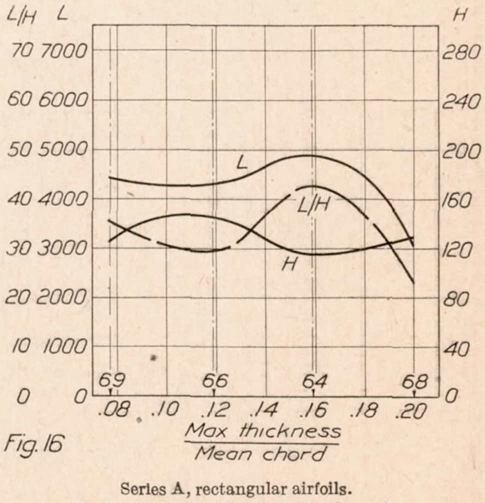
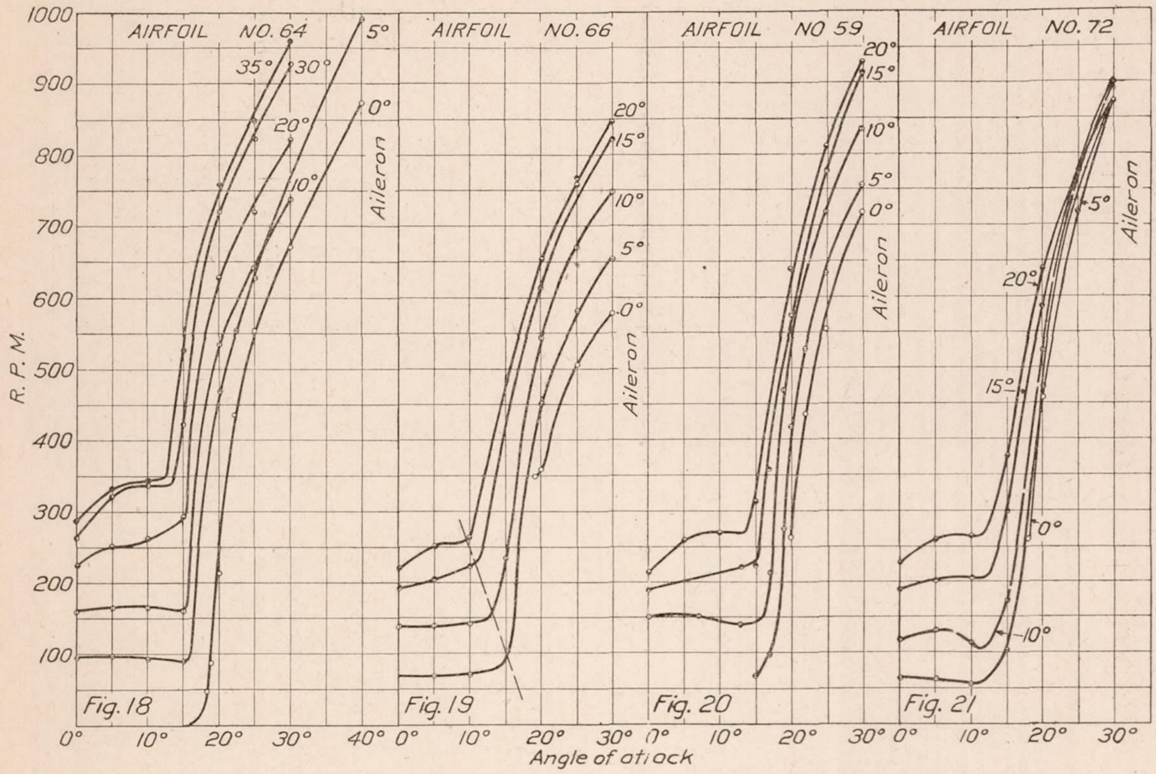
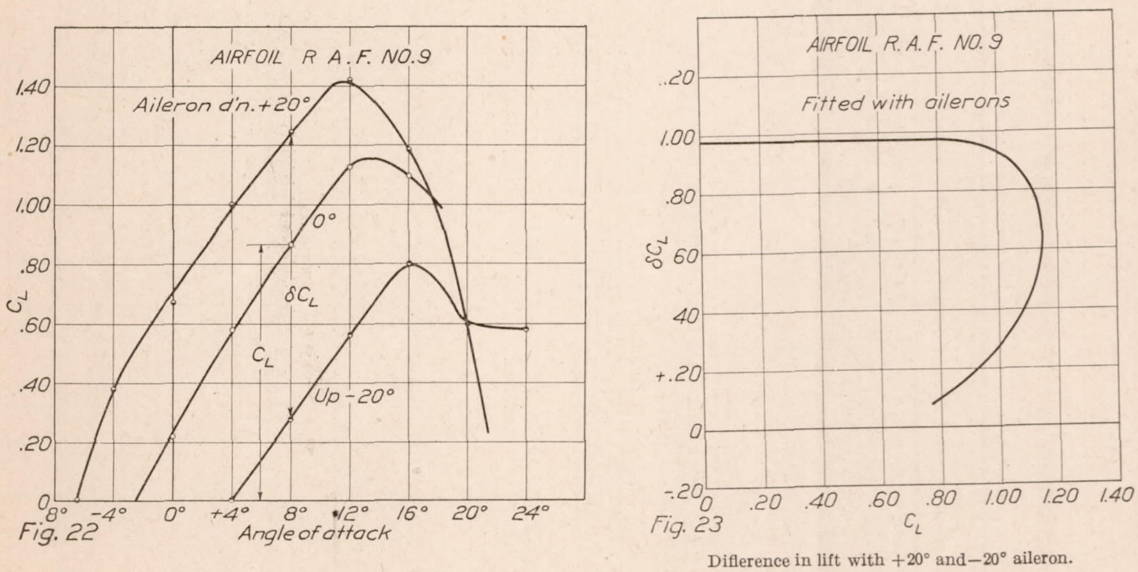


Fig. 16

Series A, rectangular airfoils.
Angle of attack=10°; aileron angle=10°.



FIGS. 18, 19, 20, and 21.—Effect of ailerons on angular velocity (*R. P. M.*) about *X* axis. Airspeed 30 m/sec. (79.4 ft./sec.)



Difference in lift with +20° and −20° aileron.

The angular velocity of the wings gives us a very close criterion of the maneuvering properties of a similar wing when used in flight. At low angles of aileron the tapered airfoils, contrary to what we should expect, show a lower spinning velocity than the rectangular ones, but at higher angles of aileron the spinning velocity is practically identical for all of the sections tested.

Ordinates for Airfoil No. 64—Constant section throughout.

TABLE I.

Station in per-cent of chord.	Upper camber.	Lower camber.
0	2.00	2.00
1.25	4.50	.20
2.50	5.75	.00
5.00	7.80	.00
7.50	9.60	.00
10	11.07	.00
15	13.08	.00
20	14.33	.00
30	15.73	.00
33.33	15.90	.00
40	15.73	.00
50	14.85	.00
60	13.15	.00
70	10.95	.00
80	8.40	.00
90	5.50	.00
95	3.95	.00
100	1.15	1.15

TABLE II.

Airfoil No.	Ordinates of No. 64 center line per cent of span.	Maximum ordinates in inches in per cent of maximum chord.		Description of plan form.
		Upper.	Lower.	
59	133	0.636	0	Tapered 4-inch chord at center to 2-inch chord at tip.
64	100	.477	0	Constant 3-inch chord.
66	75	.358	0	Do.
68	126	.600	0	Do.
69	48	.230	0	Do.
72	200	.954	0	Tapered 6-inch chord at center to 0-inch chord at tip.

TABLE III.

Rolling moment coefficient.

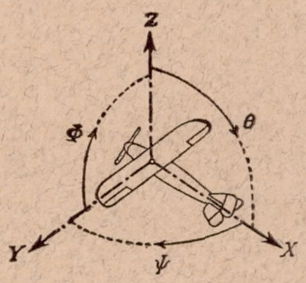
Aileron angle δ.	Angle of attack α.	No. 68.	No. 64.	No. 69. C_{RM}	No. 66.	No. 59.	No. 72.
°	°						
0	0	0.026	0.050	0	0	0	0.012
	5	.044	.038	−.002	0	0	.030
	10	.038	.042	−.014	0	.014	.010
	15	−.192	.040	−.048	0	.016	.010
	20	−.084	.190	−.132	−.138	−.042	.034
	25	−.021	....	−.046	−.108	.040	−.044
5	0	.212	.264	....	.242	.254	.134
	5	.202	.254	....	.246	.242	.146
	10	.320	.244	....	.244	.214	.126
	15	−.110	.264	....	.136	.160	.084
	20	−.028	....	....	−.074	.054	.086
	25	.063	....	....	.116	.010	0
10	0	.342	.394	.532	.412	.428	.246
	5	.294	.406	.536	.426	.404	.230
	10	.416	.378	.340	.388	.354	.218
	15	−.064	.356	.128	.254	.268	.164
	20	.056	0	0	.200	.128	.146
	25	.172	.092	.034	.098	.012	.020
15	0	.507	.520	....	.326	.568	.310
	5	.483	.548	....	.392	.584	.280
	10	.450	.526	....	.346	.504	.220
	15	.081	.342	....	.366	.396	.226
	20	.176	.076	....	0	.216	.184
	25	.209	.102	....	.108	.106	.020
20	0	.652	.600	.596	.632	.644	.464
	5	.608	.654	.700	.672	.700	.430
	10	.588	.620	.604	.648	.612	.332
	15	.198	.476	.266	.486	.528	.350
	20	.242	.164	.146	.250	.268	.248
	25	.242	.120	.134	.160	.158	.108
25	0	.778	....	....	....	....	.518
	5	.773	....	....	....	....	.484
	10	.745	....	....	....	....	.390
	15	.284	....	....	....	....	.440
	20	.294	....	....	....	....	.276
	25	.250	....	....	....	....	.102
30	0	.852	.822	.736	....	....	....
	5	.830	.900	.792	....	....	....
	10	.880	.926	.754	....	....	....
	15	.384	.680	.364	....	....	....
	20	.378	.406	.192	....	....	....
	25	.362	.112	.192	....	....	....
35	0	.960	....	....	....	....	....
	5	.984	....	....	....	....	....
	10	.906	....	....	....	....	....
	15	.310	....	....	....	....	....
	20	.352	....	....	....	....	....
	25	.410	....	....	....	....	....

TABLE IV.

Hinge moment coefficients.

		No. 68. C_H		No. 64. C_H		No. 69. C_H		No. 66. C_H	
Angle of attack α.	Aileron angle δ.	(+Down) C_H	(−Up) C_H	(Down+) C_H	(−Up) C_H	(Down+) C_H	(Up−) C_H	(Down+)	(Up−)
°	°								
0	0	−0.32	−0.28	−0.23	−0.25	0.03	−0.08	−0.19	−0.21
	10	−.58	.31	−.44	.12	−.42	.42	−.55	.23
	20	−.84	.53	−.71	.40	−.90	.79	−.90	.62
	30	−1.08	.72	−1.10	.82	−1.38	1.24	−1.44	1.05
	35	−1.37	.78	−1.27	.62	....	....	....	....
5	0	−.31	−.31	−.62	.01	−.19	−.21	−.28	−.29
	10	−.50	−.04	−.59	.00	−.39	.31	−.72	.17
	20	−.81	−.29	−.89	.28	−1.04	.83	−1.09	.51
	30	−1.46	.64	−1.29	1.18	−1.27	.95	−1.64	.88
	35	−1.71	.82	−1.47	1.36	....	....	....	....
10	0	−.49	−.69	−.40	−.38	−.33	−.32	−.37	−.36
	10	−.81	−.15	−.69	−.06	−.44	−.14	−.56	−.06
	20	−1.26	.22	−.96	.26	−.74	.64	−1.06	.58
	30	−1.92	.42	−1.35	.61	−1.28	.93	−1.55	1.00
	35	−2.62	.64	−1.54	.82	....	....	....	....
15	0	.55	−.52	−.46	−.51	−.37	−.49	−.51	−.05
	10	−.94	−.16	−.78	−.18	−.61	−.02	−.83	−.05
	20	−1.46	.14	−1.10	.21	−.95	.34	−1.25	.28
	30	−2.06	.35	−1.51	.58	−1.34	.74	−1.85	.68
	35	−2.21	.48	−1.59	.80	....	....	....	....
20	0	−.65	−.65	−.46	−.62	−.63	−.80	−.69	−.68
	10	−1.21	−.35	−.85	−.21	−.89	−.11	−1.16	−.14
	20	−1.62	.10	−1.23	.10	−1.10	.01	−1.36	.10
	30	−2.09	.19	−1.39	.32	−1.42	.40	−1.63	.31
	35	−2.77	.26	−1.55	.52	....	....	....	....
25	0	−.81	−.62	−.77	−.74	−.68	−.84	−.91	−.72
	10	−1.08	−.35	−.92	−.40	−.85	−.18	−1.18	−.41
	20	−1.41	−.20	−1.18	−.11	−1.21	−.12	−1.52	−.17
	30	−1.83	.13	−1.71	.26	−1.57	+.12	−1.96	.16
	35	−1.98	.15	−1.87	.36	....	....	....	....

		No. 59. C_H		No. 72. C_H	
Angle of attack α.	Aileron angle δ.	(Down+)	(Up−)	(Down+)	(Up−)
°	°				
0	0	−0.02	−0.10	−0.07	....
	5	−.24	.03	−.16	....
	10	−.35	.21	−.21	0.06
	15	−.46	.39	−.28	.11
	20	−.66	.53	−.35	.19
	25	−.77	.62	−.45	.28
5	0	−.24	−.15	−.12	−.09
	5	....	....	−.21	−.02
	10	−.50	.08	−.23	.03
	15	....	....	−.37	.09
	20	−.79	.39	−.46	.15
	25	−.89	.62	−.53	.28
10	0	−.26	−.22	−.14	−.13
	5	....	....	−.27	−.07
	10	−.51	.03	−.35	−.01
	15	....	....	−.52	.03
	20	−.74	.46	−.55	.06
	25	−.94	.55	−.62	.14
15	0	−.31	−.29	−.24	−.14
	5	....	....	−.31	.06
	10	−.51	....	−.36	0
	15	....	....	−.46	.01
	20	−.83	.23	−.52	.15
	25	−1.06	.34	−.60	.12
20	0	−.42	−.03	−.26	−.13
	5	....	....	−.50	−.08
	10	−.71	.60	−.41	−.05
	15	....	....	−.47	....
	20	−1.00	1.20	−.58	.03
	25	−1.30	....	−.63	.11



Positive directions of axes and angles (forces and moments) are shown by arrows.

Axis.		Force (parallel to axis) symbol.	Moment about axis.			Angle.		Velocities.	
Designation.	Symbol.		Designation.	Symbol.	Positive direction.	Designation.	Symbol.	Linear (component along axis).	Angular.
Longitudinal	X	X	rolling	L	$Y \longrightarrow Z$	roll	Φ	u	p
Lateral	Y	Y	pitching	M	$Z \longrightarrow X$	pitch	Θ	v	q
Normal	Z	Z	yawing	N	$X \longrightarrow Y$	yaw	Ψ	w	r

Absolute coefficients of moment

$$C_l=\frac{L}{q\,b\,S} \quad C_m=\frac{M}{q\,c\,S} \quad C_n=\frac{N}{q\,f\,S}$$

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS.

Diameter, D
Pitch (a) Aerodynamic pitch, p_a
(b) Effective pitch, p_e
(c) Mean geometric pitch, p_g
(d) Virtual pitch, p_v
(e) Standard pitch, p_s
Pitch ratio, p/D
Inflow velocity, V'
Slipstream velocity, V_s

Thrust, T
Torque, Q
Power, P
(If "coefficients" are introduced all units used must be consistent.)
Efficiency $\eta=T\,V/P$
Revolutions per sec., n; per min., N
Effective helix angle $\Phi=\tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS.

1 HP = 76.04 kg. m/sec. = 550 lb. ft/sec.
1 kg. m/sec. = 0.01315 HP
1 mi/hr. = 0.44704 m/sec.
1 m/sec. = 2.23693 mi/hr.

1 lb. = 0.45359 kg.
1 kg. = 2.20462 lb.
1 mi. = 1609.35 m. = 5280 ft.
1 m. = 3.28083 ft.