NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 695

DETERMINATION OF GROUND EFFECT FROM TESTS OF A GLIDER IN TOWED FLIGHT

By J. W. WETMORE and L. I. TURNER, Jr.

1940

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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 meters per second	k.p.h. m.p.s.	miles per hour feet per second	m.p.h. f.p.s.

2. GENERAL SYMBOLS

W, Weight $=mg$

g, Standard acceleration of gravity $=9.80665$ m/s² 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 J. W. WETMORE and L. I. TURNER, Jr.
Langley Memorial Aeronautical Laboratory

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By J. W. Wetmore and L. I. Turner, Jr.

SUMMARY

An investigation was made to find the effect of the ground on the aerodynamic characteristics of a Franklin PS–2 glider. The lift, the drag, and the angle of attack of the glider in towed flight were determined at several heights from 0.14 to 1.19 span lengths and at various speeds for each height. Two wing arrangements were tested: the plain wing, and the wing with a nearly full-span 30-percent-chord split flap deflected 45°.

For both wing arrangements, the results showed a decrease in the drag coefficient and the angle of attack for a given lift coefficient when the wing was affected by the ground; for the flapped wing, which was the only one tested at two different heights near the ground (0.14 and 0.33 span length), the reduction in drag was greater at the smaller height but the change in angle of attack was approximately the same at both heights.

The experimental results for the plain wing were in good agreement with theoretical values calculated by the method of Wieselsberger for both the angle of attack and the drag coefficient at a height of 0.21 span length; Tani's refinements of the theory had a practically negligible effect on the computed values in this case. For the flapped wing, the ground effect on the drag coefficient as calculated by the extended treatment of Tani was in better agreement with experiment, in general, than the predictions by Wieselsberger's method. With regard to ground effect on the angle of attack of the wing with split flap, the results did not indicate either treatment as definitely preferable although it appeared that, in this case, Wieselsberger's method probably agreed better with experiment.

INTRODUCTION

The fact that the close approach of an airplane to the ground is accompanied by substantial changes in its aerodynamic characteristics has been known for some time; and a considerable amount of research, both theoretical and experimental, has been directed toward the explanation and evaluation of these effects, which may be of importance in take-off and landing. Most of the experimental work has been conducted on small-scale models in wind tunnels (references 1 to 8), where the presence of the ground was usually simulated by a so-called ground board or by an image model. The results of such tests are subject to some question regarding jet-boundary effects, validity of ground simulation, and scale effect. Only a comparatively few flight investigations have been made, owing, perhaps, to the difficulty and the hazard associated with powered flight close to the ground. These tests (references 2, 7, 9, 10, and 11) were rather limited in scope and the results include uncertainties due to the effects of the propeller.

In the present investigation, the use of a glider towed by an automobile permitted the determination of ground effect in flight at Reynolds Numbers between 1,400,000 and 2,530,000 without the uncertainties introduced by a propeller, thereby eliminating the chief sources of doubt associated with previous investigations. A series of tests was made with each of two wing arrangements, the plain wing and the wing with a split flap. The tests included variations in height above the ground and variations in speed, or angle of attack. During the runs, suitable instruments were used to take records from which the lift and the drag coefficients and the angles of attack could be evaluated.

Ground effect on the aerodynamic characteristics as determined from the tests is compared in the report with the effect calculated in accordance with theory.

APPARATUS

The glider and the tow car used in the tests are shown in figure 1. The glider is a Franklin PS–2 having an externally braced rectangular wing with rounded tips. Its principal dimensional characteristics are given in figure 2 and in the following table:

CHARACTERISTICS OF THE FRANKLIN PS-2 GLIDER

Wing	
Area (S)	175 sq ft
Span (b)	36 ft 5 in
Chord (c)	5 ft 0 in
Flap	
Span	32 ft 5 in. (0.89b)
Chord (c_f)	18.5 in. (0.308c)
Deflection	45°
Weight	
Gross weight without flap	580–591 lb
Gross weight with flap	708–739 lb

For some of the tests, a 30-percent-chord split flap was affixed to the wing at an angle of 45° to the chord (fig. 3). The flap was nearly full span, extending from the rather narrow fuselage to the rounded section of the wing tips. The gaps between the flap and the could fly approximately at a prescribed altitude by alining himself with the two targets. The towline used between the car and the glider was 500 feet long. It could be released quickly from either the glider or the tow car.

FIGURE 1.—Franklin PS-2 glider and tow car.

wing and between the flap and the fuselage were sealed.

The tow car has a standard light chassis with a specially faired body designed to minimize the disturbance of air in its wake and thus avoid interference with

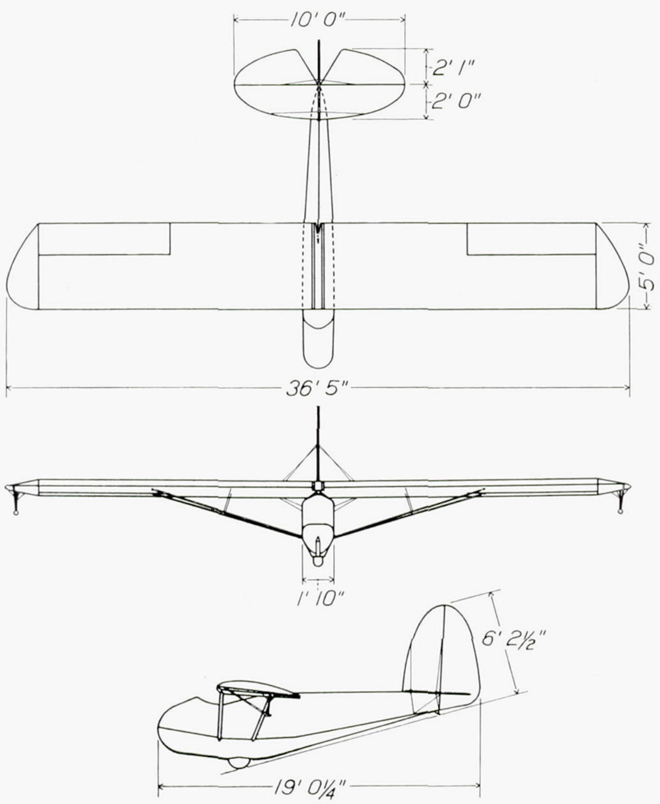


FIGURE 2.—Franklin PS-2 glider.

the glider. (See fig. 1.) A mast supporting a target or sight was mounted at each end of the car. The rear target could be raised or lowered so that, when it had been adjusted to the proper position, the glider pilot

The following standard N. A. C. A. recording instruments were mounted in the glider:

An air-speed recorder, which was connected to a swiveling air-speed head located one chord length forward of the leading edge of the wing and slightly below the plane of the chord.

A recording accelerometer, located near the center of gravity of the glider, which provided a measure of its Z acceleration due to the normal, or Z, component of the resultant of the external forces, other than the weight, acting on the glider.

A pendulum inclinometer, which recorded the direction of this resultant.

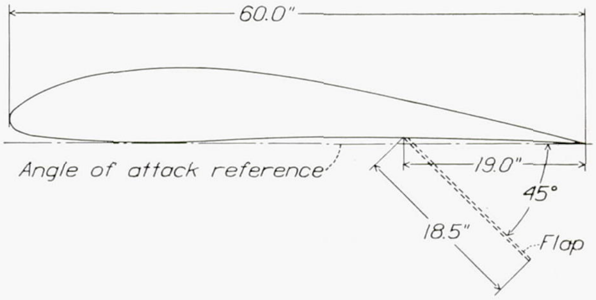


FIGURE 3.—Section sketch of wing, showing split-flap arrangement. Franklin PS-2 glider.

In addition to these standard instruments, two special instruments were designed for the tests: a recording dynamometer and a recording photoinclinometer. The dynamometer was mounted in the nose of the glider and the towline was directly attached to a quick-release coupling in the instrument. This instrument recorded the magnitude and direction of the force exerted on the glider by the towline. The recording photoinclinometer was essentially a camera designed to take a continuous photograph of the forward horizon on a moving film. The photograph was taken through a slot so placed that the field of the camera was limited to a narrow vertical element. The instrument was mounted above the wing with its optical axis lying in the plane of symmetry and making a suitable angle with the X-axis of the glider. The position of the horizon image on the film was a measure of the attitude angle of the longitudinal axis of the glider.

Half-second periods of time were indicated on all the instrument records by a standard N. A. C. A. timer in the glider. Another timer was used in conjunction with an N. A. C. A. recording phototheodolite, which measured the height of the glider and its position along the towing course.

Correlation of the time scales of the glider instrument records and the phototheodolite record was accomplished by means of a synchronizing device mounted on the glider. This device discharged a cloud of smoke when the glider instruments were started; the appearance of the smoke in the phototheodolite photographs thus afforded a means of synchronizing the records.

During the tests, the wind speed near the ground was measured by an indicating vane-type anemometer.

TESTS

The towing tests were made on a concrete runway about one-half mile long. Approximately a third of the available distance was used in accelerating to the desired speed, attaining the prescribed height with the glider, and then establishing as nearly steady conditions as possible before taking records. During the second third of the run, the phototheodolite and the glider instruments were switched on for a period of 6 to 8 seconds. The rest of the course provided space in which to land the glider and bring it to a stop. Tests were made only when the wind was less than 5 miles per hour and parallel to the course in order to avoid, as far as possible, discrepancies due to vertical currents and yawing of the glider. This precaution also permitted making test runs in both directions.

With the plain wing, two groups of tests at different heights were made, each covering a range of speeds from 36 to 54 miles per hour. For one of these groups, the average height of the wing above the ground was $0.21b$ and for the other, $1.17b$. Three series of tests at different heights were made with the split flap. The speeds ranged from 30 to 38 miles per hour and the average heights were $0.14b$, $0.33b$, and $1.19b$.

The towing tests were originally expected to show the effect of the ground on the maximum lift as well as on the aerodynamic characteristics in the unstalled-flight range. It was found impossible, however, to obtain steady conditions in towed flight near maximum lift because the longitudinal control was insufficient to overcome the nose-down pitching moment of the towing force, which became relatively large at the higher angles of attack. Special tests made to investigate maximum lift consisted in determining the lift coefficient in actual landings and in simulated landings at a considerable altitude to which the glider was towed with an airplane. Before each of these maneuvers, the glider was released from the towline so that the difficulty due to the moment of the towing force was avoided. The simulated landings at altitude were made only with the plain wing because it was considered inadvisable to attempt an airplane tow with the split flap installed.

REDUCTION OF DATA

Inasmuch as the duration of the instrument records obtained in different runs varied appreciably, the records of the glider instruments were divided into sections, each covering 2 seconds of time in order that the final values computed from the data might all be of equal weight. Mean values of the quantities measured by the various instruments were then determined for each 2-second period.

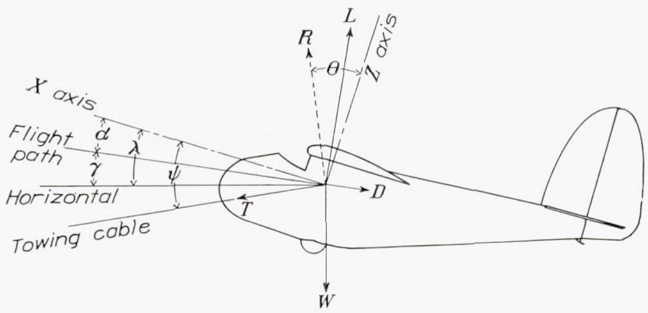


FIGURE 4.—Forces on glider in towed flight.

The forces acting on the glider in towed flight are shown in figure 4. The symbols used in reducing the data are as follows:

- W gross weight.
- L lift.
- D drag.
- T towing force measured by dynamometer.
- R resultant of L, D, and T.
- R_Z component of R along normal, or Z, axis of glider.
- A_Z ratio R_Z/W measured by accelerometer.
- θ angle of R relative to Z-axis measured by pendulum inclinometer.
- ψ angle of T relative to X-axis measured by dynamometer.
- λ attitude angle of X-axis relative to horizontal measured by photoinclinometer.
- γ flight-path angle.
- α angle of attack.
- V air speed along flight path.
- V_v vertical velocity.
- h height of quarter-chord point of wing above ground.
- ρ density of air.
- S wing area.
- C_L lift coefficient.
- C_D drag coefficient.

The X-axis and the Z-axis of the glider were defined as parallel and normal, respectively, to the angle-of-attack reference shown in figure 3, which was a line tangent to the lower surface of the wing at two points.

Values of lift, drag, and angle of attack were derived from the instrument data for each 2-second interval in accordance with the following procedure:

The value of the resultant of L, D, and T was obtained from the relations

$$R_Z = WA_Z$$

and

$$R = \frac{R_Z}{\cos \theta}$$

The flight-path angle was given by the expression

$$\gamma = \sin^{-1}\frac{V_v}{V}$$

where V_v was found by differentiation of the curve of height against time obtained from the phototheodolite record. The angle of attack was then determined from

$$\alpha = \lambda - \gamma$$

This procedure does not take account of vertical wind currents but, since the wind was very light, its effect was probably small and, in any case, was not a source of consistent error.

Values of lift and drag were obtained by resolution of the forces R and T into components normal and parallel to the flight path; i. e., in the lift and the drag directions, or

$$L = R \cos (\theta - \alpha) + T \sin (\psi - \alpha)$$

and

$$D = T \cos (\psi - \alpha) - R \sin (\theta - \alpha)$$

The lift and the drag coefficients were found from the usual relations

$$C_L = \frac{L}{\frac{\rho}{2}SV^2}$$

and

$$C_D = \frac{D}{\frac{\rho}{2}SV^2}$$

RESULTS

The experimental values of lift and drag coefficients and angles of attack for all the test conditions are plotted in figures 5 to 9. Figures 5 and 6 present the results obtained with the plain wing at heights of 1.17*b* and 0.21*b*, respectively. Figures 7, 8, and 9 show the results with the split flap at heights of 1.19*b*, 0.33*b*, and 0.14*b*, respectively.

The faired curves for various conditions, defined by the experimental points of the foregoing figures, are plotted together for comparison in figures 10 and 11. Figure 10 shows the effect of variation in height on the aerodynamic characteristics of the plain wing, and figure 11 gives corresponding results for the split flap. In addition to the experimental values, these figures include the results of theoretical calculations of the effect of the ground. The calculations were based on the experimental values at the greatest height for each wing arrangement (about 1.2*b*, at which the effect of the ground is practically negligible) and were made in accordance with both the basic method of Wieselsberger (reference 3) and the more extended treatment of Tani and coworkers (references 4 and 5), which gives consideration to several additional effects not taken into account by Wieselsberger.

PRECISION

The precision of the final results of the tests is indicated to some extent by the dispersion of the experimental points in figures 5 to 9. It is evident that the dispersion of points for the split-flap condition (figs. 7, 8, and 9) is considerably greater than for the plain-wing condition (figs. 5 and 6); and, consequently, the fairing of the data for the split flap was less certain. This difference is probably the result, in part, of considerable unsteadiness in flight, apparently due to a reduction in longitudinal stability of the glider caused by the split flap.

The probable deviation of the results, as defined by the faired curves, is estimated to be as follows:

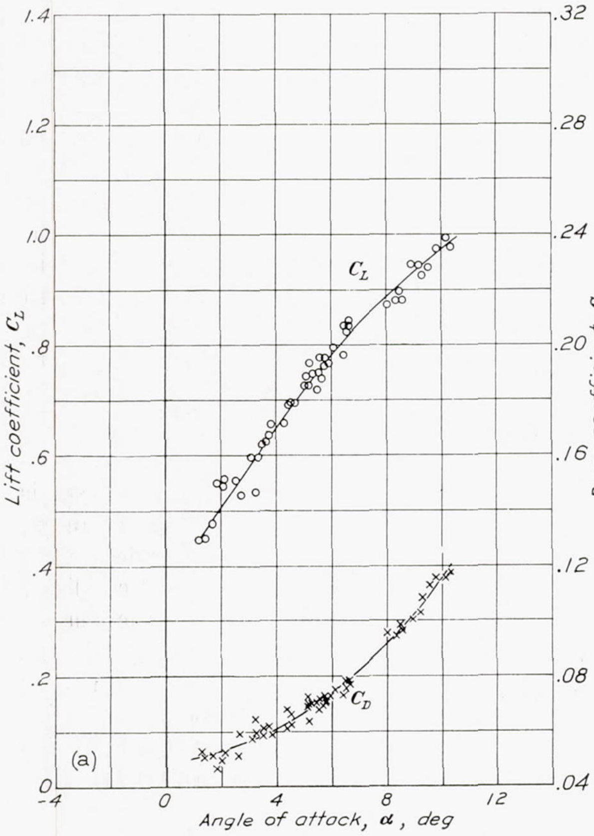
With the plain wing:	With the split flap:
$C_L, \pm 0.01$	$C_L, \pm 0.02$
$C_D, \pm 0.001$	$C_D, \pm 0.004$
$\alpha, \pm 0.1°$	$\alpha, \pm 0.2°$

These estimates for the split flap should be considered as applying only up to a lift coefficient of 1.5. Slightly above this value there is a sharp break in the lift curve, beyond which the precision is uncertain.

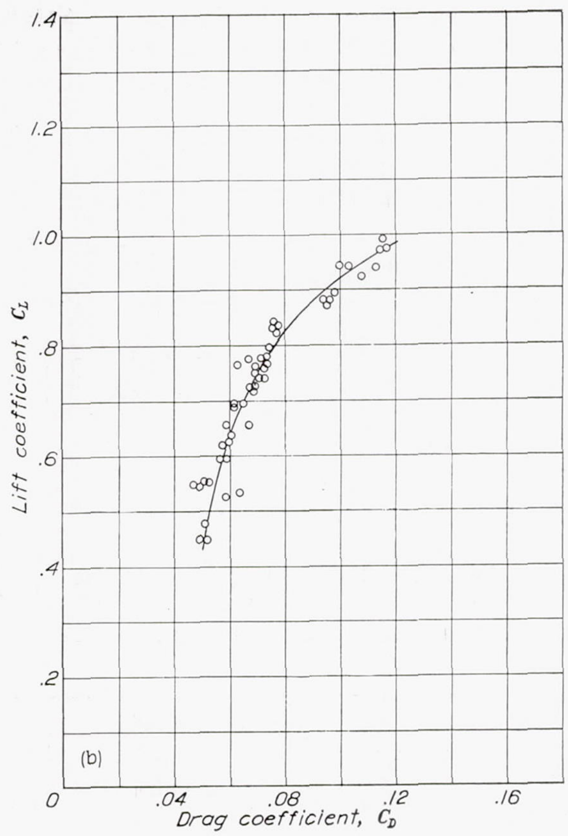
DISCUSSION

The results of the tests with the plain wing, as summarized in figure 10, show that at a given lift coefficient both the angle of attack and the drag coefficient of the glider were appreciably reduced throughout the range of lift coefficients tested (0.45 to 1.0) when the height of the wing was decreased from 1.17*b* to 0.21*b*; the differences increased with increasing lift coefficient.

With the split flap, the range of lift coefficients covered in the tests was considerably higher than with the plain wing, as shown in figures 10 and 11. As previously explained, the reliability of the results at lift coefficients above 1.5 is very uncertain; hence, such results will not be considered in this discussion. Below this value of lift coefficient, the angle of attack and the drag coefficient for a given lift coefficient were decreased when the wing was near the ground, as in the case of the plain wing, but the reduction was considerably greater.

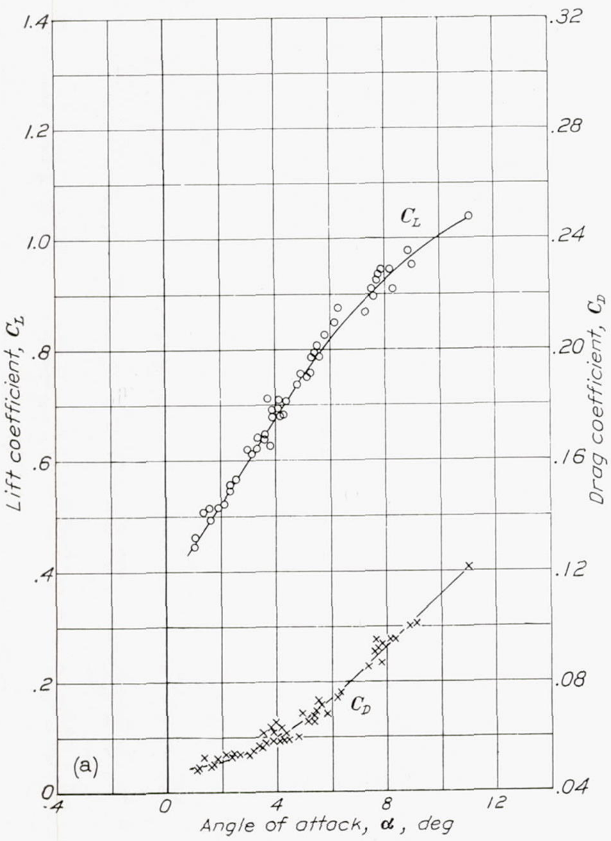


(a) Variation with angle of attack.

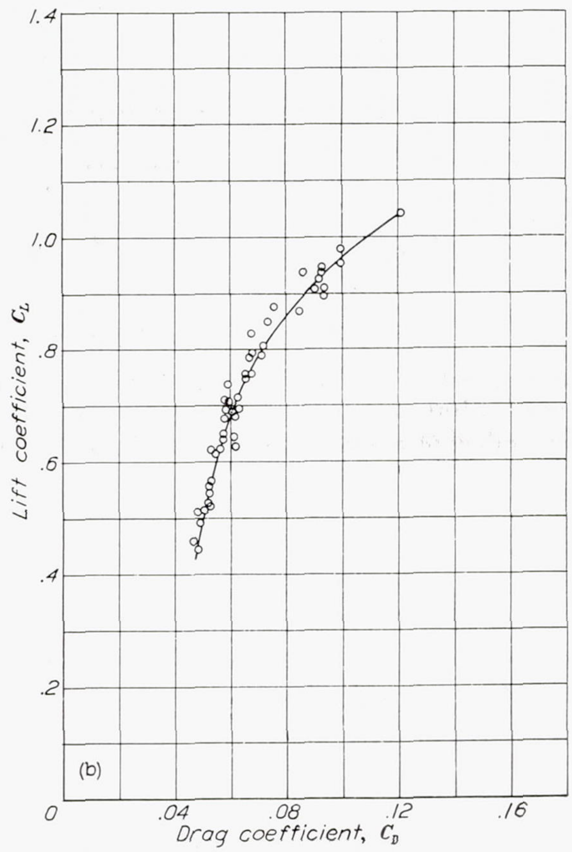


(b) Polar diagram.

FIGURE 5.—Lift and drag characteristics; plain wing; h/b=1.17. Franklin PS-2 glider.



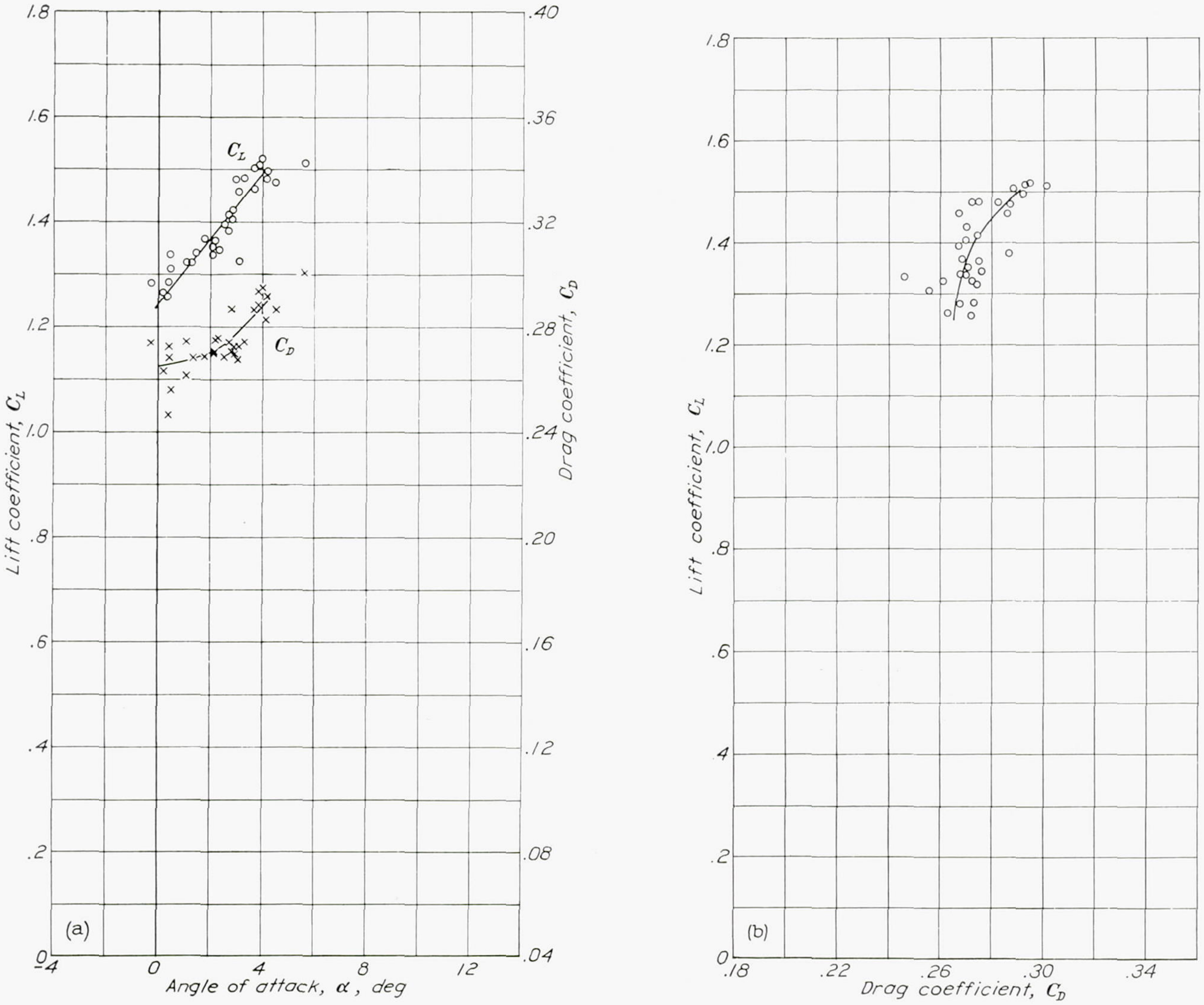
(a) Variation with angle of attack.



(b) Polar diagram.

FIGURE 6.—Lift and drag characteristics; plain wing; h/b=0.21. Franklin PS-2 glider.

The theoretical treatment of Wieselsberger (reference 3) has for some time been generally accepted as a fairly satisfactory explanation of the influence of the ground and as a means of calculating its effect with reasonable accuracy. More recently the theory has been extended by the method of references 4 and 5 to include factors that were not considered by Wieselsberger. A brief résumé of these treatments of ground effect may be of interest here in connection with the experimental results. Ground-effect theory is a particular case of multiplane theory; the actual system composed of the airfoil and the ground is assumed to be replaced by a



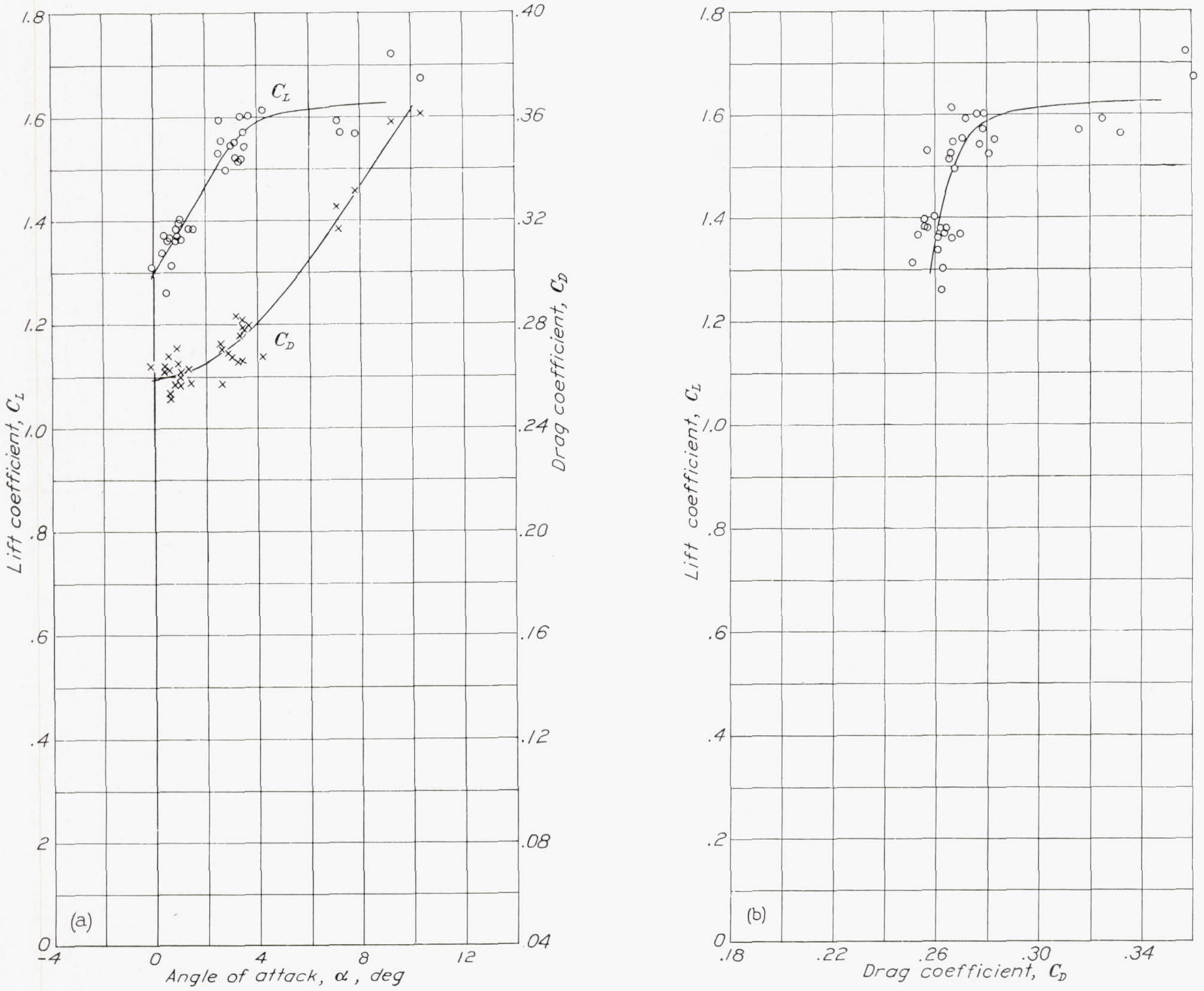
(a) Variation with angle of attack.

(b) Polar diagram.

FIGURE 7.—Lift and drag characteristics; split flap deflected 45°; h/b=1.19. Franklin PS-2 glider.

hypothetical biplane cellule consisting of the real wing and its image reflected in the ground plane. The problem then becomes that of a biplane in free air with equal spans, equal chords, zero stagger, and a gap twice the distance of the real wing from the ground. The lifts of the wings are of equal magnitude and opposite sign.

The change in the aerodynamic characteristics of the real wing in the presence of the ground may then be considered to be the result of: (1) reduction of the induced vertical velocity at the real wing due to the trailing vortices of the image wing; (2) reduction of the longitudinal velocity at the real wing due to the

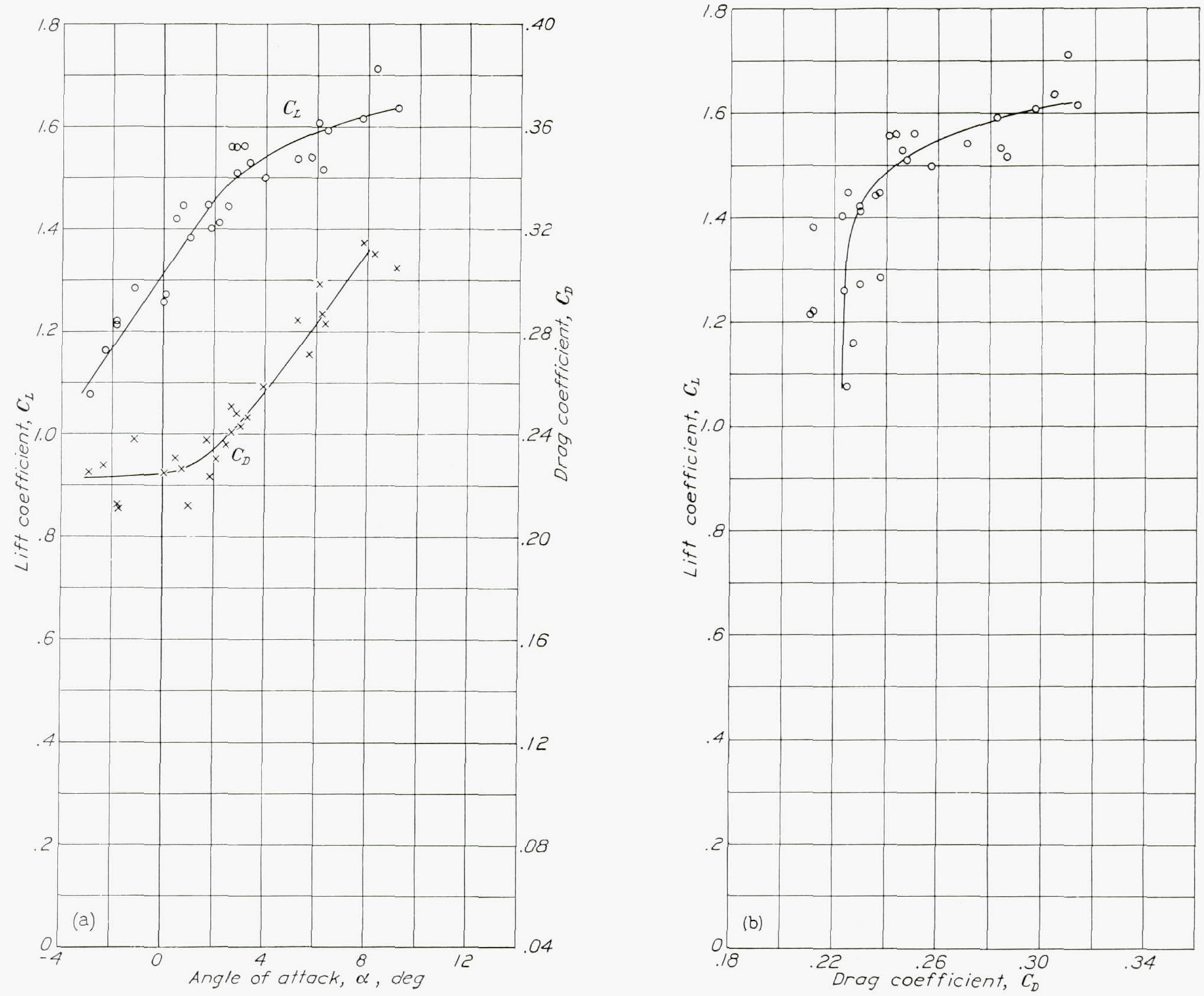


(a) Variation with angle of attack.

(b) Polar diagram.

FIGURE 8.—Lift and drag characteristics; split flap deflected 45°; h/b=0.33. Franklin PS-2 glider.

circulation about the image wing; (3) change of circulation about the real wing due to the bound vortices of the image wing; and (4) change in the flow pattern due to the finite thickness of the wing. Wieselsberger's method considers only (1). The extended treatment of references 4 and 5 approximates, in addition, (2), (3), and (4) in the case of α, and (2) in the case of C_D. The results of the investigation, as subsequently discussed, indicate that the refinements had a practically negligible effect on both α and C_D for the plain wing and that, for the flapped wing, the use of these refinements produced a less good agreement between theory



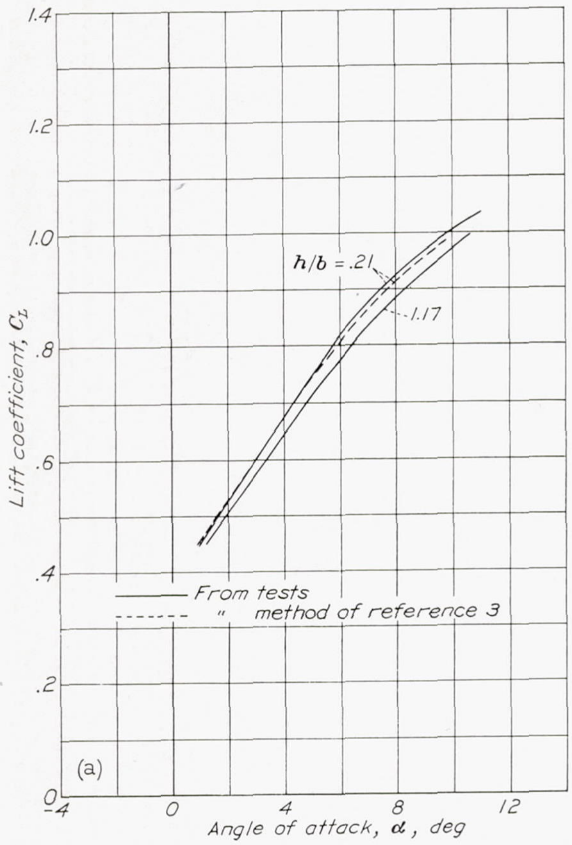
(a) Variation with angle of attack.

(b) Polar diagram.

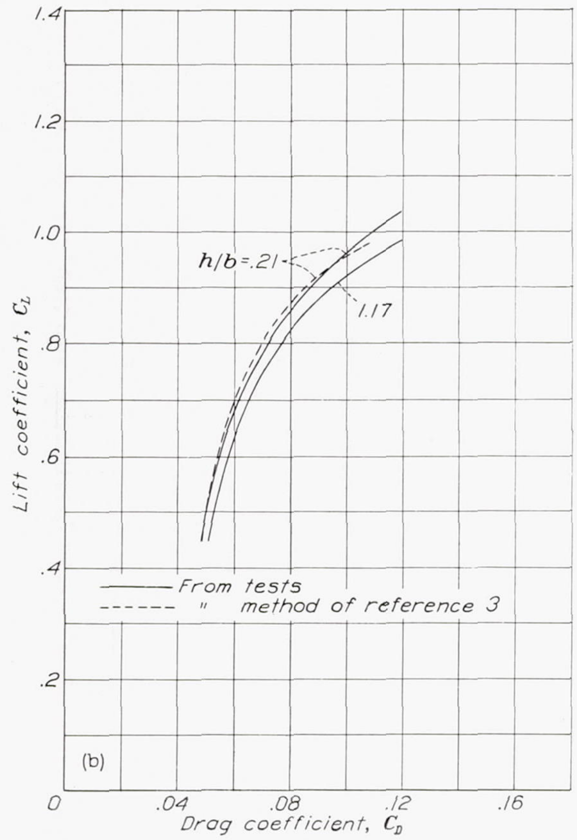
FIGURE 9.—Lift and drag characteristics; split flap deflected 45°; h/b=0.14. Franklin PS-2 glider.

and experiment in the case of α than Wieselsberger's method alone. For small heights and high drags (as with flaps), however, the effect of (2) on the drag appears to be of importance and should be considered. The theory is further discussed in the appendix and the formulas developed in references 3, 4, and 5 for the prediction of ground effect are presented therein.

Calculations of the influence of the ground on the angle of attack and the drag coefficient of the glider are compared with the test results in figures 10 and 11. For the plain wing (fig. 10), both the reduction in angle of attack and the reduction in drag coefficient at a constant lift coefficient when the height is decreased from 1.17*b* to 0.21*b*, as computed from Wieselsberger's method, agree very well with the measured values. In this case the additional factors considered in references 4 and 5 were found to have so nearly negligible an effect that the results obtained with the two methods were practically identical. For this reason, only the values computed by Wieselsberger's method are shown in the figure.



(a) Effect on angle of attack.

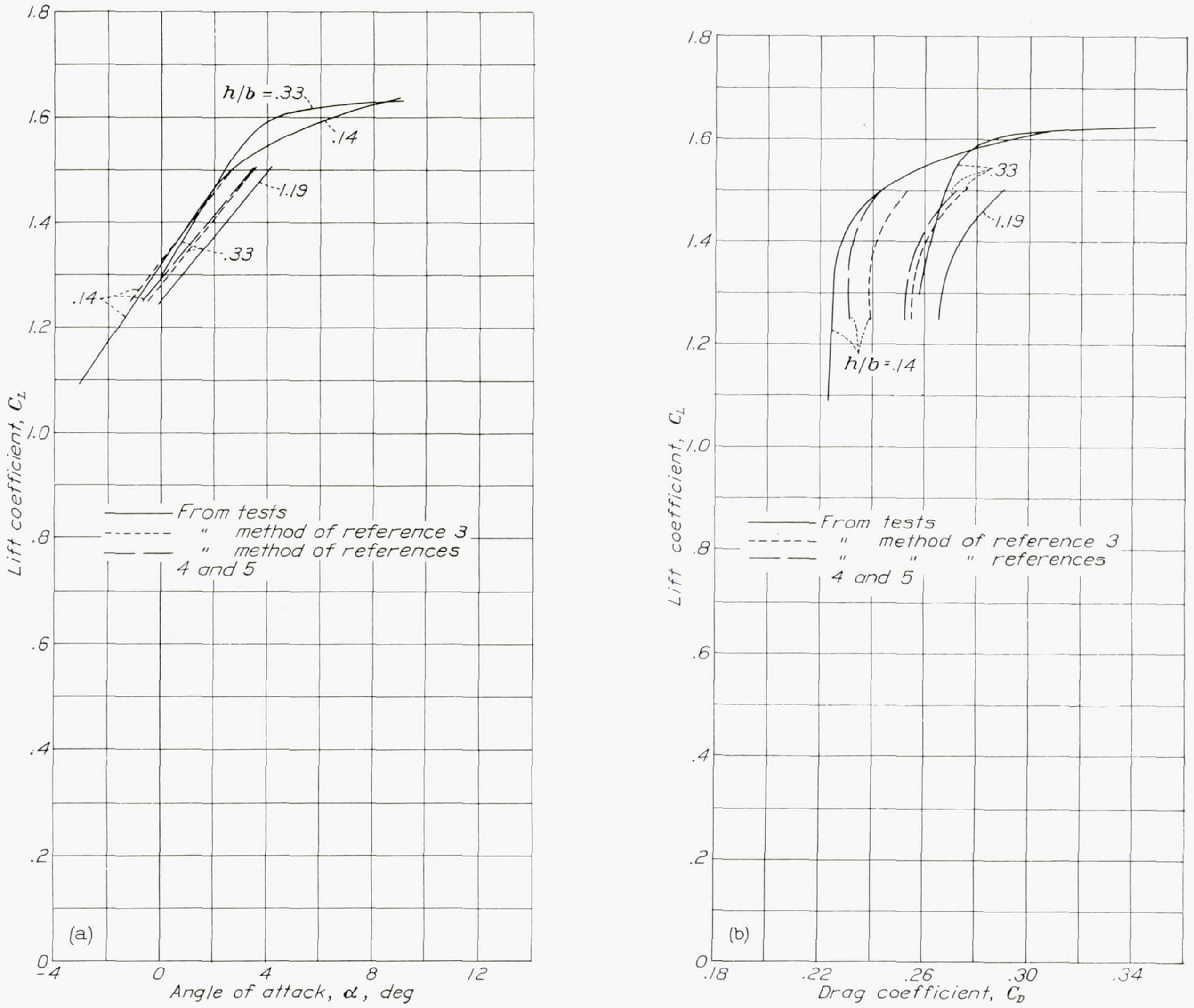


(b) Effect on drag coefficient.

FIGURE 10.—Ground effect on aerodynamic characteristics of Franklin PS–2 glider; plain wing.

With the split flap, calculations by Wieselsberger's method give reasonably good agreement with the test results as regards the reduction in angle of attack (fig. 11 (a)) for the smallest height investigated (0.14*b* or one chord length). The method of references 4 and 5, on the other hand, indicates a reduction only half as great as the measured value. A similar discrepancy exists in the results presented in reference 5, which likewise show that, at the higher lift coefficients obtained with split flaps, the ground effect on angle of attack as predicted by the method of references 4 and 5 was considerably less than the measured value. An application of Wieselsberger's method will be found to give better agreement in this case also.

The test results for the intermediate height (0.33*b*) with the split flap show approximately the same reduction in angle of attack as for the lowest height. The calculated effect, according to Wieselsberger's method, is approximately half as great. No comparison with the method of references 4 and 5 at this height is made in figure 11 (a); reference 4 does not include values of one of the parameters necessary for theoretical calculation of the effect on angle of attack at this height-chord ratio. It appears very unlikely, however, that the parameter would have any appreciable influence at this height-chord ratio. If it is neglected, the method of references 4 and 5 predicts a reduction in angle of attack slightly less than Wieselsberger's, making the discrepancy between the experimental and the calculated curves somewhat larger.



(a) Effect on angle of attack. (b) Effect on drag coefficient.

FIGURE 11.—Ground effect on aerodynamic characteristics of Franklin PS-2 glider; split flap deflected 45°.

Theoretical and experimental values of the drag coefficient with the split flap are compared in figure 11 (b). At the lowest height, Wieselsberger's method accounts for only about two-thirds of the experimental reduction in drag; whereas, the method of references 4 and 5 gives a considerably closer approach to the test results. For the intermediate height, there is little difference in the reductions of drag calculated by the two methods; both predict a slightly greater effect than is shown by the test results.

It should be pointed out in connection with the foregoing comparisons that strict reliance on the experimental results may not be justified. As has been discussed under Precision, the final results are subject to a possible plus or minus error. It is therefore possible that, in a comparison of two test conditions, the errors in the two sets of results may in some cases be cumulative. This possibility may partly explain some of the discrepancies noted in comparing the calculated and the experimental ground effects.

Ground effect on the tail plane was not taken into account in performing the theoretical calculations. It appears likely, however, that this effect would be too small to have an appreciable influence on the results.

The average maximum lift coefficients for the plain wing determined during actual landings, in which the wing was about one chord length or 0.14*b* from the ground, and during simulated landings at an altitude well beyond the influence of the ground were 1.55 and 1.35, respectively. These results indicate that ground effect increased the maximum lift about 15 percent. The absolute values given are probably somewhat higher than would be obtained in steady flight owing to the fact that the angle of attack was increasing at the time the measurements were made. The difference between the two values is believed to be fairly representative because each is the average of several tests.

With the split flap, values of the maximum lift coefficient ranging from 1.55 to 1.80 were obtained in the actual landings. Simulated landings at altitude could not be made in this case so that corresponding data for free-air conditions are not available. The values obtained with the wing close to the ground are somewhat lower than would normally be expected in free air, judging from previous tests with split flaps. For example, in the full-scale tests described in reference 12, values of $C_{L_{max}}$ as high as 2.0 were obtained with full-span split flaps of only 20-percent chord. It therefore seems unlikely that the proximity of the ground caused any material gain in maximum lift with the split flap, and quite possibly there may have been a reduction.

Existing theory being inapplicable at angles of attack near the stall, theoretical prediction of ground effect on maximum lift is impossible.

CONCLUSIONS

1. The results of the tests showed that, within the range of angles of attack investigated, the drag coefficient and the angle of attack for a given lift coefficient were reduced when the wing was influenced by the ground; for the flapped wing, the reduction in drag coefficient became larger as the wing approached the ground more closely, but the change in angle of attack was approximately the same for heights of 14 and 33 percent of the span.

2. Calculation by Wieselsberger's method of ground effect on the drag coefficient and the angle of attack of the plain wing at a height of 21 percent of the span gave satisfactory agreement with the experimental results. The effect of Tani's refinements was practically negligible in this case.

3. For the wing with split flap, ground effect on the drag coefficient as calculated by the more extended treatment appeared, in general, to be in better agreement with experiment than the predictions of Wieselsberger's method. As regards the effect on angle of attack, the results did not show either method to be definitely preferable, although there was some indication that Wieselsberger's method might approach the experimental values more closely than the refined method.

4. Ground effect at a height of 14 percent of the span, or one chord length, was found to increase the maximum lift of the plain wing about 15 percent.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *April 8, 1940.*

APPENDIX

GROUND-EFFECT THEORY

In the development of the theory, the method of reference 3 and that of references 4 and 5 both employ the hypothesis that the effects of the ground on a wing are the same as the effects which would be induced by the flow about an identical image wing symmetrically disposed with respect to the real wing on the opposite side of the ground plane. Wieselsberger takes account only of the effect of the trailing vortices of the image wing in reducing the induced vertical velocity at the real wing. The resulting changes in angle of attack and drag coefficient at a constant lift coefficient are expressed by the equations

$$\Delta\alpha = -57.3\,\frac{C_L}{\pi A}\,\sigma \quad \text{(deg)}$$

and

$$\Delta C_D = -\frac{C_L^2}{\pi A}\,\sigma$$

where A is the aspect ratio and σ is Prandtl's interference coefficient from multiplane theory. This factor is given closely enough by the expression

$$\sigma = e^{-2.48(2h/b)^{0.768}}$$

which was derived from the information presented graphically in reference 13. Such changes are equivalent to those produced by a change in aspect ratio. The effective aspect ratio, when the wing is influenced by the ground, is expressed by

$$A_G = \frac{A}{1-\sigma}$$

where A_G is the effective value near the ground.

In addition to the effect of the trailing vortices, the method of references 4 and 5 considers also the effects of the bound vortices of the image wing on the circulation and the longitudinal velocity at the real wing and takes account of wing thickness. The influence of these factors on the angle of attack and the drag coefficient at a constant lift coefficient is approximated by the equations

$$\Delta\alpha = -57.3\,\frac{C_L}{\pi A}\,\sigma + rTC_L^2 - rB + Ke \quad \text{(deg)}$$

and

$$\Delta C_D = -\frac{C_L^2}{\pi A}\,\sigma - \left(C_{D_a} - \frac{C_L^2}{\pi A}\,\sigma\right)\frac{m}{57.3}\,rTC_L$$

where

- σ represents the reduction in induced vertical velocity, as before.
- T takes account of the reduction in longitudinal velocity for wings of infinite span.
- B is the effective change in angle of attack due to the change in circulation, likewise for infinite span.
- r is the appropriate factor for reducing B and T to the condition of finite span.
- Ke is the effect of wing thickness, e being the ratio of maximum thickness to chord.
- C_{D_a} is the wing drag coefficient corresponding to the given lift coefficient under free-air conditions.
- m is the slope of the lift curve, $\frac{dC_L}{d\alpha}$, (α in radians) for infinite span. (This quantity is taken as $2\pi \times 7/8$ in reference 4.)

The coefficient T is obtained from the equation

$$T = \frac{57.3}{8\pi m} \times \frac{\frac{h}{c}}{\left(\frac{h}{c}\right)^2 + \frac{1}{64}}$$

where h is the height of the quarter-chord point above the ground and c is the chord of the wing.

Instead of reproducing the rather extensive system of equations involved in computing B, values of this parameter have been taken from reference 4 and plotted in figure 12 for height-chord ratios below 1.2.

The factor r is given by the relation

$$r = \sqrt{1 + \left(\frac{2h}{b}\right)^2} - \frac{2h}{b}$$

The quantity K is expressed by

$$K=57.3(0.00300)\left(\frac{h}{c}\right)\left\{\frac{1}{\left[\left(\frac{h}{c}\right)^2+\frac{1}{64}\right]^2}+\frac{3}{\left[\left(\frac{h}{c}\right)^2+\frac{9}{64}\right]^2}\right\}$$

For moderate lift and drag coefficients such as are obtained with a plain wing and for ordinary conditions where an airplane wing is seldom much less than one chord length from the ground, the effects of the bound vortices of the image wing on the angle of attack and the drag coefficient of the real wing will be small in comparison with the effect of the trailing vortices; in the rather unusual case of a wing very close to the ground, as in a landing with wheels retracted, the influence of the bound vortices would probably assume considerable magnitude.

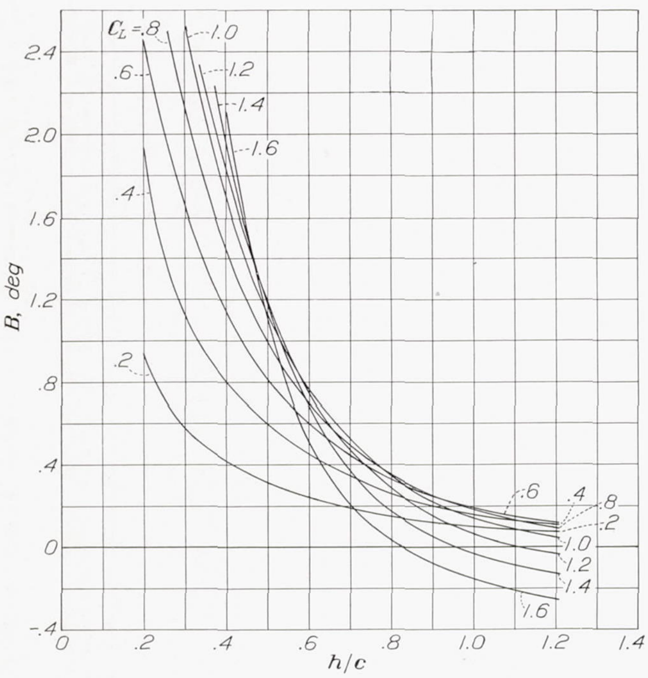


FIGURE 12.—The parameter B used in calculation of ground effect by the method of references 4 and 5. (Reproduced from reference 4.)

With the lift and the drag of the wing considerably augmented, as with split flaps, the reduction in longitudinal velocity may have a substantial effect on the angle of attack and the drag coefficient even at heights above one chord length; the effect of the change in circulation at such heights would probably still be relatively small (fig. 12).

The effect of wing thickness will ordinarily be inappreciable except when the height of the wing is only a small fraction of the wing chord.

As pointed out in reference 4, the necessity of making various approximations in the development of the method probably limits its applicability to cases in which $C_L < 0.8 C_{L_{max}}$ and $h > 0.3c$.

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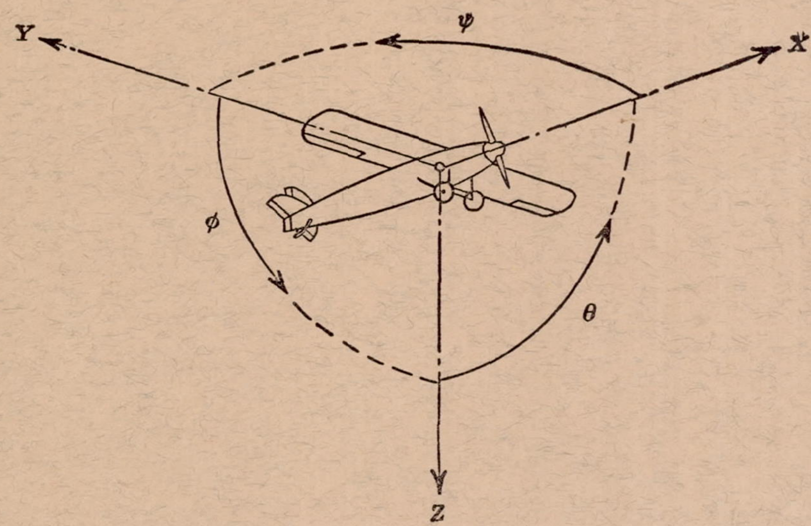

Positive directions of axes and angles (forces and moments) are shown by arrows

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) $C_m=\frac{M}{qcS}$ (pitching) $C_n=\frac{N}{qbS}$ (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.