CoA. Note Aero 159

THE COLLEGE OF AERONAUTICS

CRANFIELD

A REVIEW OF AERODYNAMIC ASPECTS OF RAM WING RESEARCH

by

P. R. Ashill

CoA Note Aero. 159

November, 1963

THE COLLEGE OF AERONAUTICS

DEPARTMENT OF AERODYNAMICS

A review of aerodynamic aspects of ram wing research

- by -

P.R. Ashill, B.Sc., D.C.Ae

S U M M A R Y

Theoretical and experimental research into the aerodynamics of ram wings is reviewed. The theories of two-dimensional and finite wings in ground effect are discussed and mention is made of the various experimental techniques available for ground effect tests. The possible shortcomings of each method are noted.

In the final section it is concluded that there is a considerable need for research into the dynamic stability of ram wings. It is suggested that any dynamic tests should include measurements of the effect of the movement of the ground, as might be experienced when in transit over a wavy sea.

Contents

Notation

h	Height of point vortex, 'lifting line' or datum from the ground
U	Free stream velocity
Γ	Circulation
ρ	Density of air
α	Geometric incidence
$\gamma(\theta)$	Vorticity distribution
c	Chord of the aerofoil
$A_o, A_1 \ldots A_n$	Coefficients in the vorticity distribution
x	Chordwise distance from the mid-chord position
b	Span
AR	Aspect ratio
L	Lift
C_L	Lift coefficient based on wing planform area
C_{D_i}	Induced drag coefficient based on wing planform area
$\sigma = \frac{\pi AR C_{D_i}}{C_L^2}$	Induced drag factor
$\Delta\alpha$	Correction applied to the geometric incidence
δ^*_{LE}	Displacement thickness of the ground-board boundary layer immediately under the leading edge of the aerofoil
δ^*_{TE}	Displacement thickness of the ground-board boundary layer immediately under the trailing edge of the aerofoil
A	Moment of inertia of a wing in the roll plane
ϕ	Roll angle
$p = \frac{\partial\phi}{\partial t}$	Rate of roll

$L_p = \frac{\partial L}{\partial p}$	Rate of change of rolling moment with rate of roll
$L_\phi = \frac{\partial L}{\partial \phi}$	Rate of change of rolling moment with roll angle
$L(t)$	Arbitrary roll input
θ	Pitch angle
z	Downward distance from the mid-chord position
λ	Vortex wake wavelength

Suffices

G	Refers to conditions in ground effect
t	Refers to trailing edge
o	Refers to mid-span
∞	Refers to conditions out of ground effect

1. Introduction

As the title suggests this paper is not concerned with the practical aspects of the ram wing concept. It will attempt to review some of the fundamentals of the subject and examine some of the more important findings of workers in this field. In the final section possible scope for future research is discussed. Part of this work represents a paper presented to The Hovercraft Symposium held at Southampton University in March 1963.

The words 'ram wing' are used to denote an aerofoil shaped craft having a flat or concave lower surface and capable of flying near the ground. In so doing, it utilises the beneficial properties of aerodynamic ground effect. The reason for the name 'ram' wing is not clear, but it is believed this is meant to imply that the wing obtains a large part of its lift by the ram compression of the air between the ground and the wing. If this is the implication then this term is a misnoma, because it is possible to show theoretically that large undersurface pressures are present with a wing near the ground in a purely incompressible flow. Nevertheless, this name appears to be accepted and it will continue to be used in this paper.

The phenomenon known as aerodynamic ground effect has been well known for some time. It was observed in all probability first by pilots who, on nearing the ground during the landing phase, found their aircraft began to float, seemingly on a cushion of air. During the pre-war era it was realised that the use of ground effect offered the possibility of increasing the range of aircraft. The twelve engine Dornier Do X demonstrated this by crossing the Atlantic entirely in ground effect.

Since the advent of the hovercraft, interest has again been shown in the possibility of using favourable aerodynamic ground effect as a means of providing lift for higher speed versions of the already well established hovercraft. Wind tunnel experiments conducted on ram wing models support theory in indicating that lift to drag ratios of as high as 50 may be possible with this form of transport. At least two firms in the United States are studying the ram wing principle applied to the design of high speed ships. One of these, Lockheed Aircraft Corporation has built a small prototype. This craft is equipped with an outboard motor, hydrofoils and a wing with endplates. The firm claims that it is capable of a speed of 45 knots, which is almost 50 per cent higher than that of the wingless version of the same craft. The other firm, Vehicle Research Corporation, is studying a project of a large ram wing called the Columbia.[1,2,3] It is designed to have a maximum speed in excess of 100 knots.

2. Theoretical concepts

2.1 Basic ideas

In general, aerodynamic ground effect is defined as the modification of the aerodynamic derivatives in ground proximity. The effect on the steady derivatives may be divided broadly into three main categories:

1. On approaching the ground the streamline pattern around an aerofoil is altered and accordingly the bound circulation of the wing is modified.

2. It is often convenient to replace the ground plane by a mirror image of the aerofoil. It is apparent from this model that the mirror system induces a velocity at the aerofoil opposite in sense to the flow.

3. The reflection of the trailing vorticity induces an upwash on the wing, which increases its effective incidence and reduces the induced drag coefficient.

The second effect may be demonstrated very simply by considering a point vortex, in a free stream near a plane wall. The expression for the lift is found to be

$$L = \rho\Gamma\left(U - \frac{\Gamma}{4\pi h}\right) \qquad (1)$$

The second term in the bracket is due to the induced longitudinal velocity of the image vortex. The first two effects are found in two-dimensional flow whereas the third effect is peculiar to a wing of finite aspect ratio.

2.2 Two-dimensional exact theories

There are several exact theories for the inviscid incompressible flow about aerofoils near the ground. The special case of the flat plate aerofoil has been solved by Tomotika(4) using the method of conformal transformation and by employing the elliptic functions of Weierstrass. He obtained expressions for lift and pitching moment in series form, the convergence of which could not be established for small height to chord ratios. De Haller(5) improved this approach with the aid of Jacobi's theta functions and the series thus obtained were found to be more rapidly convergent. He was able to show that the limiting case of his theory compared exactly with Dätwyler's theory(6), which considers the special case of a flat plate aerofoil with its trailing edge touching the ground. De Haller's results for the lift coefficient of a flat plate are shown in figure 1.

Green(7) and Tomotika(8) have developed exact theories for the case of a circular-arc aerofoil, but as with the flat plate theories, the results are not obtained in closed form. De Haller(5) examined the case of a circular-arc touching the ground at its trailing edge.

The effect of finite aerofoil thickness has been investigated by Green(9), Fujikawa(10) and Tomotika(11). The latter theory gives results for approximate Joukowski aerofoils having thickness and camber.

All of these theories support a law of ground effect on lift, which says that 'Any means which tends to promote an increase in the circulation around an aerofoil will, at a fixed trailing edge height, cause a reduction in the lift magnification $\frac{L}{L_\infty}$. An increase in thickness will act in the same direction'. The effect of ground proximity on the centre of pressure position of an aerofoil is not so obvious. For instance, ground effect does not alter the centre of pressure position of a circular arc aerofoil at zero incidence, but displaces the centre of pressure of a flat plate at incidences below 18° aft with reduction in height.

2.3 Two-dimensional approximate theories

From the computational point of view the exact theories are unwieldy. For this reason, approximate theories have been considered by Tani[12], Pistolesi[13], Bagley[14], Braunss[15] and Licher[16]. Tani replaced a flat plate near the ground by a Birnbaum distribution of vorticity on the chord-line, together with its image.

The distribution chosen may be written in the form

$$\frac{\gamma(\theta)}{2U} = A_o \operatorname{Cot} \frac{\theta}{2} + \sum_{1}^{N} A_n \sin n\,\theta \qquad (2)$$

where $$\theta = \cos^{-1}\left(\frac{-2x}{c}\right) \qquad (3)$$

The first term in the series is the form of the vorticity distribution for a flat plate at incidence in unbounded flow. The remaining terms are due to the change in the curvature of the streamlines around the plate near the ground. A_o, A_1 ... A_N are found by satisfying the boundary conditions at $(N + 1)$ discrete points on the chord-line. Tani took $N = 2$ and simulated aerofoil thickness by a single doublet placed at mid-chord and the image position.

Bagley used Weber's approximate aerofoil theory, which enables a better approximation to be made for the boundary condition of an aerofoil with thickness and camber than does linearised aerofoil theory. He employed the same vorticity distribution as Tani, but represented thickness by a suitable distribution of sources on the chord-line. Unlike Tani he ignored the effect of the image system on the longitudinal velocity. Bagley compared the pressure distribution obtained by his method with the pressure distribution given by the exact theory of Reference 11 for an 8.5 per cent thick aerofoil, of nearly zero camber, at 5.17 degrees incidence and mid-chord height to chord ratio of 0.287. Agreement was found to be good.

Licher approached the problem in the following manner. He divided the chord-line of the aerofoil into several equal strips. At the quarter-chord of each strip he placed a point vortex and imposed the aerofoil boundary condition at the corresponding three quarter-chord points. His results are plotted in figure 1, for the two lowest incidences. Although these calculations have been made for the one vortex and two vortices cases only, any desired degree of accuracy may be achieved by increasing the number of vortices.

Pistolesi replaced a flat plate by one vortex at the quarter-chord point and satisfied the boundary condition at the three-quarter chord point. This may be considered to be a first approximation to Licher's method and does not allow for the change in the curvature of the stream-lines (or the effective camber of the plate) which occurs near the ground.

The theory of Braunss is similar to Tani's work, but he considers higher order terms in the Birnbaum series and therefore has more boundary condition check-points. For this approach a computer is used.

2.4 Finite wing theories

Figure 2 shows the different nature of ground effect on a finite wing and indicates how the image of the trailing vorticity induces an upwash and sidewash at the wing.

The first contribution to the theoretical knowledge of the ground effect on finite wings was that of Wieselsberger[17]. In his analysis he ignored the first and second effects discussed in 2.1 and replaced the wing by an elliptically loaded 'lifting line'.

De Haller[6] solved the problem of the lift distribution of a 'lifting line' near the ground for minimum induced drag employing the Trefftz Plane technique. He also ignored the first and second effects of 2.1. Span-wise circulation distributions obtained by this method are shown in figure 3. It will be observed that whereas the distribution for minimum induced drag in an unbounded flow is elliptic, in the limit as the height of the 'lifting line' approaches zero it is parabolic. De Haller's and Wieselsberger's results for induced drag are shown on figure 4, with some theoretical results given by Blenk[18] for the induced drag of a delta wing.

Tani[12] and Licher[16] have extended their two-dimensional theories to the finite wing case. In these theories account is taken of the change in the bound vorticity due to the ground. However, Tani underestimates the lift by using equation (1), which should be applied only in the case of a single vortex. Licher replaces the wing by a horseshoe vortex lattice in the same manner as Falkner's vortex lattice theory. The ground plane is replaced by a corresponding set of images.

3. Experimental methods

Since the early experiments of Betz[19] there have been many and varied attempts to measure ground interference. Cowley and Lock[20] were the first in Britain to publish results of experiments on ground effect. Unfortunately these tests were concerned with biplane models. However, they did make an important contribution by being the first to record doubts about the validity of the fixed ground-board method for wind tunnel tests. These doubts arose because of the presence of a boundary layer on the ground-board, which they said would affect the results of the experiments. Bagley[14] used a fixed ground-board in his tests, but allowed for the ground-board boundary layer by the wing incidence correction

$$\Delta\alpha = \frac{1}{c}\left(\delta^*_{TE} - \delta^*_{LE}\right) \qquad (4)$$

where δ^*_{TE} and δ^*_{LE} refer to the ground-board boundary layer displacement thickness immediately under the trailing edge and leading edge of the aerofoil respectively.

The use of such a correction cannot be justified if either

(a) the ground-board boundary layer touches the model boundary layer

or (b) the pressure field of the model causes a separation bubble on the ground-board. An example of this is shown in figure 5.

An alternative technique known as the method of images is shown in figure 6. The ground is replaced by an image of the test wing. Cowley and Lock also raised doubts about this method. Apparently when the models are at incidence the interaction of the wakes causes unsteady forces on the models. Figure 7 indicates a way of overcoming this problem by placing a thin plate along the plane of symmetry, near the trailing edge of the aerofoils. As the boundary layer on the plate is thin it does not noticably affect the flow over the aerofoils. This method has been utilised by Katzoff and Sweberg[21] and Cowley and Lock. A recent paper by Werlé[22] appears to substantiate these conclusions. He compared the fixed ground-board and image methods with the moving ground method in the O.N.E.R.A. water tunnel.

The effect of a moving ground in a wind tunnel can be simulated by a continuous belt on rollers. The belt is driven so that the 'ground' moves with zero speed relative to the air-stream. This is shown in figure 8 and has been described by Klemin[23].

Carter[24] has discussed some ram wing tests made in the N.A.S.A. towing tank over water. The whirling arm offers similar possibilities and is shown diagrammatically in figure 9.

4. Areas for future study

On reviewing previous work it has become evident that steady aerodynamic ground effect is well understood in inviscid incompressible flow. However, as far as the author is aware, there has been no work published on the effect of the ground on the stability of wings. As an illustration, consider the dynamical equation, having an arbitrary input, of a wing in the roll plane out of ground effect,

$$A\ddot{\phi} - L_p\dot{\phi} = L(t). \tag{5}$$

In ground effect,

$$A\ddot{\phi} - L_{p_G}\dot{\phi} - L_{\phi}\phi = L(t) \tag{6}$$

where the suffix G denotes the fact that L_p is different near the ground. The derivative L_{ϕ} indicates the dependence of the stability on roll attitude. This is because at a fixed mid-span height from the ground the lift distribution is modified by change in roll attitude. Similar reasoning may be applied to the other two planes and there would appear to be scope for a great deal of work in this field.

Figure 10 shows a tentative theoretical model for the unsteady problem of the oscillations of a two-dimensional thin wing in ground proximity. According to Reissner(25), who considered the similar problem of the oscillations of a two-dimensional wing midway between two plane walls, the amount of interference on the unsteady derivatives is dependent not only on the chord to height ratio, but also the wake wavelength to height ratio. As the height of the wing approaches zero, the trailing vorticity behaves like a vortex doublet sheet, with correspondingly smaller effect on the bound system. The model proposed is referred to as tentative because it is not known whether the vortex wake will behave in the manner prescribed when near a ground-plane. This problem has yet to be solved and there has been no information published on the experimental determination of unsteady derivatives of wings near the ground.

Another possibility which should be admitted in a study of the stability of ram wings is the effect of the oscillations of the ground. The whirling arm and towing carriage methods offer unique possibilities in this respect, as grounds of any desired shape may be simulated. For instance, tests could be conducted over grounds of simple harmonic shape giving a simple harmonic height variation. The behaviour of ram wings over water could also be studied with these facilities. Comparison between tests over water and on a rigid ground would afford a determination of wave drag.

When an aerofoil approaches the ground, the boundary layer development is modified by virtue of the alteration in the pressure distribution. There is a need for an experimental investigation of this effect, including measurements of profile drag using the wake survey technique.

As a result of the large sidewash component which develops on finite wings near the ground, endplates are extremely effective in reducing the induced drag and increasing the lift. It is possible to show theoretically, using a 'lifting line'/Trefftz Plane approach, that the induced drag is zero when the endplates, which are designed for zero sidewash, touch the ground.

It seems that ram wings will be equipped with endplates and in view of this there is a need for 'lifting line' and lifting surface theories to assess the effect of endplate height on the induced drag and the lift.

5. References

1. Strand, T., Royce, W.W. and Fujita, T. — Cruise performance of channel-flow ground effect machines. J. Aero. Space Sci., Vol. 29, 1962, p. 702.

2. Strand, T. — Vehicle Research Corporation's channel flow ground effect machine concept. Paper presented at the G.E.M. Contractors Meeting, Washington D.C., November 16-18th, 1960.

3. Rethorst, S. — 'Columbia in Detail' Abstracts from a paper read to the National Meeting on Hydrofoils and Air Cushion Vehicles, sponsored by the I.A.S. Hovering Craft and Hydrofoil, Vol. 2, No. 1, 1962, pp. 22-23.

4. Tomotika, S., Nagamiya, T., and Takenouti, Y. — The lift on a flat plate placed near a plane wall with special reference to the effect of the ground upon the lift of a monoplane aerofoil. Aero. Research Inst., Tokyo Imperial University Rep. No. 97. August 1933. (Also Rep. 120, 1935; Rep. 152, 1937; Rep. 182, 1939).

5. de Haller, P. — La Portance et la traînée induite minimum d'une aile an voisinge du sol. Mitt. Inst. Aerodyn. Zurich 5, 1936, p. 99.

6. Dätwyler, G. — Untersuchungen über das Verhalten von Tragflügelprofilen sehr nähe am Boden. Mitt. Inst. Aerodyn. Zurich, 1934.

7. Green, A.E. — The forces acting on a circular-arc aerofoil in a stream bounded by a plane wall. Proc. Lond. Math. Soc. Vol. 46, 1940, pp. 19-54.

8. Tomotika, S., Tamada, K., and Umemoto, H. — The lift and moment acting on a circular-arc aerofoil in a stream bounded by a plane wall. Quart. J. Mech. Appl. Math. Vol. 4, 1950, pp. 1-22.

9. Green, A.E. — The two-dimensional aerofoil in a bounded stream. Quart. J. Math. Vol. 18, 1947, pp. 167-177.

10. Fujikawa, H. — The lift on the symmetrical Joukowski aerofoil in a stream bounded by a plane wall. J. Phys. Soc. Japan, Vol. 9, 1954, p. 233.

11. Tomotika, S., Hasimoto, Z., and Urano, K. — The forces acting on an aerofoil of approximate Joukowski type in a stream bounded by a plane wall. Quart. J. Mech. Appl. Math. Vol. 4, 1951, p. 289.

12. Tani, I. — On the effect of the ground upon the lift of a monoplane wing. Aero. Research Inst., Tokyo Imperial University, Rep. 96, August 1932 (in Japanese). (Also I. Tani, M. Taima, S. Simidu, A.R.I. Tokyo Imperial University Rep. 156, 1937 (in English).

13. Pistolesi, E. — Il Problema dell'ala in vicinanza del suolo. L'Aerotecnica, Vol. 13, 1933, pp. 351-360.

14. Bagley, J.A. — The pressure distribution on two-dimensional wings near the ground. A.R.C. R. and M. 3238, February, 1960.

15. Braunss, G., and Linke, W. — Die Auftriebsverteilung einer Ebenen Platte in Bodennähe. Zeitschrift für Flugwissenschaften 10, 1962.

16. Licher, R.M. — Increase in lift for two and three-dimensional wings near the ground. Douglas Aircraft Co. Rep. SM-22615, October 1956.

17. Wieselsberger, C. — Wing resistance near the ground. N.A.C.A. TN. 77, 1922.

18. Blenk, H. — Recent German contributions to aerodynamics and flight dynamics. J. Roy. Aero. Soc., Vol. 66, 1962, pp. 619-621.

19. Betz, A. — Auftrieb und Widerstand einer Tragfläche in der Nähe einer horizontal Ebenen. Z.F.M. No. 17, 1912, pp. 217-220.

20. Cowley, W.L., and Lock, C.N.H. — Cushioning effect on aeroplanes close to the ground. A.R.C. R. and M. 754, 1920.

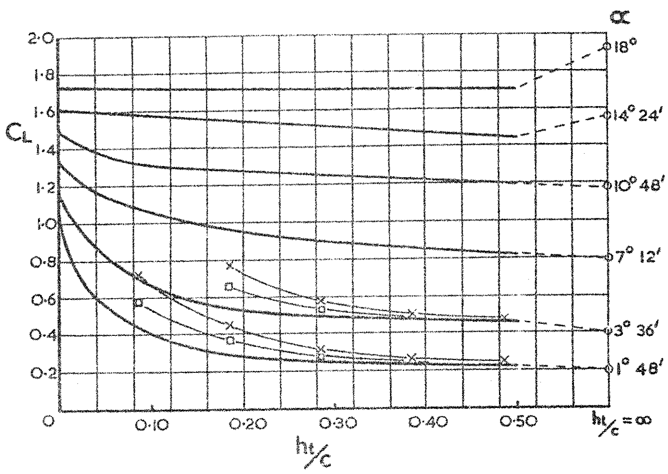
21. Katzoff, S., and Sweberg, H.H. — Ground effect on downwash angles and wake location. N.A.C.A. Rep. 738, 1943.

22. Werlé, H. — Simulation de l'effet de sol au tunnel hydrodynamique. La Recherch Aérospatiale, O.N.E.R.A. Bimonthly Bulletin July-August, 1963.

23. Klemin, A. — A belt method of representing the ground. J. Aero. Sci., Vol. 1, 1934, p. 198.

24. Carter, A.W. — Effect of ground proximity on the aerodynamic characteristics of aspect ratio - 1 aerofoils. NASA TN. D-970, October 1961.

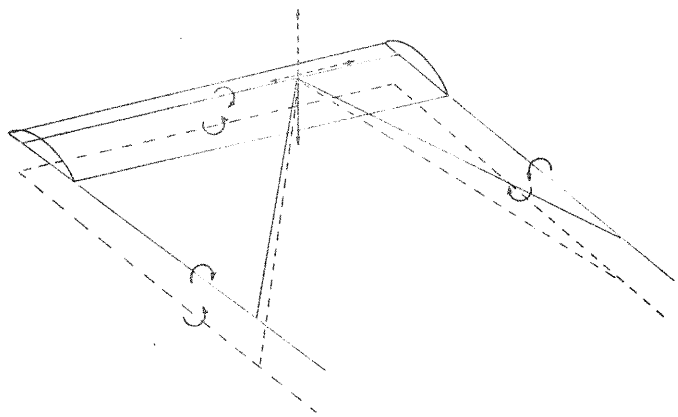
25. Reissner, E. — Wind tunnel corrections for the two-dimensional theory of oscillating airfoils. Cornell Aeronautical Laboratory, Rep. SB-318-S-3, April, 1947.



THE GROUND EFFECT ON LIFT OF A TWO-DIMENSIONAL FLAT PLATE.

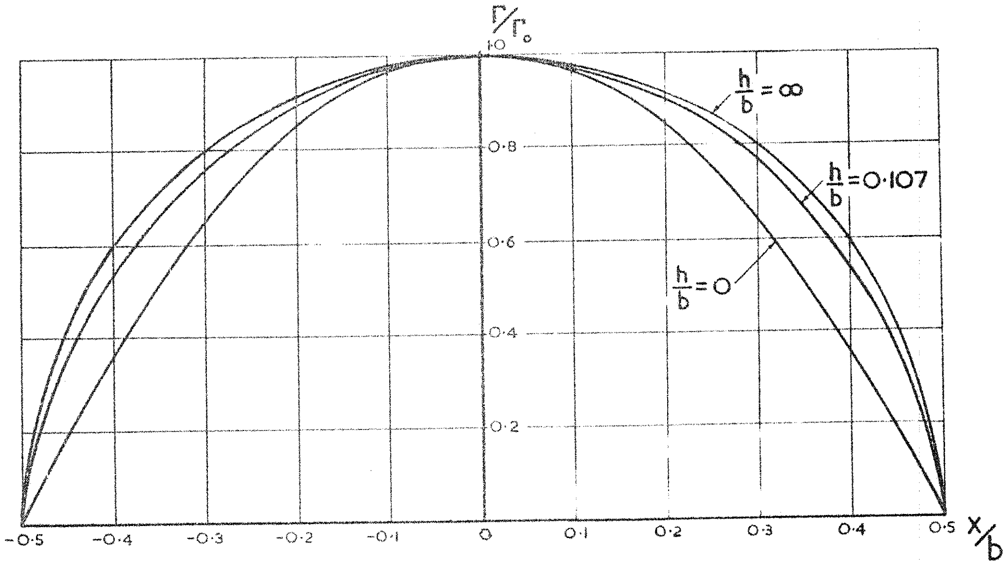
h_t = TRAILING EDGE HEIGHT.
—— EXACT METHOD.
—x— ONE VORTEX METHOD.
—□— TWO VORTEX METHOD.

FIG. I.



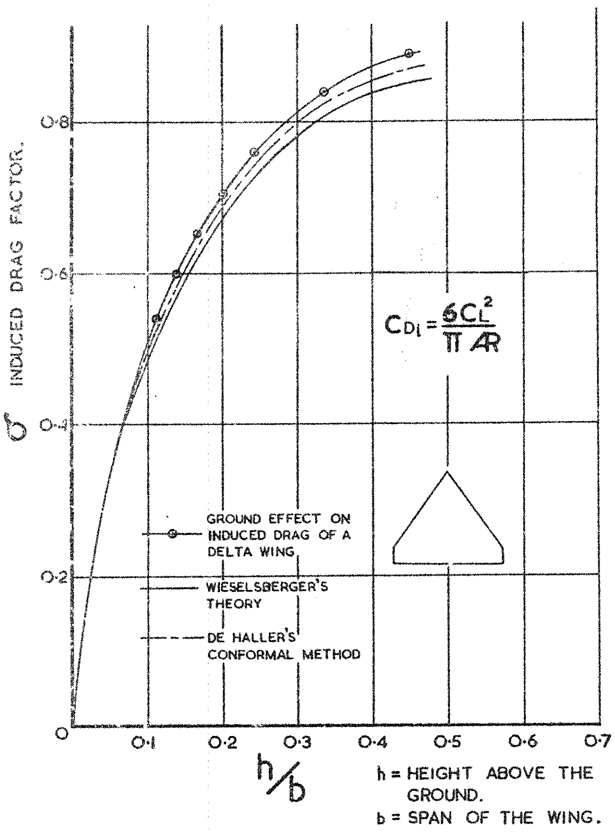
THE GROUND EFFECT ON A THREE-DIMENSIONAL AEROFOIL.

FIG. 2.



SPANWISE LIFT DISTRIBUTION FOR A WING OF MINIMUM INDUCED DRAG IN GROUND EFFECT. (AFTER DE HALLER.)

FIG. 3.



GROUND EFFECT ON INDUCED DRAG.

FIG. 4.

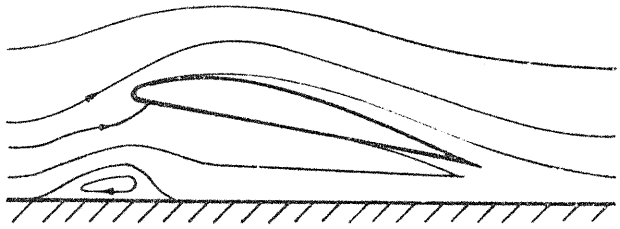


FIG. 5. FLOW AROUND AN AEROFOIL NEAR A FIXED GROUND.

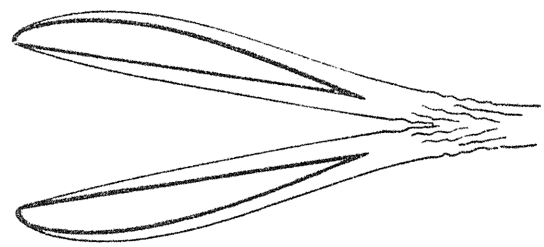


FIG. 6. IMAGE MODEL TECHNIQUE.

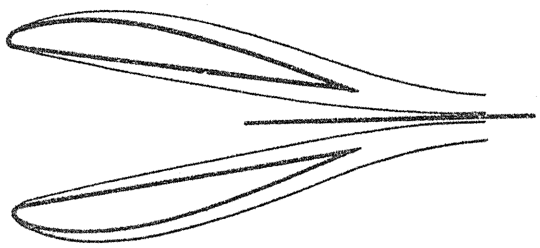


FIG. 7. PARTIAL IMAGE/GROUND PLATE TECHNIQUE.

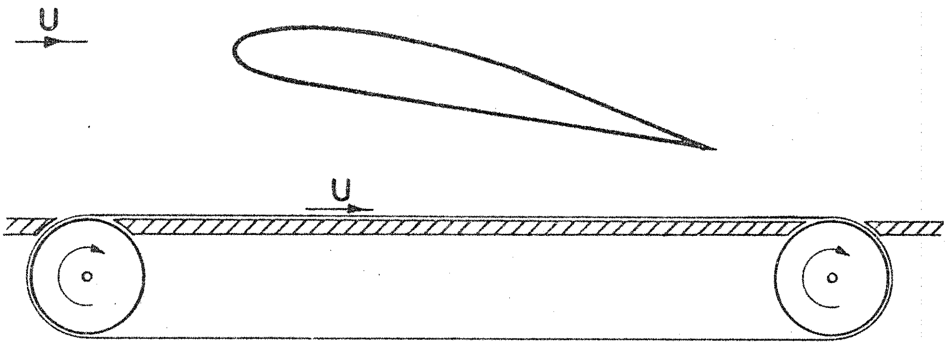
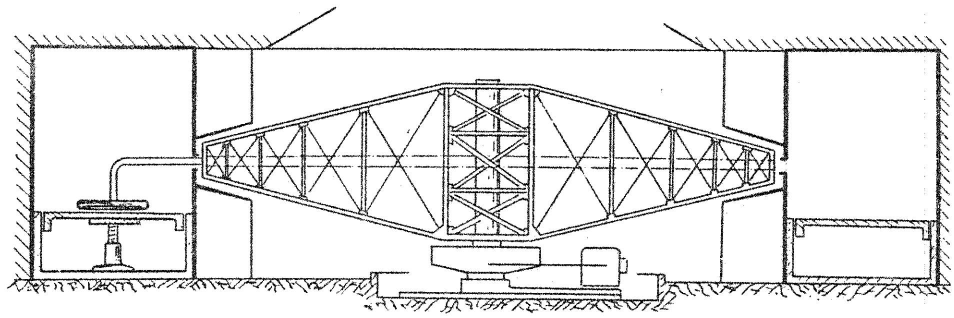


FIG. 8. CONTINUOUS BELT 'MOVING GROUND' METHOD.



A DIAGRAMMATIC ARRANGEMENT OF THE WHIRLING ARM FACILITY FOR GROUND EFFECT TESTS.

FIG. 9.

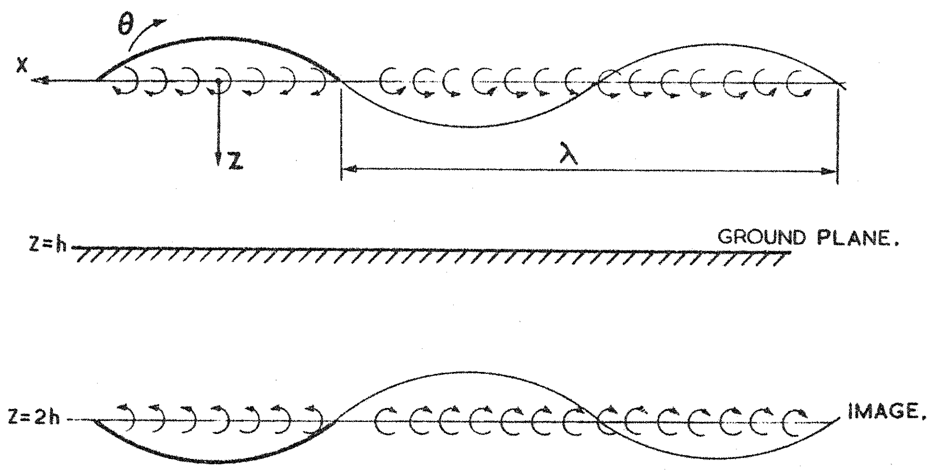


FIG. 10. A TENTATIVE THEORETICAL MODEL FOR THE OSCILLATIONS OF A TWO-DIMENSIONAL WING NEAR THE GROUND.