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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 265

A FULL-SCALE INVESTIGATION OF GROUND EFFECT

By ELLIOTT G. REID

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PRICES SUBJECT TO CHANGE

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		km/hr		mi./hr	M. P. H.
		m/sec		ft./sec	f. p. s.

2. GENERAL SYMBOLS, ETC.

W, Weight, $=mg$

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

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

ρ, Density (mass per unit volume).

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

Specific weight of "standard" air, 1.2255 kg/m$^3=0.07651$ lb./ft.^{3}

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

S, Area.

S_w, Wing area, etc.

G, Gap.

b, Span.

c, Chord length.

b/c, Aspect ratio.

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

μ, Coefficient of viscosity.

3. AERODYNAMICAL SYMBOLS

V, True air speed.

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

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

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

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

R, Resultant force. (Note that these coefficients are twice as large as the old coefficients L_C, D_C.)

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

i_t, Angle of stabilizer setting with reference to to thrust line.

γ, Dihedral angle.

$\rho\frac{Vl}{\mu}$, Reynolds Number, 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° C., 230,000;

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

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

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

α, Angle of attack.

ϵ, Angle of downwash.

REPORT No. 265

A FULL-SCALE INVESTIGATION OF GROUND EFFECT

By ELLIOTT G. REID
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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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REPORT No. 265

A FULL-SCALE INVESTIGATION OF GROUND EFFECT

By Elliott G. Reid

SUMMARY

This report describes flight tests which were made with a Vought VE-7 airplane to determine the effects of flying close to the ground.

It is found that the drag of an airplane is materially reduced upon approaching the ground and that the reduction may be satisfactorily calculated according to theoretical formulas.

Several aspects of ground effect which have had much discussion are explained.

INTRODUCTION

It is a well-known fact that the aerodynamic characteristics of an airplane undergo marked changes near the surface of the earth. However, little has been definitely known concerning either the nature or the magnitude of these changes. Although model tests which appear to substantiate a certain well-founded theory of "ground effect" have been made, the theory has been neither well known nor generally accepted. The lack of general acceptance is probably explained by the fact that no full scale test results have been published and that the methods used in some of the model tests have been questioned on the ground of incomplete or incorrect simulation of the conditions of flight close to the ground.

The above-mentioned theory of ground influence on airfoil characteristics is developed in a paper by C. Wieselsberger (Reference 1); it is an extension of the Lanchester-Prandtl theory and in it are utilized the basic concepts of the induced drag of multiplanes (Reference 2). Wieselsberger presents monoplane model test results which agree very well with his theoretical calculations. The results of other model tests (References 3, 4, and 5), when plotted in polar form, closely resemble those of Reference 1.

The tests which form the subject of this report were made to determine the effects of proximity of the ground upon the aerodynamic characteristics of a full-scale airplane. The experimental results are compared with theoretical calculations.

METHOD OF TESTING

The tests consisted in determining the lift and drag characteristics of an airplane under two conditions: (1) At an altitude sufficient to avoid any possibility of ground influence, and (2) close to the ground.

A Vought VE-7 airplane was selected for the tests. The aerodynamic characteristics of this airplane had been previously determined by glide tests which are described in Reference 6 but, in order to make certain that the normal aerodynamic characteristics of the airplane had not changed, check tests were made at approximately 500 feet altitude. In these tests the R. P. M. of a propeller which had been tested as described in Reference 6 were determined in level flight at several speeds. These values were then compared with the ordinates of the R. P. M. versus air-speed curve obtained from the original propeller test results.

The other tests consisted in measuring the R. P. M. and air speed in level flights made very close to the ground (height of lower wing 5 to 9 feet). The lift and drag characteristics of the airplane were calculated from these data by use of the previously established propeller thrust coefficients. It is assumed that there is no ground effect upon the propeller characteristics as the production of thrust involves only horizontal acceleration of the air.

The details of the method of obtaining the R. P. M. versus air-speed values in level flight at some distance from the ground are given here because the process may be applied to other work in which the same problem exists. This method has the great advantage of eliminating the necessity of maintaining horizontal flight. Three or four runs were made at the same air speed but with different throttle settings. The gain or loss of altitude during 30 seconds and the engine revolutions for the same period were recorded by an observer who read the first from a

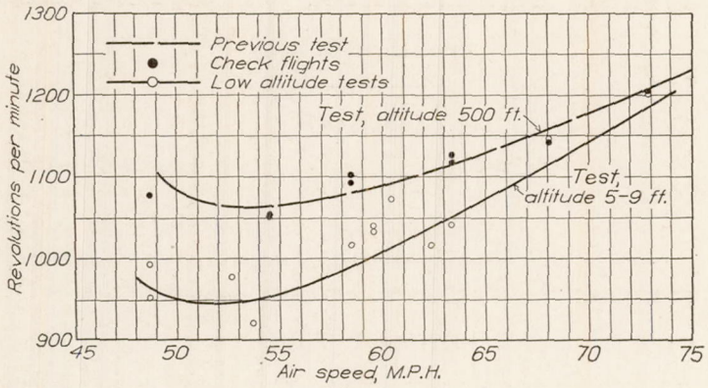


FIG. 1

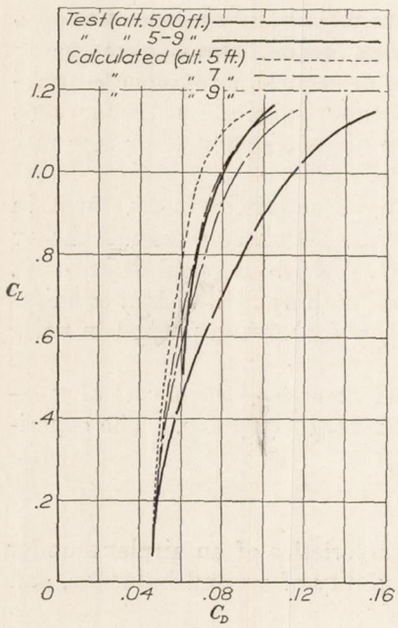


FIG. 2

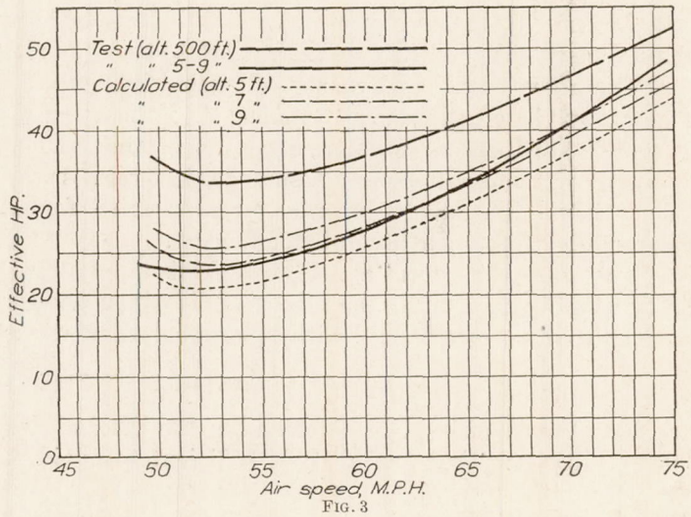


FIG. 3

very sensitive altimeter and the second from a direct-driven revolution counter. The R. P. M. for level flight was obtained from a plot of altitude change versus R. P. M.

RESULTS

The results of the tests are presented in Figures 1–3.

In Figure 1 will be seen the curve of R. P. M. versus air speed for 500 feet altitude which was obtained from the propeller test data, the corresponding check points, and the R. P. M. versus air-speed curve of the low-altitude tests.

The normal polar curve of the VE–7 airplane, as determined by the glide tests of Reference 6 and confirmed by the present experiments, is shown in Figure 2. In the same illustration are the polar which was derived from the low-altitude tests results and the polars which were

derived from the normal one by application of the theoretical formulas. The formulas are summarized in the appendix.

The curves of required thrust horsepower versus air speed, which constitute Figure 3, correspond to the polar curves of Figure 2.

DISCUSSION

It should be understood, before comparing the experimental and theoretical results, that the low-altitude curves are representative of flight at approximately 7 feet from the ground. Only the results of flights in which the height of the lower wing had been estimated by the observers to be between 5 and 9 feet (wheels 2 to 6 feet above the ground) are plotted in Figure 1. In this figure the curve is faired to represent an average of the data and, therefore, an average height of about 7 feet. The fairing at the higher speeds may be criticized on first inspection, but it is felt that this fairing is justifiable as the high-speed flights were made at consistently greater heights than the low-speed ones. This is only natural, as the danger connected with striking the ground increases with the air speed.

The ordinates of the curve for 500 feet altitude vary 5 R. P. M. or less, at speeds above 60 M. P. H., from those of the previously established curve. At the lower speeds the curve represents a mean between the previous and present results.

The agreement of the experimental and theoretical curves, both in absolute value and in shape, is so good at the low speeds that the apparent discrepancies at higher speeds are ascribed to experimental errors. This conclusion is substantiated by the fact that a careful comparison failed to reveal any measurable difference between the maximum speeds of the VE–7 at approximately 10 and 500 feet altitude. The experimental polar for low altitudes is thus shown to be practically coincident with the normal one at low lift coefficients. In view of the excellent correspondence over that range in which the experimental results are considered to be most accurate, and the previously demonstrated agreement of model test results with theory in the range not covered in the present tests, the conclusion that the theory is satisfactorily accurate appears well justified.

Several phases of ground effect can now be explained. The possibility of obtaining an increased maximum speed by flying very close to the ground has frequently been suggested. If the induced power is an appreciable portion of the total power required by an airplane at maximum speed, then an appreciable increase of maximum speed may be obtained by flying close to the ground. This will be the case only when the speed range of the airplane is comparatively small. The case of the VE–7 is treated in the appendix.

"Floating" during the landing glide is obviously caused by the increase of the lift-drag ratio which occurs upon approaching the ground. The tests show this ratio to be increased from 9 to 12.5 for the VE–7 airplane.

The reduction of the power required for level flight, as shown in Figure 3, may become of considerable importance. The climbing ability is affected to a large extent when the airplane is close to the ground, particularly if the available power is only slightly greater than the required power. Demonstrations of this condition are frequently seen. It has been noticed that light airplanes having large power loadings climb rapidly upon leaving the ground, but soon suffer a rapid reduction of climbing speed. A striking example was recently observed at Langley Field when a heavily-loaded seaplane was taken off and kept in the air, although at a low air speed, for about 10 miles, at the end of which distance some of the load had to be discharged because it had not been possible to gain enough altitude to allow a turn to be made safely.

Although both theory and experiment indicate a reduction of induced drag as the ground is approached, there seems to be a critical altitude, or combination of altitude and air speed, at which some radical change of air flow takes place. It was found that the VE–7, when flying very low, would sometimes drop to the ground without any warning such as a sudden change of angle or of air speed. Pilots report that this is a frequent occurrence in landing; an airplane will "float" for some distance, the air speed gradually decreasing, and then "pancake" for no

apparent reason. Discussions with several pilots have not made it clear whether this characteristic is common to all types of airplanes, or to only a few. It would be interesting to know whether the stall is more abrupt close to the ground than at altitude, and to what extent the tendency to "pancake" depends on design.

As the extent of the disturbance created by the wings of an airplane, i. e., the quantity of air given downward momentum in producing the lift, is directly connected with the induced drag, an alternative explanation of the cause of ground effect could be made if the extent of the disturbance could be determined at altitude and close to the ground. An attempt to obtain such information was made by photographing the pattern left in a smoke screen through which the airplane was flown. Satisfactory pictures have not yet been obtained at altitude, but in Figure 4 are some which were taken close to the ground. These pictures, which are the first of their kind, are presented here as an interesting side-light only. However, as the photographic study of air flow is now being pursued at numerous laboratories, it is possible that this method may prove very useful.

CONCLUSIONS

The induced drag of an airplane is reduced upon approaching the ground and the theory of Wieselsberger offers a satisfactory explanation and method of calculation of the reduction.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *October 19, 1926.*

APPENDIX

The following formulas and explanation are summarized from Reference 1. A comment on a practical simplification of the biplane computations is added.

The induced drag coefficient of a monoplane at height $h/2$ above the ground is

$$C_{Di} = (1-\sigma)\ \frac{C_L^2\ S}{\pi\ b^2} \tag{1}$$

wherein

σ is the "influence coefficient."
C_L is the lift coefficient.
S is the wing area.
b is the span.

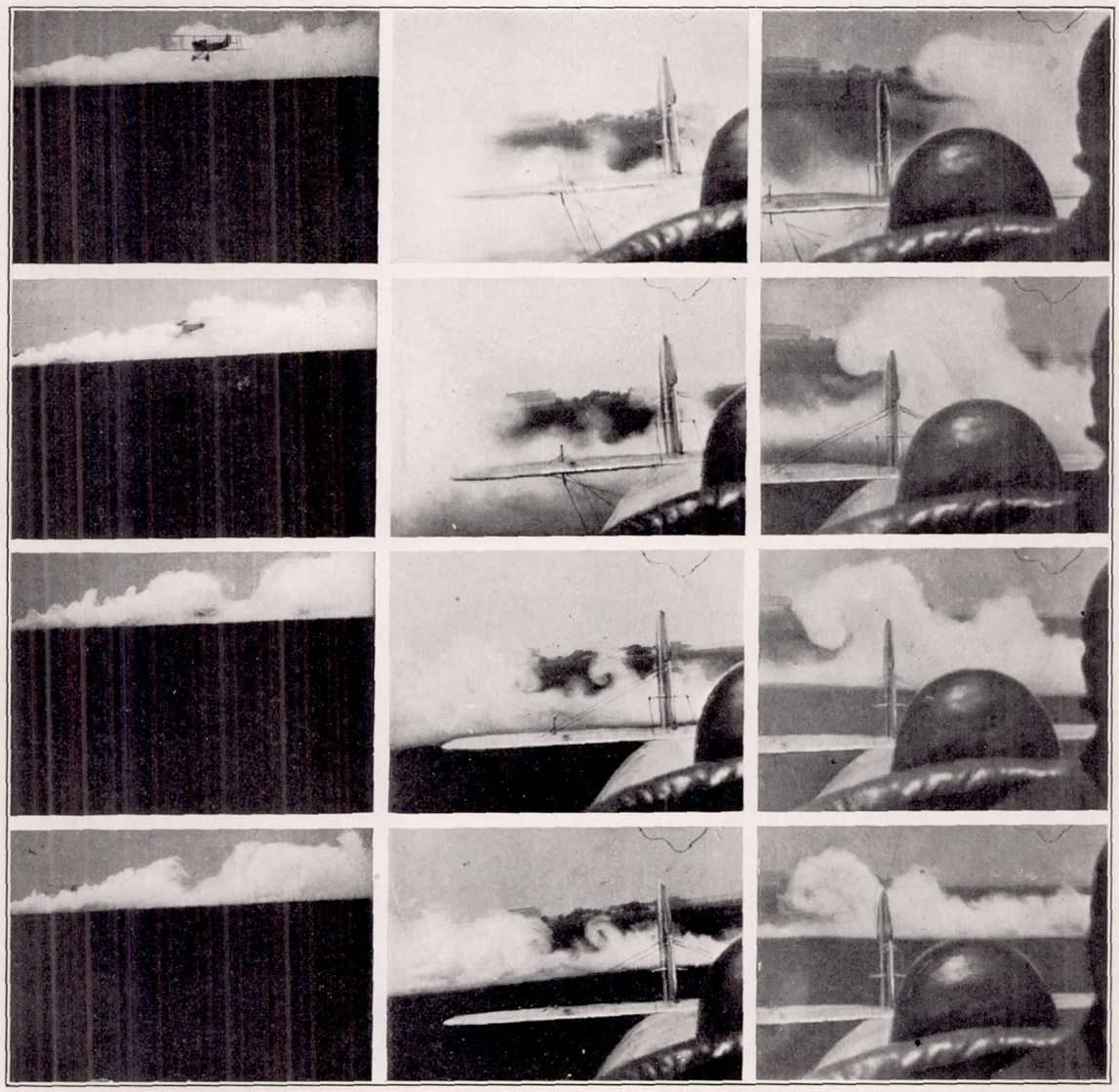
The value of σ may be computed from the formula

$$\sigma = \frac{1-0.66\ \frac{h}{b}}{1.05+3.7\ \frac{h}{b}} \tag{2}$$

which applies over the range of h/b from 1/15 to 1/2. Values of σ for $\frac{h}{b} > \frac{1}{2}$ which occurred in the computations of this report were taken from a graphical extrapolation of the curve computed from (2).

To compute the ground effect upon the characteristics of a biplane, Wieselsberger divides the reduction of induced drag into four parts—i. e., each wing is considered as a monoplane which is influenced by the action of its own image in the ground plane as well as by that of the other wing. The components all have the same sign and two are considered to be of equal value. These are the reductions of the drag of the upper and lower wings brought about by the action of the images of lower and upper wings, respectively.

To be strictly accurate, the lift coefficients of the individual wings should be taken into account. However, the reduction of induced drag which is calculated for a biplane with



From ground | Complete pattern | Half pattern

From cockpit of airplane

FIG. 4.—Photographs of pattern left in smoke screen by VE-7 airplane

40272—27. (To face p. 6.)

6a

wings of equal span under the assumption that the average lift coefficient applies to both wings is in error by only about 2 per cent if the lift coefficients of the individual wings differ by 20 per cent at $\frac{h}{b}=0.3$. The theoretical calculations for the VE–7 are based on the average (or cellule) lift coefficient.

The increase of maximum speed obtainable by flying the VE–7 with its lower wing 5 feet from the ground is calculated below. The following values are assumed to be true in the absence of ground influence:

$V_{max}=120$ M. P. H.
B. HP. = 180.
Propeller efficiency = 76 per cent.

The total power required is therefore,

$$HP_r=180\times.76=136.8$$

and the induced power is

$$HP_i=\frac{W^2}{3k^2b^2V}=\frac{(2075)^2}{3\times1.37\times(34.11)^2\times120}=7.5$$

W = weight, b = span, k^2 = Munk biplane constant.

According to the theory, the coefficient of induced drag of this airplane with its lower wing 5 feet above the ground is 0.27 of that without ground effect. Hence, at 120 M. P. H. the induced power is

$$HP_{i(5')}=7.5\times.27=2.0$$

and the total power required is

$$HP_{r(5')}=136.8-(7.5-2.0)=131.3.$$

Assuming that the power required varies with the cube of the speed, the maximum speed at 5 feet height is

$$V_{max(5')}=120\sqrt[3]{\frac{136.8}{131.3}}=121.6 \text{ M. P. H.}$$

The increase of maximum speed is therefore only 1.6 M. P. H., or 1.3 per cent.

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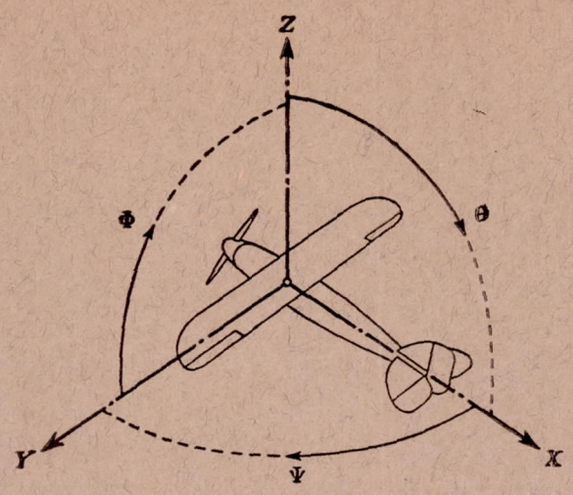

Positive directions of axes and angles (forces and moments) are shown by arrows

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

$$C_L = \frac{L}{qbS} \quad C_M = \frac{M}{qcS} \quad C_N = \frac{N}{qfS}$$

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

4. PROPELLER SYMBOLS

D, Diameter.
p_e, Effective pitch
p_g, Mean geometric pitch.
p_s, Standard pitch.
p_v, Zero thrust.
p_a, Zero torque.
p/D, Pitch ratio.
V', Inflow velocity.
V_s, Slip stream velocity.

T, Thrust.
Q, Torque.
P, Power.
(If "coefficients" are introduced all units used must be consistent.)
η, Efficiency $= T\,V/P$.
n, Revolutions per sec., r. p. s.
N, Revolutions per minute., R. P. M.
Φ, Effective helix angle $= \tan^{-1}\left(\frac{V}{2\pi rn}\right)$

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. = 0.4535924277 kg.
1 kg = 2.2046224 lb.
1 mi. = 1609.35 m = 5280 ft.
1 m = 3.2808333 ft.