NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 618

COMPARATIVE FLIGHT AND FULL-SCALE WIND-TUNNEL MEASUREMENTS OF THE MAXIMUM LIFT OF AN AIRPLANE

By ABE SILVERSTEIN, S. KATZOFF, and JAMES A. HOOTMAN

1938

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb.
Power	P	horsepower (metric)		horsepower	hp.
Speed	V	kilometers per hour	k.p.h.	miles per hour	m.p.h.
		meters per second	m.p.s.	feet per second	f.p.s.

2. GENERAL SYMBOLS

W, Weight$=mg$

g, Standard acceleration of gravity$=9.80665$ m/s^2 or 32.1740 ft./sec.^{2}

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

I, Moment of inertia$=mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ, Coefficient of viscosity

ν, Kinematic viscosity

ρ, Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C. and 760 mm; or 0.002378 lb.-ft.$^{-4}$ sec.^{2}

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb./cu. ft.

3. AERODYNAMIC SYMBOLS

S, Area

S_w, Area of wing

G, Gap

b, Span

c, Chord

$\frac{b^2}{S}$, Aspect ratio

V, True air speed

q, Dynamic pressure$=\frac{1}{2}\rho V^2$

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

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

D_0, Profile drag, absolute coefficient $C_{D_0}=\frac{D_0}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i}=\frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p}=\frac{D_p}{qS}$

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

R, Resultant force

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

i_t, Angle of stabilizer setting (relative to thrust line)

Q, Resultant moment

Ω, Resultant angular velocity

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension (e.g., for a model airfoil 3 in. chord, 100 m.p.h. normal pressure at 15° C., the corresponding number is 234,000; or for a model of 10 cm chord, 40 m.p.s., the corresponding number is 274,000)

C_p, Center-of-pressure coefficient (ratio of distance of c.p. from leading edge to chord length)

α, Angle of attack

ϵ, Angle of downwash

α_0, Angle of attack, infinite aspect ratio

α_i, Angle of attack, induced

α_a, Angle of attack, absolute (measured from zero-lift position)

γ, Flight-path angle

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By Abe Silverstein, S. Katzoff, and James A. Hootman

SUMMARY

Determinations of the power-off maximum lift of a Fairchild 22 airplane were made in the N. A. C. A. full-scale wind tunnel and in flight. The results from the two types of test were in satisfactory agreement. It was found that, when the airplane was rotated positively in pitch through the angle of stall at rates of the order of 0.1° per second, the maximum lift coefficient was considerably higher than that obtained in the standard tests, in which the forces are measured with the angles of attack fixed. Scale effect on the maximum lift coefficient was also investigated.

INTRODUCTION

The purpose of the present investigation was to obtain a direct comparison between flight and full-scale wind-tunnel measurements of the maximum lift coefficient of a Fairchild 22 airplane. The comparison was desirable in order to indicate the extent to which the various wind-tunnel effects and both wind-tunnel and flight techniques might influence maximum-lift determinations. The turbulence in the full-scale tunnel (reference 1) was of particular concern.

Obviously, a high order of accuracy must exist in both flight and wind-tunnel measurements if the comparison is to be significant. The many possibilities for experimental error in both series of tests required that great care be exercised in obtaining the test data. Previous comparisons between flight and full-scale wind-tunnel results (references 2 and 3) were incidental to other studies and unsuited for the accuracy here desired.

Inasmuch as, in the flight determinations of maximum lift, the airplane was rotated through the angle of stall, some wind-tunnel tests were made with the airplane rotating at corresponding angular velocities in order to investigate the effect of this technique on the results.

Wind-tunnel tests to determine the Reynolds Number effects on the maximum lift coefficient and on the minimum drag coefficient were also made.

FULL-SCALE WIND-TUNNEL INVESTIGATION

APPARATUS AND TESTS

The N. A. C. A. full-scale wind tunnel and its equipment are described in reference 2. Figure 1 is a 3-view drawing of the Fairchild 22 parasol monoplane. Two positions of the center of gravity are indicated, corresponding to two airplane loadings used in the flight tests. The airplane was equipped for these tests with a specially surfaced wing of N. A. C. A. $2R_112$ section. A paint filler was applied over the forward 15 percent

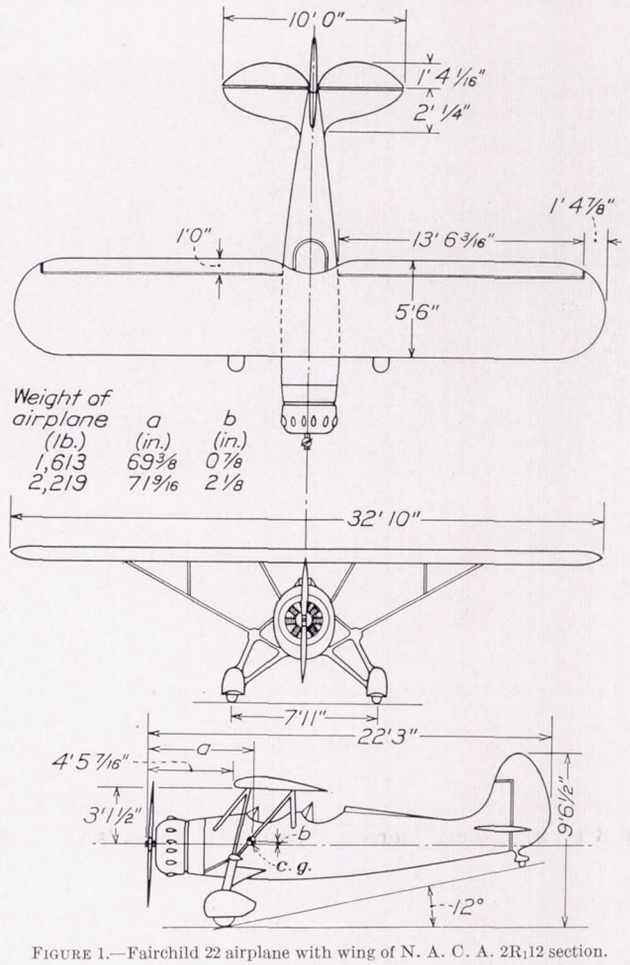


FIGURE 1.—Fairchild 22 airplane with wing of N. A. C. A. $2R_112$ section.

of the wing surface and waxed to a reflecting finish, the polish being maintained throughout both wind-tunnel and flight tests. The purpose of the polish was not only to provide a reproducible surface but also to increase any differences between the wind-tunnel and flight results due to turbulence in the wind tunnel. All the tests were made with the airplane at 0° yaw and

roll and with the ailerons locked in the neutral position. The propeller was locked in the vertical position except where otherwise noted. Figure 2 shows the airplane mounted on the wind-tunnel balance supports.

The tests were of two types. The tests designated "standard" were similar to those normally made in the wind tunnel, in which the force readings are not taken until a number of seconds after the airplane has been brought to rest at the desired attitude. In the other type of test, force readings were taken at regular intervals while the angle of attack was being changed at a constant rate. The rates of change of angle of attack in these runs were varied between 0.025° and 0.2° per second, this range including that used in the flight tests.

Except in the tests to determine minimum drag, all measurements were made in the region of maximum lift, the angle-of-attack range being usually from 12° to 20°.

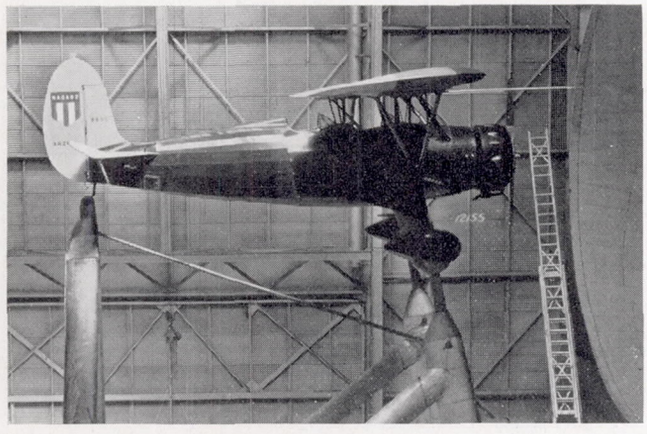


FIGURE 2.—Fairchild 22 airplane in full-scale wind tunnel.

Air speeds ranged from 29 to 63 miles per hour, except for the minimum-drag tests, in which air speeds up to 119 miles per hour were used. Much of the work was done at an air speed of 56 miles per hour, which is approximately flight speed at maximum lift.

RESULTS AND DISCUSSION

The results of the wind-tunnel tests are summarized in figures 3 to 19. Except where otherwise noted, the figures refer to tests of the standard type. All measurements were corrected for jet-boundary effect at the wing, balance-support tare values, and blocking, as described in reference 4.

In figure 3 the lift, the drag, and the pitching-moment coefficients, and the lift-drag ratio are plotted against the angle of attack of the thrust axis, α_T, for the airplane with the horizontal tail removed. The test data were obtained at an air speed of 56 miles per hour. The pitching-moment coefficient was based on a center-of-gravity position as determined for a gross weight of 1,613 pounds. (See fig. 1.)

Scale effect.—Figure 4 shows the lift curves obtained at five different air speeds for the airplane with the horizontal tail removed. It will be observed that, with increasing air speed, the maximum lift coefficient reaches higher values and the entire lift curve is slightly raised, even over the linear range. The break in the lift curve at the peak becomes sharper with increasing air speed, indicating a variation in the mechanism of stalling. It may be noted that beyond the stall the lift curve represents only a rough average, for there is wide scatter of the points in this region.

The variation of the maximum lift coefficient with air speed is shown in figure 5 for three different test

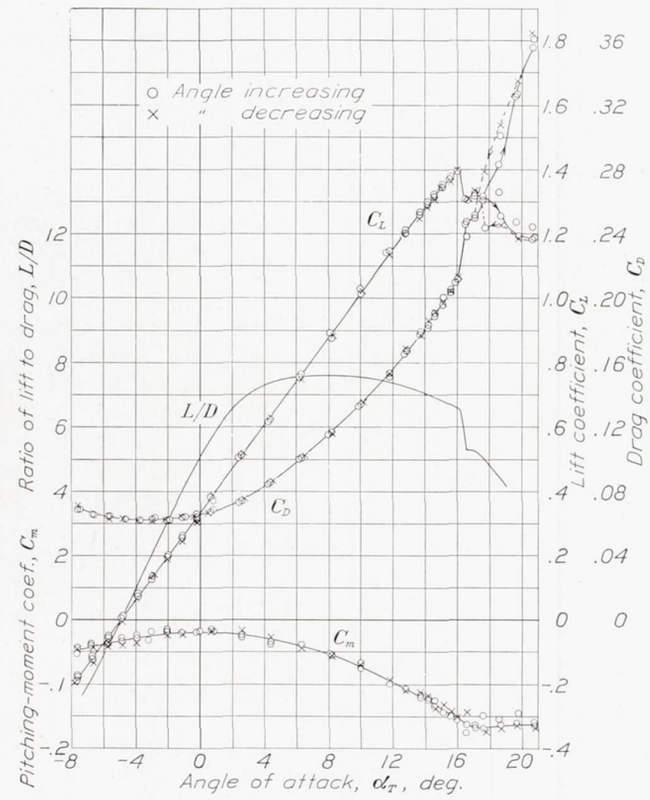


FIGURE 3.—Characteristics of Fairchild 22 airplane with the horizontal tail removed. C_m for airplane based on weight of 1,613 pounds. Air speed, 56 m. p. h.

conditions, namely, tail removed, tail on, and tail on with the angle changing at the rate of 0.1° per second. The indicated stabilizer angle (δ_s) and elevator angle (δ_e) correspond approximately to trim at maximum lift. All the tests show essentially the same variation of maximum lift coefficient with air speed. Results from the tests in the variable-density tunnel of the plain airfoil are also shown in the figure, and it will be seen that, except for a vertical displacement due to difference in plan form and to the effect of the fuselage, the agreement is very good.

Experiments to determine whether the presence of the propeller fixed in the vertical or the horizontal position materially influenced the maximum lift showed that the propeller in either position had a negligible effect (fig. 6).

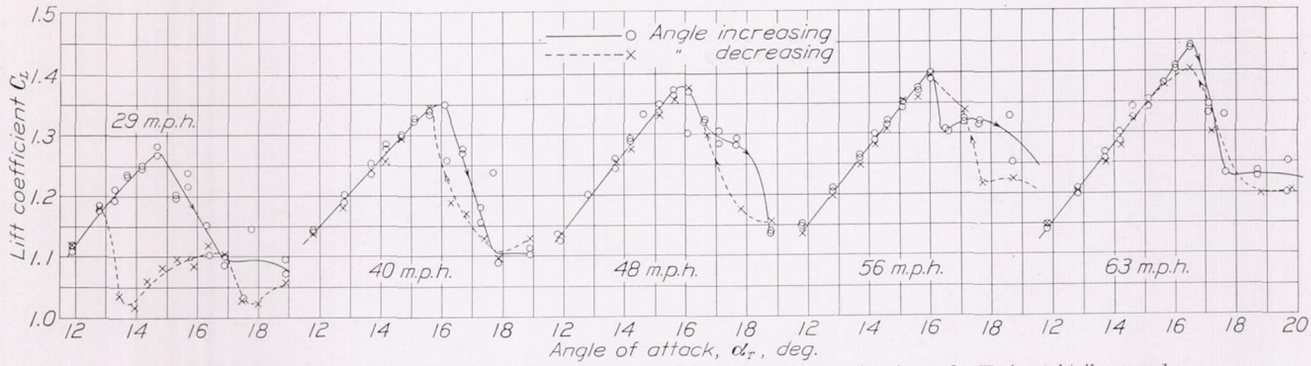
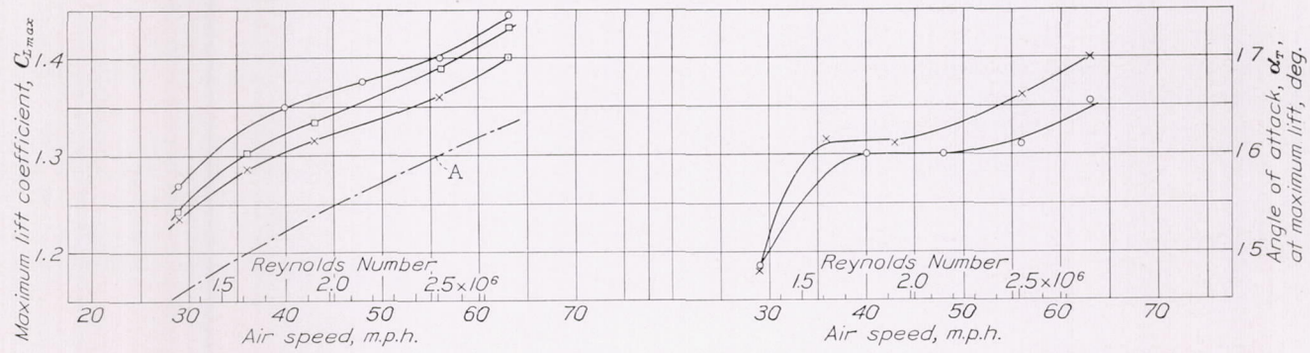


FIGURE 4.—Scale effect, Fairchild 22 airplane. Variation of maximum lift coefficient with air speed. Horizontal tail removed.



○ Horizontal tail removed, $\frac{d\alpha}{dt}=0$

× Horizontal tail on, $\delta_s=-1.6°$, $\delta_e=-25°$, $\frac{d\alpha}{dt}=0$

□ Horizontal tail on, $\delta_s=-1.6°$, $\delta_e=-25°$, $\frac{d\alpha}{dt}=0.1$°/sec.

A, From V. D. T. tests of N. A. C. A. 2R$_1$12 airfoil (plotted against equivalent Reynolds Number)

FIGURE 5.—Scale effect, Fairchild 22 airplane. Variation with air speed of α_T at maximum lift and of the maximum lift coefficient, for three test conditions.

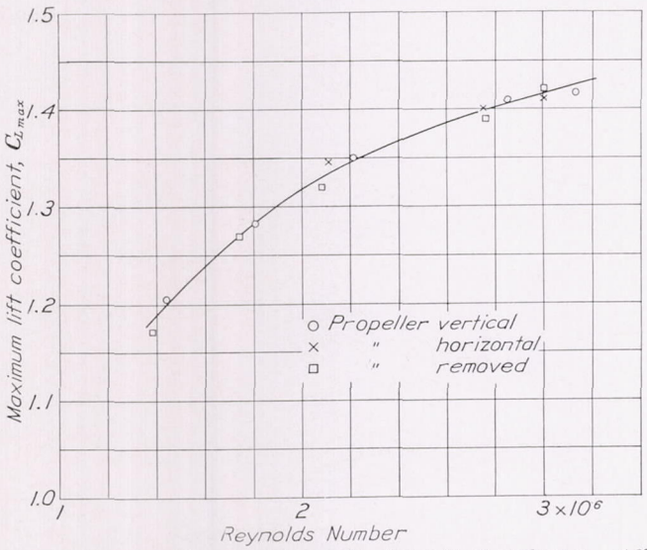


FIGURE 6.—Propeller effect on maximum lift. Fairchild 22 airplane; δ_s, −1.6°; δ_e, −25°.

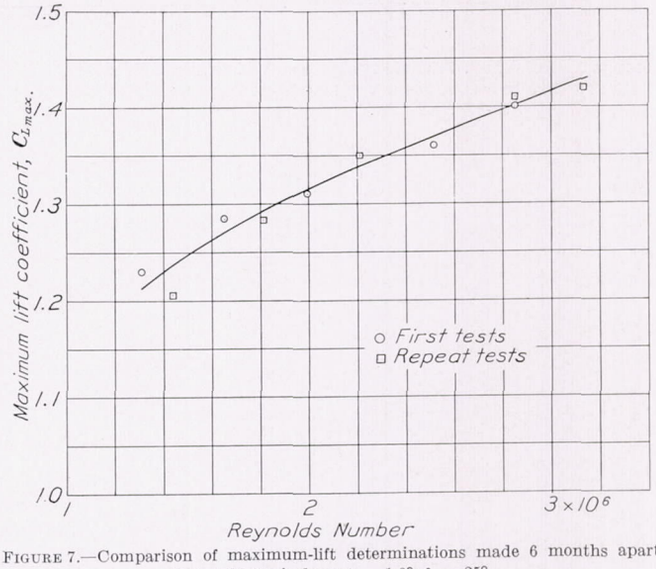


FIGURE 7.—Comparison of maximum-lift determinations made 6 months apart. Fairchild 22 airplane; δ_s, −1.6°; δ_e, −25°.

Six months after the completion of the wind-tunnel tests, some of the measurements were repeated in order to test for a suspected deterioration of the wing. The repeat tests failed to show any appreciable effect of deterioration, the results being in satisfactory agreement with the earlier measurements (fig. 7).

The scale effect on minimum drag is shown in figure 8. The minimum drag coefficient decreases from 0.058 to 0.042 as the speed increases from 30 to 119 miles per hour. This decrease in the drag coefficient is many times greater than that to be expected from the wing alone and may be attributed to a large scale effect on the junctures, struts, and smaller parts of the airplane.

The effects of scale on the pitching-moment coefficient and on the angle of attack for trim are shown in figure 9 to be negligible, except where reduction in air speed causes stalling, as at the first point on the 14° curve. The elevator angle for trim at maximum lift is plotted against air speed in figure 10; the variation is due to the scale effect on maximum lift.

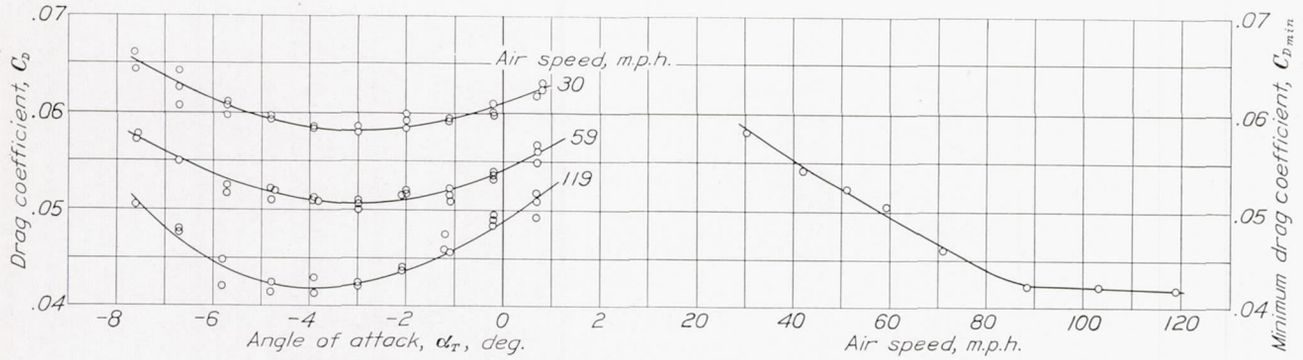


FIGURE 8.—Scale effect, Fairchild 22 airplane. Variation of C_D and $C_{D_{min}}$ with air speed. Horizontal tail removed.

Trim lift curves.—In order to obtain lift curves corresponding to flight, the wind-tunnel results were adjusted to the trim condition at all angles of attack. Trim lift curves were determined from the wind-tunnel data for two positions of the center of gravity, corresponding to the two airplane loadings used in the flight tests. The plots used in deriving the trim lift curves are shown in figures 11, 12, and 13. In figure 11 the effect of elevator deflection on the pitching-moment coefficient is shown. At each elevator setting, the angle of attack for trim is found where the curve crosses the axis. Cross plots of these data are shown in figure 12 where the elevator angle for trim is plotted against angle of attack for both airplane weights and for two stabilizer settings. In figure 13 the variation of lift coefficient with elevator angle is shown for several angles of attack. From figures 12 and 13 the trim lift curves are constructed (fig. 14) for a constant speed of 56 miles per hour.

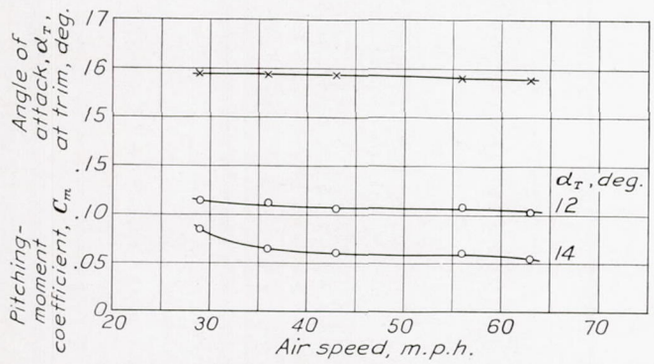


FIGURE 9.—Scale effect, Fairchild 22 airplane. Variation with air speed of angle of attack for trim and of pitching-moment coefficient at two angles of attack. Weight, 1,613 pounds; δ_s, −1.6°; δ_s, −25°.

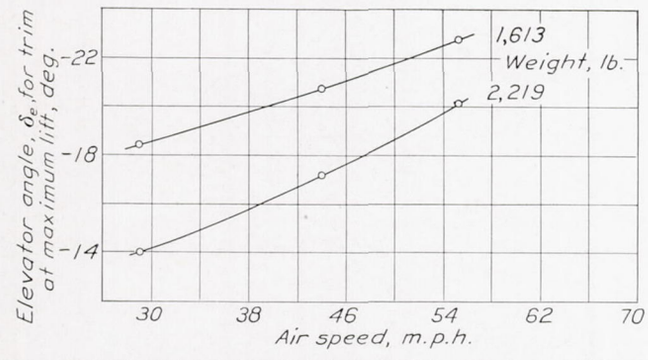


FIGURE 10.—Scale effect, Fairchild 22 airplane. Variation with air speed of elevator setting for trim at maximum lift. δ_s, −3.6°.

These trim lift curves, however, do not actually represent the conditions that would be found in flight tests, for in flight (1) the air speed varies with the lift coefficient, thus giving rise to a small scale effect, and (2) the changing of the angle of attack has an effect, apparent mainly as increased maximum lift. Both of these corrections were applied in the construction of the "flight-speed" curves of figure 14. The variation with Reynolds Number of the maximum lift coefficient, determined at $d\alpha/dt=0.1°$ per second and corrected to the trim condition, is compared with flight results in figure 15.

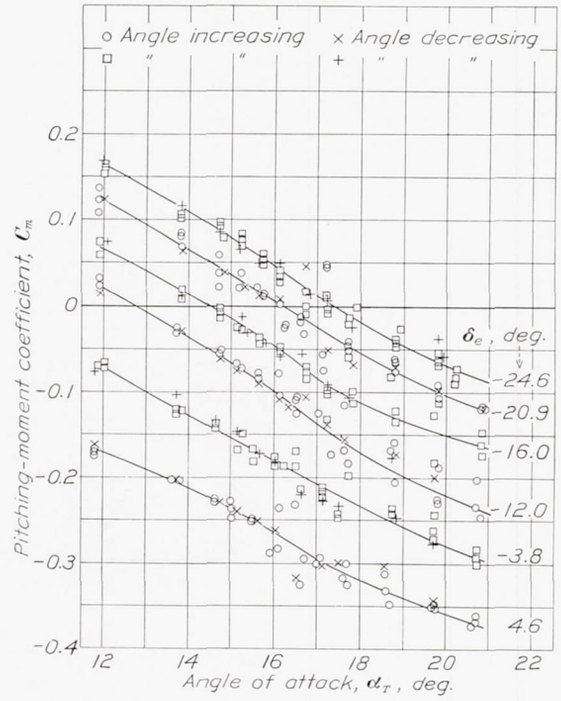


FIGURE 11.—Pitching-moment curves at different elevator angles. Fairchild 22 airplane; weight, 1,613 pounds; δ_s, −3.6°; air speed, 56 m. p. h.

The effect of angular velocity on maximum lift.—During the course of the investigation it was observed, as previously mentioned, that the maximum lift coefficients obtained in the tests with changing angle of

attack were considerably higher than those obtained in the standard tests. In figure 16 are given lift curves showing the manner in which the peak of the lift curve rises with increasing rate of change of angle. For the standard tests the maximum value is 1.405, whereas, with the angle changing at the rate of 0.2° per second, it is 1.480. In figure 17 the maximum lift coefficients

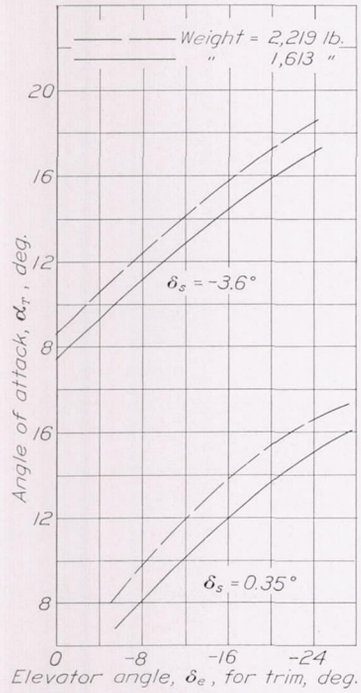


FIGURE 12.—Elevator settings for trim. Fairchild 22 airplane; air speed, 56 m. p. h.

for two different airplane conditions are plotted against the nondimensional parameter $\frac{c}{V}\frac{d\alpha}{dt}$, in which c and V are the chord and the velocity, respectively. The upper curve is for the tail-removed condition, while the lower curve represents a tail-on condition with the elevator set approximately for trim at maximum lift. The angle of attack at maximum lift is also plotted in the figure; the variation parallels that of the lift coefficient.

In order to establish the validity of these results, particularly as regards the possibility of error due to balance characteristics, it was ascertained that, on the one hand, the damping was too low and, on the other hand, the natural frequency of the balance was too high to cause any appreciable discrepancy between the indicated and the actual forces. As a further check on the work, a small airfoil of N. A. C. A. $2R_112$ section was tested at corresponding rates of change of angle of attack in the N. A. C. A. variable-density tunnel. The results of these tests were in very good agreement with the results just discussed.

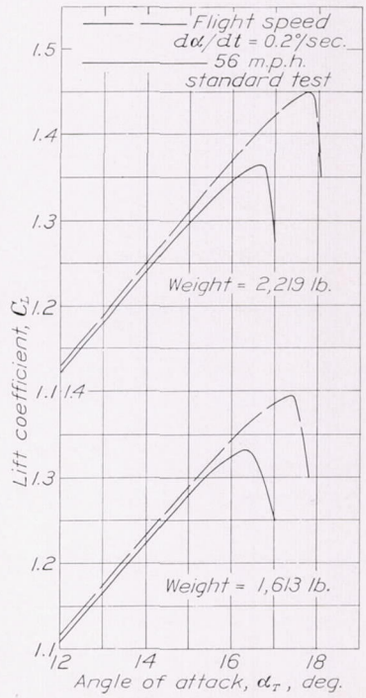


FIGURE 14.—Trim lift curves. Fairchild 22 airplane.

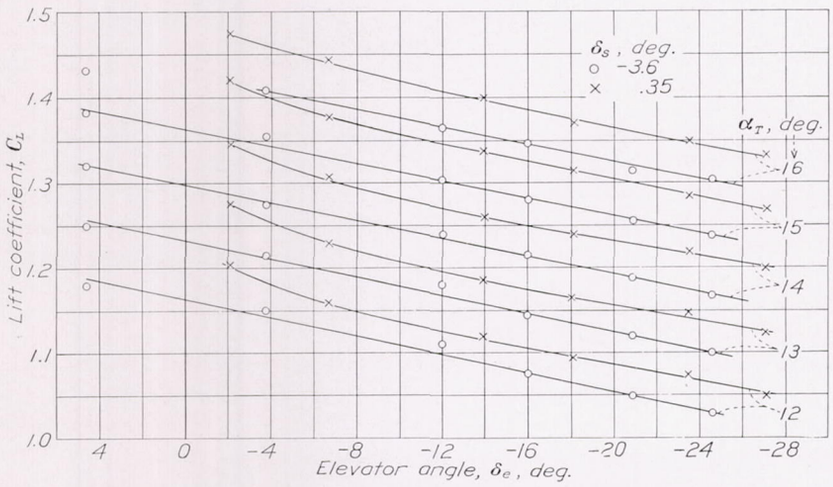


FIGURE 13.—Effect of tail setting on lift. Fairchild 22 airplane; air speed, 56 m. p. h.

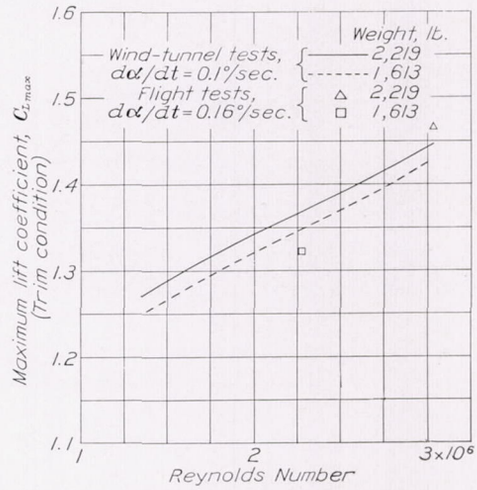


FIGURE 15.—Comparison of wind-tunnel with flight determination of the maximum lift coefficient. Variation with air speed of the maximum lift coefficient at trim. Fairchild 22 airplane.

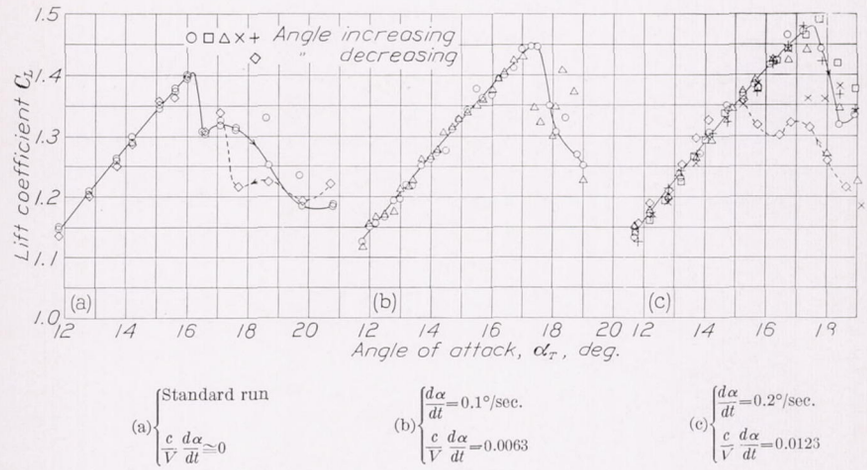


FIGURE 16.—Lift curves for different angular velocities. Fairchild 22 airplane; horizontal tail removed; air speed, 56 m. p. h.

The effect upon the maximum lift of the rate of change of angle of attack is well known, but the magnitude observed here was much higher than had been anticipated on the basis of previous investigations. Thus, Kramer's formula (reference 5), which has been approximately confirmed both at low Reynolds Numbers (reference 6) and in flight (reference 7), predicts only 1/20 of the observed increase. The failure of Kramer's formula in this case may be due to the fact

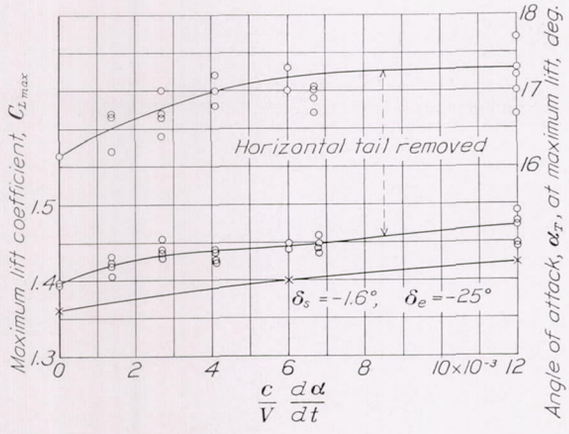


FIGURE 17.—Variation with $\frac{c}{V}\frac{d\alpha}{dt}$ of α_T at maximum lift and of the maximum lift coefficient. Fairchild 22 airplane; air speed, 56 m. p. h.

that the formula was based on experimental results obtained at very high values of $\frac{c}{V}\frac{d\alpha}{dt}$. It is also possible that the phenomenon is not so independent of the wing section characteristics as has been heretofore supposed.

The influence of air speed on the phenomenon is shown in figure 5, where a set of standard runs at different air speeds is compared with a corresponding set in which the angle of attack was changed at the rate of 0.1° per second.

It is clear that the value of the lift coefficient in the neighborhood of and beyond the maximum is not uniquely determined by the angle of attack. In order to investigate the general character of the time variation of the lift at fixed angles of attack in this range, a few tests were made in which the angle was increased at a rate of 0.1° per second up to a certain value and then held constant while observations of lift force were made. The results are shown in figure 18. The highest angle of attack at which the lift is maintained indefinitely is about 16.6°. When the angle of attack is increased above this value and then fixed, the flow breaks down within a few seconds and wide fluctuations occur in the lift.

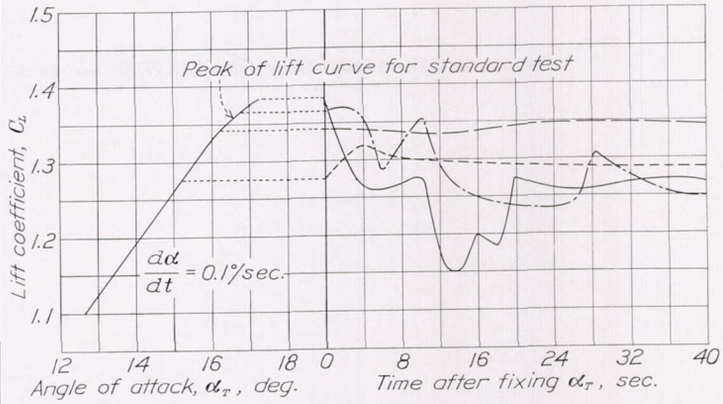


FIGURE 18.—Decay with time of added lift due to angular velocity, and fluctuations in lift beyond the stall. Angle of attack increased at 0.1° per second up to the values shown, and then fixed. Fairchild 22 airplane; δ_s, −1.6°; δ_e, −25°; air speed, 56 m. p. h.

Figure 19 further illustrates the vagaries in the behavior of the lift coefficient near and beyond the angle of maximum lift. Three separate lift curves are shown, obtained under apparently identical conditions. Each is fairly smooth, yet different from the other two.

FLIGHT TESTS

The flight tests consisted in recording in flight sufficient data to obtain the acceleration normal to the flight path, the angle of attack, and the dynamic pressure while the angle of attack was being slowly increased over a range of several degrees below and

including the angle of stall. The recording instruments consisted of an air-speed meter, an angle-of-attack meter, a two-component accelerometer, and a timer. The air-speed recorder was connected to a swiveling pitot-static head mounted on a light boom about one chord length forward of the leading edge at the semispan and slightly below the plane of the chord. This head was calibrated against a suspended static head down to the minimum stalling speed of the airplane. The angle-of-attack recorder, which was calibrated in steady glides, consisted of a differential-pressure type of yaw head mounted on a boom similar to that employed for the air-speed head, but on the opposite side of the airplane.

The lift was computed from the normal acceleration and the gross weight at the time of the test. After the

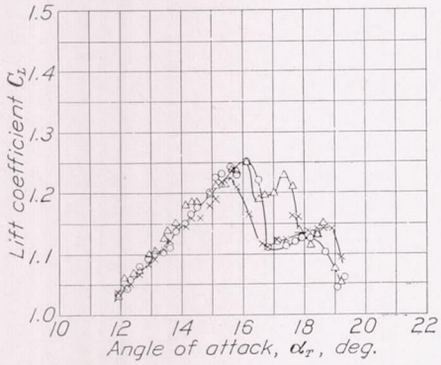


FIGURE 19.—Three different lift curves obtained under apparently identical conditions. Fairchild 22 airplane; δ_s, −1.6°; δ_e, −25°; $\frac{c}{V}\frac{d\alpha}{dt}$=0.0124; air speed, 29 m. p. h.; $\frac{d\alpha}{dt}$, 0.1°/sec.

approximate time of stall was determined by inspection of the records, calculations of C_L were made for different instants during the maneuver until the maximum value was obtained.

The tests were made with the propeller stopped in the vertical position and with an average rate of change of angle of attack of 0.16° per second for 3° to 4° preceding the stalling angle.

The variation of the Reynolds Number was obtained by flying the airplane first heavily loaded at the lowest possible safe altitude and then with the least possible load at high altitude (approximately 10,000 feet). A number of flights were made, several tests being made in each flight. The corresponding average Reynolds Numbers for the 14 individual tests made at low altitude and the 16 tests at high altitude were 3.04×10^6 and 2.28×10^6, respectively. For the various flights, the average deviation of the individual results from the mean was about 1 percent.

COMPARISON OF FLIGHT AND WIND-TUNNEL RESULTS

Points representing the average maximum lift coefficients for the two flight Reynolds Numbers are plotted in figure 15 for comparison with the wind-tunnel results. It will be noted that the values are not directly comparable, since the rates of change of angle of attack are slightly different. Correcting the wind-tunnel results to the angular velocity used in flight would, however, increase the wind-tunnel values by only one-half percent. The agreement, accordingly, is satisfactory and indicates that, within the experimental accuracy, there is no important systematic discrepancy, such as might be due to turbulence, between the two types of measurement.

CONCLUSIONS

1. Satisfactory agreement exists between the maximum lift coefficients measured in flight and those measured in the full-scale wind tunnel.

2. It is necessary, in the comparison of flight and wind-tunnel measurements of the maximum lift coefficient, that the comparison be made at corresponding rates of change of angle of attack. Values of $\frac{c}{V}\frac{d\alpha}{dt}$ of the order of 0.01 may appreciably increase the maximum lift coefficient of an airplane over the values obtained in the standard test, in which the forces are measured with the angles of attack fixed.

LANGLEY MEMORIAL AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *October 26, 1937.*

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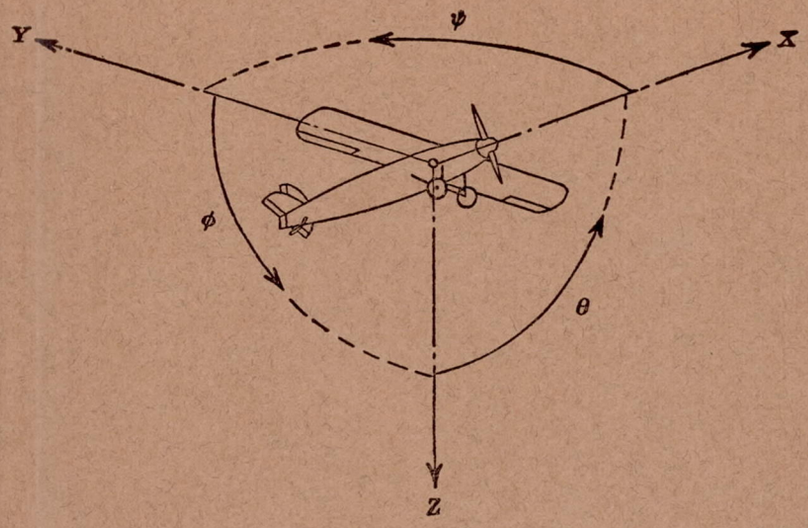

Positive directions of axes and angles (forces and moments) are shown by arrows

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

$C_l = \frac{L}{qbS}$ (rolling) $\quad C_m = \frac{M}{qcS}$ (pitching) $\quad C_n = \frac{N}{qbS}$ (yawing)

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

4. PROPELLER SYMBOLS

D, Diameter

p, Geometric pitch

p/D, Pitch ratio

V', Inflow velocity

V_s, Slipstream velocity

T, Thrust, absolute coefficient $C_T = \frac{T}{\rho n^2 D^4}$

Q, Torque, absolute coefficient $C_Q = \frac{Q}{\rho n^2 D^5}$

P, Power, absolute coefficient $C_P = \frac{P}{\rho n^3 D^5}$

C_s, Speed-power coefficient $= \sqrt[5]{\frac{\rho V^5}{P n^2}}$

η, Efficiency

n, Revolutions per second, r.p.s.

Φ, Effective helix angle $= \tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp.=76.04 kg-m/s=550 ft-lb./sec.

1 metric horsepower=1.0132 hp.

1 m.p.h.=0.4470 m.p.s.

1 m.p.s.=2.2369 m.p.h.

1 lb.=0.4536 kg.

1 kg=2.2046 lb.

1 mi.=1,609.35 m=5,280 ft.

1 m=3.2808 ft.