NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 201

THE EFFECTS OF SHIELDING THE TIPS OF AIRFOILS

By ELLIOTT G. REID

WASHINGTON
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1925

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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By ELLIOTT G. REID
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SYNOPSIS OF REPORT NO. 201

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

THE EFFECTS OF SHIELDING THE TIPS OF AIRFOILS.

By Elliott G. Reid.

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All of the modified forms were slightly inferior to the plain airfoil at small lift coefficients; however, by mounting thin plates, in planes perpendicular to the span, at the wing tips, the characteristics were improved throughout the range above three-tenths of the maximum lift coefficient. With this form of limitation the detrimental effect was slight; at the higher lift coefficients there resulted a considerable reduction of induced drag and, consequently, of power required for sustentation. The slope of the curve of lift versus angle of attack was increased.

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THE EFFECTS OF SHIELDING THE TIPS OF AIRFOILS

By Elliott G. Reid

SUMMARY

Tests have recently been made at Langley Memorial Aeronautical Laboratory to ascertain whether the aerodynamic characteristics of an airfoil might be substantially improved by imposing certain limitations upon the airflow about its tips.

All of the modified forms were slightly inferior to the plain airfoil at small lift coefficients; however, by mounting thin plates, in planes perpendicular to the span, at the wing tips, the characteristics were improved throughout the range above three-tenths of the maximum lift coefficient. With this form of limitation the detrimental effect was slight; at the higher lift coefficients there resulted a considerable reduction of induced drag and, consequently, of power required for sustentation. The slope of the curve of lift versus angle of attack was increased.

OUTLINE OF TESTS

These tests were directed toward the discovery of some economical means of increasing the "effective aspect ratio" of an airfoil.

As it is recognized that the induced drag of an airfoil is inversely proportional to its aspect ratio and that elimination of the transverse velocity components of the airflow about a wing reproduces, in effect, the conditions which would exist with infinite aspect ratio, it was planned to investigate the effects of elimination of a portion of the transverse flow by finite barriers at the tips and also by the production of an aerodynamic counterforce, in lieu of the constraints, by the localization of severe washout at the tips.

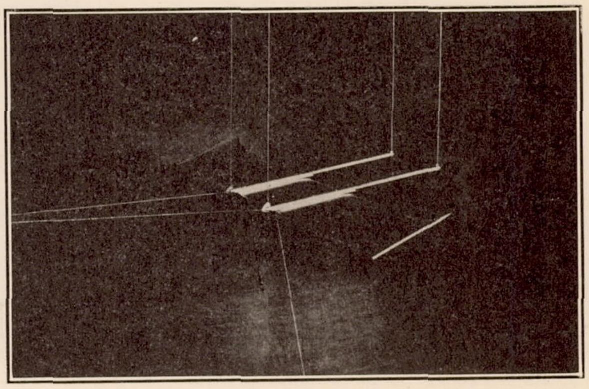

Fig. 1

To avoid confusion of the general influences of these modifications with such irregular aerodynamic characteristics as arise from shape of mean camber line, distribution of thickness, etc., the preliminary work was done on a flat steel plate, 5 x 30 in., 1/8 in. thick, having a cylindrical leading edge and a knife trailing edge, the reduction in thickness toward the latter occurring in 15 per cent of the chord.

The characteristics of the flat plate were determined by a test on the wire balance. Disks of 5 in. diameter and 1/8 in. thickness, with upstream portions blunted and aft sections thinned to an edge, were then welded to its ends and the combination tested. Next, the end plates were removed and the plate given progressive washout at the tips, amounting to 8° in 0.5 chord length along the span. As a test of the plate in this condition revealed little departure from the original characteristics, the washout was increased to 14.8°, now limited to one chord length, and another run made. In both cases the leading edge was maintained as a straight line; Figure 1 shows the plate with 14.8° washout set up for test.

The localized washout gave no promise of improvement, so the construction of an airfoil model of this kind was eliminated from the program. However, as the end-plate combination had improved the flat-plate characteristics considerably, it was decided to subject this device to a very severe test at once.

The wing selected for application was the N. A. C. A. No. 73, one of the most efficient of modern airfoils. This wing is rectangular in plan form and tapers in thickness from 22 per cent of the chord at the center to 5.5 per cent at the tip, the sections being derived from the ordinates of a master section by the application of constant multipliers.[1] Besides these reductions in thickness and camber toward the tip, the N. A. C. A. 73 has considerable washout if we consider as angle of attack that of the zero lift line of each element along the span. The model used was 4 x 24 in.

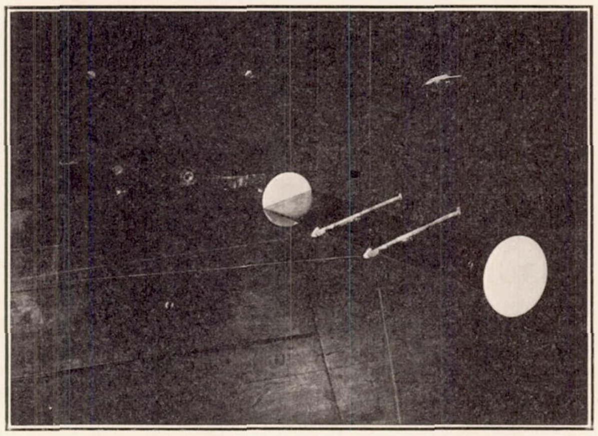

Fig. 2

The purpose of using such an airfoil was to demonstrate that improvement might be made even in the case of a very efficient wing whose maximum lift coefficient was such that its induced drag never became large.

To the tips of this airfoil, then, disks of 4 in. diameter were attached. They were made from $\frac{1}{16}$ in. sheet aluminum and shaped as zones of a large diameter sphere. Figure 2 is a photograph of the combination ready for test.

In an effort to reduce the parasite drag of the end plates, a trapezoidal shape (Fig. 3) was used in a subsequent experiment; the set-up is shown in Figure 4. With the demonstration of favorable effects in both cases the investigation was closed.

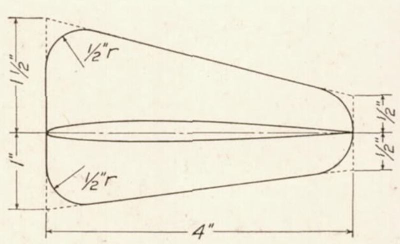

Fig. 3.—Trapezoidal end plate

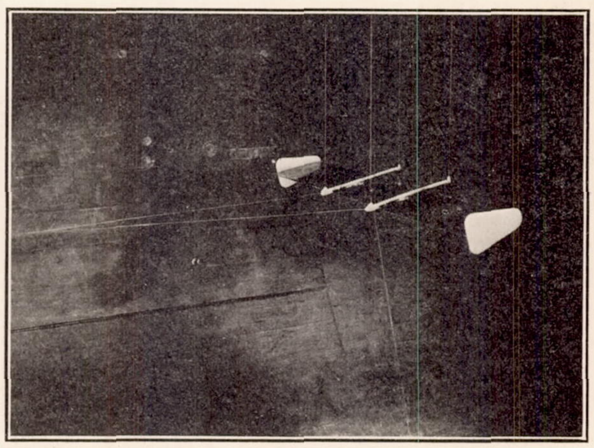

Fig. 4

RESULTS AND DISCUSSION

The data obtained by tests of the thin plate with its various modifications are given in Tables I–V; Figures 5–8 are plotted therefrom. While no numerical analysis has been made, the effects of the modifications are quite evident upon inspection.

From Figure 5 it may be seen that the addition of end plates increases the maximum lift coefficient and, although additional drag is introduced at the condition of zero lift, the effect on induced drag is sufficient to reduce the total drag coefficients at all lift coefficients greater

[1] N. A. C. A Technical Report No 152. "The Aerodynamic Properties of Thick Aerofoils, II, 1922."

than 0.2. The slope of the lift curve is somewhat augmented by this increase in "apparent aspect ratio," as shown in Figure 6.

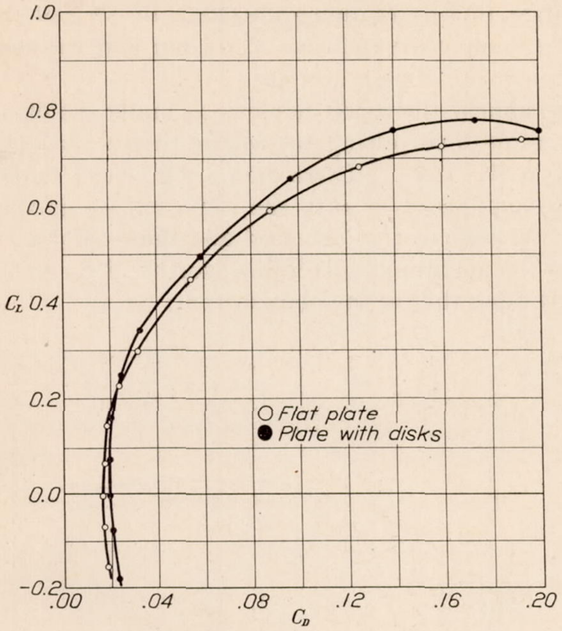

FIG. 5

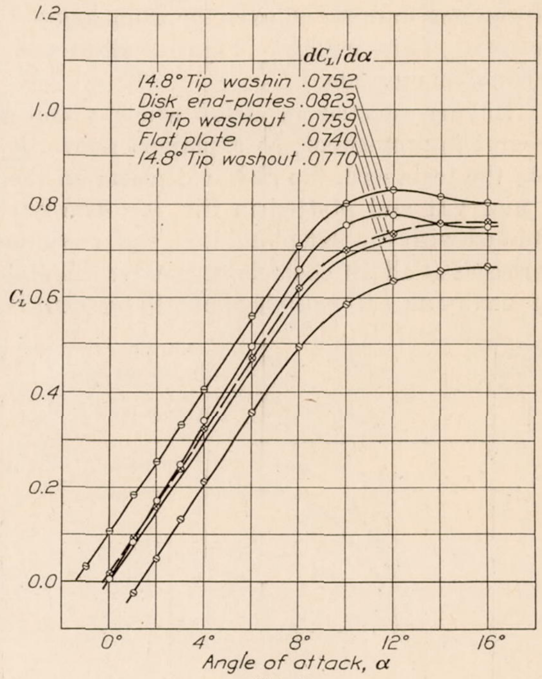

FIG. 6

Figure 7 covers the work on washed-out tips.[2] The very small effect produced by the 8° washout is rather surprising in that it is not appreciable at zero lift. The polar from the test with heavier washout shows only one important point, namely, that the addition to profile

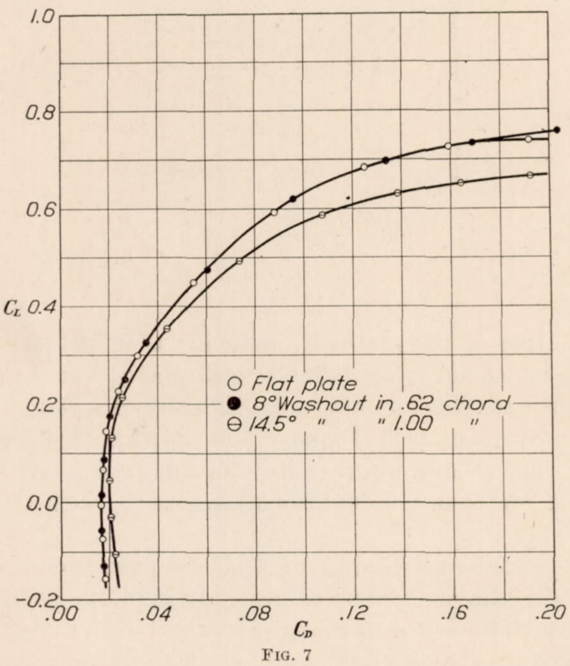

FIG. 7

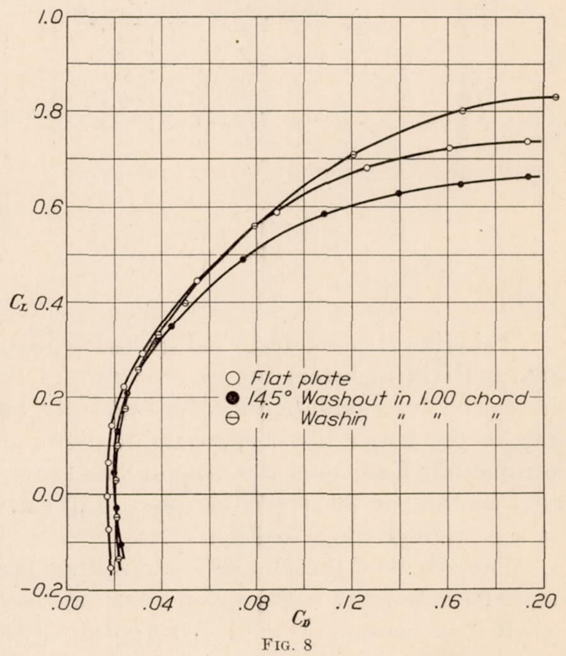

FIG. 8

drag is greater than the decrease of induced drag at all attitudes, thus demonstrating the impracticability of this device. The effects of washed-out tips upon the lift curve slope are shown in Figure 6.

[2] Ergebnisse der Aerodynamischen Versuchsanstalt zu Göttingen. P. 63-69, abb. 47 and 56.

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Figure 8 is inserted as a point of interest, although it has no direct bearing on this investigation. Due to a misunderstanding of instructions, the plate was set on the balance in the inverted position and data taken over the usual angular range, thus determining the characteristics of the plate with 14.8° washin. Figure 8 illustrates the comparative effects of washin and washout of equal magnitude.

Having selected an airfoil which would give almost the worst conditions under which to attempt improvement, as explained above, it was quite surprising to see the results obtained from the tests with the disk end plates on the N. A. C. A. 73. These data are given in Tables VI and VII and plotted in Fig. 9. The improvement is of exactly the same nature as that obtained with the flat plate, i. e., the maximum lift coefficient is increased and the total drag is decreased at all lift coefficients greater than 0.3 of the maximum. It is also worthy of note that the maximum L/D ratio is about 10 per cent larger than that of the plain airfoil.

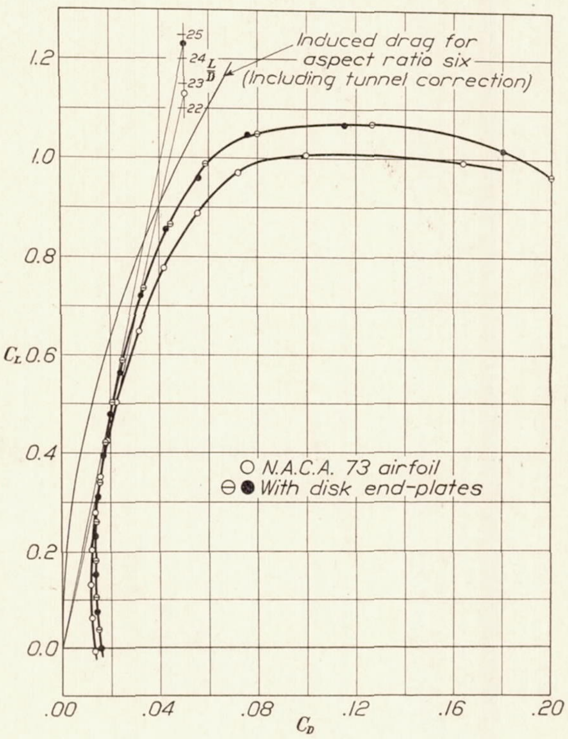

Fig. 9

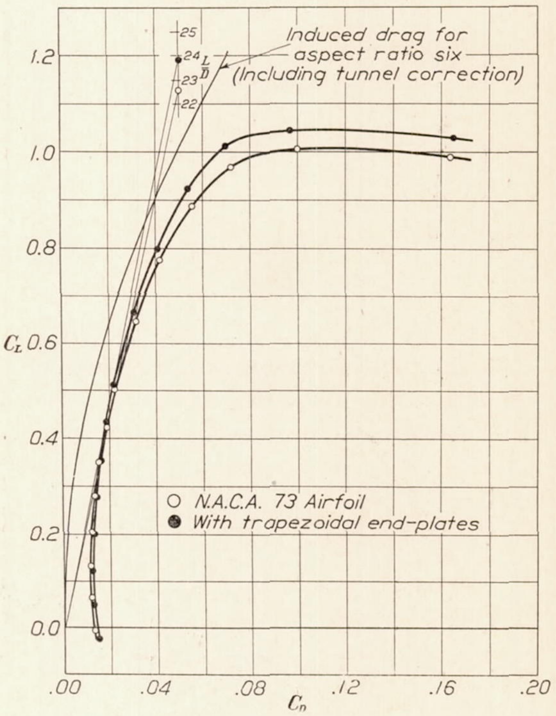

Fig. 10

Thinking it possible to reduce the parasite drag of the plates by reducing their projected area and still maintain the greater part of the beneficial effect, the circular plates were supplanted by trapezoidal ones. As shown by Figure 10, this combination still showed a reduced drag at the larger lift coefficients, a slight improvement in L/D max. and, as expected, less detrimental effect upon the drag at small lifts. The overall improvement in this case is not so great as that of the preceding one. Lift curves for both combinations are shown, with that for the original wing, in Figure 11.

The effects of these modifications upon the "apparent aspect ratio" and the power requirement characteristics of the airfoil bring out their advantages even more clearly than do the polars.

If it be assumed that the profile drag of the airfoil itself is unchanged by the addition of the end plates, we may derive a new curve of induced drag by merely stepping off the profile drag of the plain wing from the polar of the wing-disk combination and determine the "apparent aspect ratio" from the coordinates of this derived curve. Since the induced drag of a 4 x 24 in. airfoil in a 60 in. closed tunnel is:

$$C_{D\,i} = \frac{C_L^2}{\pi\,(A.\,R.)}\left[1+\frac{1}{2}\left(\frac{b}{D}\right)^2\right] = \frac{C_L^2}{\pi\times 6}\left[1+\frac{1}{2}\left(\frac{24}{60}\right)^2\right]$$

the aspect ratio is:

$$A.\ R. = \frac{C_L^2}{\pi\ C_{D\,i}}\left[1-\frac{1}{2}\left(\frac{24}{60}\right)^2\right] = 0.92 \times \frac{C_L^2}{\pi\ C_{D\,i}}$$

Calculated on this basis, the following results are obtained:

Type of end plate	Disk	Trapezoid
C_L	Apparent aspect ratio	
0.4	6.88	6.33
.5	7.17	6.38
.6	7.20	6.49
.7	7.44	6.52
.8	7.68	6.65
.9	7.95	7.07

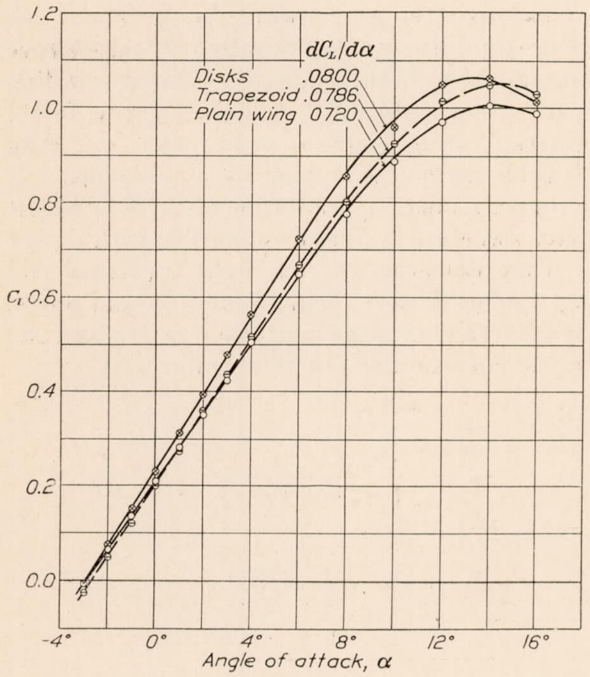

FIG. 11

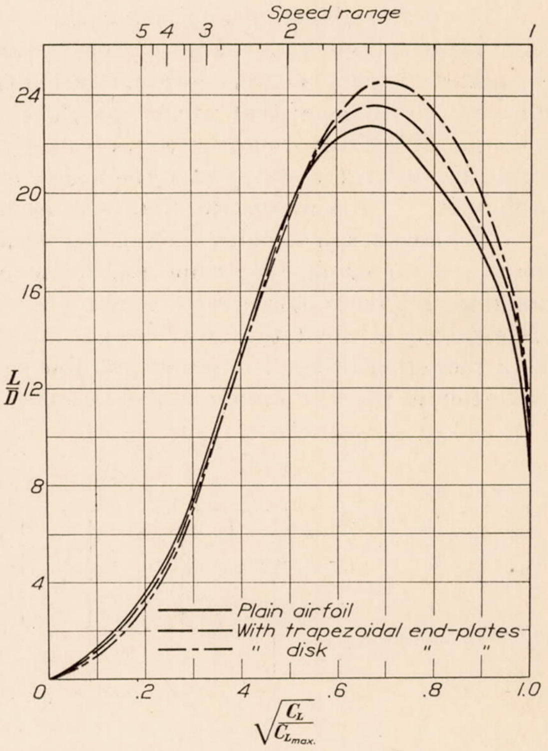

FIG. 12

It is also interesting to note that the Prandtl-Munk formula,

$$\frac{dC_L}{d\alpha} = \frac{2\pi}{\left[1+\frac{2S}{b^2}\left(1-\frac{b^2}{2D^2}\right)\right]57.3} = \frac{0.1294}{1+\frac{2}{A.R.}(0.92)}$$

which expresses the relation of lift curve slope to aspect ratio, gives much lower values for the "apparent aspect ratio." The computed values are:

Arrangement	Apparent aspect ratio
Plain airfoil	3.54
With trapezoidal end plates	4.70
With disk end plates	4.98

By shifting the polar of the airfoil with end plates along the drag axis until it coincides, at zero lift, with the polar of the airfoil alone, we would, in effect, subtract the drag of the end plates, which quantity is not liable to vary greatly. However, this artifice avails little as the maximum value of aspect ratio, calculated as above, now occurs at a low lift coefficient and has a higher maximum value which is very sharply defined. This merely demonstrates that if the plate drag is constant the profile drag is no longer equal to that of the plain airfoil—or that the effect is not purely one of aspect ratio—which seems the most rational explanation.

The improvement of the L/D ratio throughout the useful flying range is shown in Figure 12. It will be seen that the tip modifications have a beneficial influence under all conditions except that of very high speed.

The results show that it is possible to improve the two most important characteristics of an airfoil, i. e., L/D ratio and power requirement for sustentation, for all conditions except that near minimum drag. It may be seen from Figure 12 that the detrimental effect which occurs in the neighborhood of minimum drag will become of consequence only when there is available enough power to provide an extremely large speed range.

The practicability of applying such modifications to aircraft will remain in question until more is learned of the loads which they would impose upon the wing spars. As the flow which the plates obstruct is one resulting from a positive pressure below and a negative pressure above the wing, the moment they would apply to the spars would have the same sense as that resulting from the lift. This would necessitate heavier spars. It is unlikely that the transverse forces would be so large as to require the use of end plates of such thickness as to make their drag prohibitive. Pressure distribution tests seem a feasible method of solving these problems.

The conclusion remains that an aerodynamic improvement, by limitation of the flow about the tips of an airfoil, is possible and, if the necessary structure be found compatible with design practice and reasonably small dimensions, the scheme deserves trial in flight. Vertical end plates are equivalent to a greater span, the wing tips, as it were, being folded up and down. As a reduction of span is often desirable for maneuverability, transportation, or storage, the limitation of the flow around airfoil tips may prove of considerable practical value.

TABLE I

TEST OF FLAT PLATE (5 x 30 in.)

α	C_D	C_L	α	C_D	C_L	α	C_D	C_L
°			°			°		
−2	0.0182	−0.155	2	0.0185	0.144	8	0.0879	0.593
−1	.0170	−.070	3	.0237	.227	10	.1250	.685
0	.0165	−.004	4	.0318	.299	12	.1593	.726
+1	.0171	+.066	6	.0541	.449	14	.1915	.738
						16	.2200	.733

TABLE II

FLAT PLATE WITH DISK END PLATES

α	C_D	C_L	α	C_D	C_L	α	C_D	C_L
°			°			°		
−2	0.0299	−0.180	2	0.0207	0.161	8	0.0969	0.660
−1	.0203	−.079	3	.0246	.247	10	.1396	.759
0	.0195	−.004	4	.0328	.342	12	.1724	.778
+1	.0196	+.074	6	.0585	.495	14	.1990	.755
						16	.2268	.750

TABLE III

PLATE WITH 8° WASHOUT IN 0.5 CHORD

α	C_D	C_L	α	C_D	C_L	α	C_D	C_L
°			°			°		
−2	0.0177	−0.128	3	0.0267	0.249	12	0.1690	0.733
−1	.0167	−.055	4	.0352	.327	14	.2030	.757
0	.0168	+.015	6	.0607	.476	16	.2370	.761
+1	.0178	.086	8	.0960	.620	18	.2680	.770
2	.0202	.173	10	.1340	.698	20	.2960	.774

TABLE IV

PLATE WITH 14.8° WASHOUT IN 1.0 CHORD

α	C_D	C_L	α	C_D	C_L	α	C_D	C_L
°			°			°		
−3	0.0390	−0.337	2	0.0198	+0.046	10	0.1073	0.588
−2	.0304	−.264	3	.0209	.132	12	.1383	.632
−1	.0248	−.187	4	.0255	.213	14	.1640	.652
0	.0222	−.105	6	.0440	.354	16	.1922	.667
+1	.0205	−.029	8	.0735	.495	18	.2220	.682
						20	.2490	.693

TABLE V

PLATE WITH 14.8° WASHIN IN 1.0 CHORD

α	C_D	C_L	α	C_D	C_L	α	C_D	C_L
°			°			°		
−8	0.0754	−0.502	−1	0.0208	+0.031	4	0.0492	0.402
−6	.0453	−.358	0	.0209	.104	6	.0781	.564
−4	.0265	−.213	+1	.0242	.180	8	.1197	.711
−3	.0215	−.134	2	.0297	.262	10	.1650	.802
−2	.0201	−.046	3	.0381	.337	12	.2030	.830
						14	.2330	.812

TABLE VI

TEST OF N. A. C. A. 73 AIRFOIL (4 x 24 in.

α	C_D	C_L	α	C_D	C_L	α	C_D	C_L
°			°			°		
−3	0.0131	−0.006	2	0.0158	0.351	10	0.0554	0.889
−2	.0120	+.064	3	.0186	.424	12	.0719	.970
−1	.0116	.132	4	.0221	.504	14	.0998	1.006
0	.0122	.204	6	.0312	.648	16	.1638	.991
+1	.0138	.279	8	.0418	.777	18	.2290	.930

TABLE VII

N. A. C. A. 73 AIRFOIL WITH DISK END PLATES

α	C_D	C_L	α	C_D	C_L	α	C_D	C_L
°			°			°		
−3	0.0156	0.000	2	0.0170	0.395	10	0.0559	0.961
−2	.0140	+.076	3	.0198	.479	12	.0775	1.048
−1	.0133	.152	4	.0236	.563	14	.1150	1.067
0	.0137	.231	6	.0322	.721	16	.1800	1.015
+1	.0149	.311	8	.0425	.856	18	.2304	.927
				CHECK				
°			°			°		
−3	0.0148	+0.038	2	0.0177	0.421	10	0.0586	0.989
−2	.0135	.106	3	.0206	.504	12	.0798	1.050
−1	.0134	.182	4	.0243	.590	14	.1265	1.070
0	.0141	.260	6	.0335	.737	16	.2000	.964
+1	.0158	.341	8	.0443	.867	18	.2450	.882

TABLE VIII

N. A. C. A. 73 AIRFOIL WITH TRAPEZOIDAL END PLATES

α	C_D	C_L	α	C_D	C_L	α	C_D	C_L
°			°			°		
−3	0.0146	−0.024	2	0.0160	0.354	10	0.0536	0.924
−2	.0129	+.048	3	0185	.435	12	.0694	1.015
−1	.0123	.121	4	.0217	.513	14	.0968	1.046
0	.0128	.200	6	.0303	.667	16	.1650	1.030
+1	.0141	.277	8	.0405	.800	18	.2260	.943

All tests at 30 m/s (98.4 ft./sec.) air speed.
N. A. C. A. atmospheric (5 ft.) No. 1 wind tunnel.

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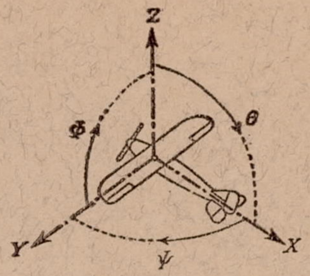

Positive directions of axes and angles (forces and moments) are shown by arrows.

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.