C.P. No. 1152

C.P. No. 1152

MINISTRY OF AVIATION SUPPLY

AERONAUTICAL RESEARCH COUNCIL

CURRENT PAPERS

The Aerodynamic Effect of Ground Proximity on Lateral Control of Slender Aircraft in the Landing Approach

by

W. J. G. Pinsker

Aerodynamics Dept., R.A.E., Bedford

LONDON: HER MAJESTY'S STATIONERY OFFICE

1971

PRICE 40p NET

U.D.C. 533.682 : 533.693.3 : 533.6.015.2 : 533.6.013.413 : 533.6.048.5 :
533.6.013.153

CP 1152*
May 1970

THE AERODYNAMIC EFFECT OF GROUND PROXIMITY ON LATERAL CONTROL OF SLENDER AIRCRAFT IN THE LANDING APPROACH

by

W. J. G. Pinsker
Aerodynamics Dept, RAE, Bedford

SUMMARY

Recent wind tunnel tests have revealed the existence of a powerful ground effect on the rolling derivatives of a slender wing model. Analogue computer studies have been made which show the consequences of this phenomenon on the lateral behaviour of a large slender aircraft during landing approaches in the presence of side gusts. The ground effect is shown to exert a powerful constraint on bank angle disturbances for this class of aircraft, almost eliminating the effects of lateral turbulence as a control problem. Other possible consequences of this ground effect on various lateral control problems are also briefly discussed.

---

* Replaces RAE Technical Report 70079 - ARC 32340

CONTENTS

0

1 INTRODUCTION

The large values of ℓ_v generated by the slender wing in high-incidence flight have been of major concern since the inception of this planform as a promising design for economic supersonic flight, and also as a possible shape for an all-wing subsonic transport.

In conjunction with the poor roll damping also inherently associated with the slender planform the slender-wing aircraft was always thought to pose considerable lateral control problems especially in the landing approach in the presence of side-gusts and/or steady cross-wind. However, flight experience on the two slender-wing research aircraft operating in this country, the HP 115 and the BAC 221 does not appear to substantiate the original apprehensions in this respect. In both aircraft the limitations derived theoretically for turbulence and cross-wind sensitivity have proved excessively pessimistic and the aircraft are now operated and landed with complete confidence in atmospheric conditions which conventional analysis would suggest to be prohibitive. Experience on Concorde again appears to confirm this trend. Although this aircraft was of course designed to permit safe lateral control in the most severe conditions demanded from a transport aircraft, it was nevertheless expected that landings in rough weather might be less than comfortable for the pilot and that in these conditions reliance on autostabilisation might be the only satisfactory answer. In contrast to these theoretical predictions and similar supporting flight-simulator results, lateral control has hardly been even mentioned by the test pilots flying the two prototypes of this aircraft.

All this evidence suggests that there may be a substantial element of error in the methods used to assess this problem or in the basic aerodynamic data fed into this work.

In view of the known extraordinary magnitude of the aerodynamic ground effect on lift and pitching moment of slender wings it had long been suspected that a similarly powerful effect may influence the lateral behaviour of this type of aircraft near the ground. In particular there was a possibility that when banked close to the ground there could be a differential ground effect, increasing the lift on the lower wing half, thus generating a roll stiffness deviative, ℓ_ϕ, which has no physical counterpart in free flight. The realisation of appropriate wind tunnel tests, however, took some time and results have only recently been published in Ref.1

These results more than confirmed these expectations. Not only was a powerful roll stiffness effect established but at the same time it was shown that ground proximity also improved roll damping by a substantial amount.

We shall review this evidence in section 2.

Mere inspection of this material leaves little doubt that this phenomenon will have a strongly beneficial effect on the lateral motions of a slender aircraft during the landing approach, but for a quantitative assessment the resulting dynamic behaviour, and in particular the alteration of the aircraft response to lateral gusts and turbulence, need to be studied more closely. Appropriate computations were carried out on an analogue computer based on a suitably simplified mathematical model representing the aircraft motion. The results are presented in this Report and suggest that ground effect completely alters the basic lateral characteristics of the slender aircraft during the period immediately preceeding touchdown. As a result, disturbances in bank angle from whatever origin are drastically attenuated just before the aircraft touches the ground.

2 THE EFFECT OF GROUND PROXIMITY ON THE ROLLING DERIVATIVES OF A SLENDER WING

The principal quantitative evidence we have so far for the existence of a significant ground effect on the rolling derivatives of an aircraft comes from wind tunnel tests reported in Ref.1. In these tests a gothic wing having the geometry illustrated in Fig.1 was subjected to forced rolling oscillations about an axis coincident with the wing centre line chord, i.e. about a body-fixed axis, at various frequencies and amplitudes. During part of the experiment, which covered other aspects not of concern here, a ground board was installed in the tunnel and this permitted the influence of ground proximity on the rolling derivatives to be established for a range of heights. It was found that within the range of frequencies relevant to aircraft stability and control, the effect of reduced frequency was negligible so that this parameter can be ignored for the present study.

By measuring the in-phase and the quadrature component of the aerodynamic rolling moment acting on the model two distinct rolling moment derivatives were obtained:

(i) a roll damping derivative

$$\ell_{\dot{\phi}} = \frac{\partial C_\ell}{\partial \frac{\dot{\phi} b}{2V}} \tag{1}$$

(ii) an apparent roll stiffness

$$\ell_{\phi} = \frac{\partial C_\ell}{\partial \phi} \quad . \tag{2}$$

In these definitions the bank angle ϕ is not the bank angle commonly used in flight dynamic theory but a roll angle derived from model rotation about its centre chord axis. Kinematically such a constrained motion generates aerodynamic sideslip as

$$\beta = \alpha_o \sin \phi \tag{3}$$

and similarly incidence changes according to

$$\alpha = \alpha_o \cos \phi \tag{4}$$

where α_o is the incidence of the roll axis with respect to the tunnel flow when $\phi = 0$. It is important not to ignore this effect since it implies that the derivatives measured by this technique contain contributions from what are normally defined as sideslip derivatives. Equally, the rolling moment coefficient C_ℓ is referred to the body-fixed roll axis of the model.

The results given in Ref.1 for these two rolling derivatives are shown in Fig.2 plotted against nondimensionalised trailing edge height h/b. Results were obtained for two values of incidence, 10° and 15°. In the original report results for two values of bank angle amplitude $\pm 1^\circ$ and $\pm 2^\circ$ are shown, but the difference is too small to concern us here. Tests were also made without this ground board to give corresponding free air values, they are represented by dashed lines in Fig.2. These are of course the values for these derivatives which are normally used in stability analysis including the study of control near the ground during take-off and landing. It is immediately apparent that for the particular wing tested at least, these are grossly unrepresentative of the situation close to the ground. A series of tests was also made to obtain the roll stiffness derivative ℓ_ϕ in static conditions, by suspending the model in the tunnel at various bank angles. The corresponding derivatives, derived from the slopes of the measured rolling moments at $\pm 2^\circ$ ϕ are also shown in Fig.2. They are seen to compare well with corresponding dynamic results with a hint perhaps that the static values are slightly larger. B.A.C. had made an estimate of the roll stiffness ℓ_ϕ to be expected for Concorde and this value is also shown in Fig.2. Since this result represents only the genuine ground effect, we must add the appropriate $\ell_v \sin \alpha_o$ contribution, which amounts to an increment in $\Delta\ell_\phi = -0.017$, before it can be properly compared with the results of Ref.1. This gives a total ℓ_ϕ of -0.104, approximately 2/3 of the corresponding value obtained for the gothic wing. The difference is most likely due to the much larger aspect ratio of the Concorde wing.

The free air value of ℓ_ϕ shown in Fig.2 for the gothic wing should be entirely due to the kinematics of the roll freedom mechanised in the tunnel tests. Equation (3) implies that the rolling moment so measured contains a sideslip contribution

$$\Delta\ell_\phi = \ell_v \alpha_o \qquad (5)$$

and when the ground effect has vanished this is then the sole contribution. This applies equally in the oscillatory tests and in the static tests. The values obtained in the static tests have been used to derive the appropriate ℓ_v values as

$$\text{for } \alpha = 10^\circ \qquad \ell_v = \frac{-0.026}{0.174} = -0.150$$

$$\text{for } \alpha = 15^\circ \qquad \ell_v = \frac{-0.067}{0.263} = -0.255 \quad .$$

Unfortunately no conventional six component results are available for this model so that these values cannot be verified, but comparisons with results from similar wings suggest them to be of the right order.

To isolate the ground effect proper from the ℓ_ϕ values of Fig.2 the appropriate ℓ_v contribution should be deducted. ℓ_v itself is of course subject to ground effect and since this has not been measured we cannot strictly make the correction. In the computations which form the main subject of the present Report, this difficulty will be circumvented by a suitably simplified choice of the mathematical model describing the lateral motion of the aircraft. In general, however, it would be desirable to have a complete set of wind tunnel data so that the aerodynamic properties of the aircraft can be rigorously defined.

3 LATERAL CONTROL AND RESPONSE DURING TAKE-OFF AND LANDING

So far, the aerodynamic effects of ground proximity on the roll derivations are available in detail only for one particular slender wing model, having a gothic planform with aspect ratio 0.75. As was indicated above, with a less slender wing the effect is likely to be reduced. Since no theoretical method exists by which the present experimental results can be scaled to other configurations no quantitative prediction can be made which is, for instance, directly applicable to Concorde or the slender research aircraft flying today. In view of this appropriate wind tunnel tests on models of these aircraft would be very desirable. Nevertheless, there is little doubt that ground effect can be expected to have a very powerful influence on lateral control of slender aircraft in general, if not of other configurations too, in flight close to the ground.

One effect that is immediately apparent is that the roll stiffness generated by ground interference will generally constrain bank angle, whether induced by aerodynamic disturbances or by pilot's control. In Ref.2 it was shown that the lateral motion of the inertially slender aircraft can be approximated by the simple model of a pure roll oscillation about the principal inertia axis of the aircraft. In its simplest form the period of this oscillation is determined by the effective roll stiffness ($\ell_v \sin \alpha_o$) and its damping by ℓ_p. In ground effect the relevant roll stiffness is of course the derivative ℓ_ϕ of Fig.2, which becomes identical with ($\ell_v \sin \alpha_o$) if ground effect and possible unsteady aerodynamic effects can be ignored.

One of the properties of this simple lateral response mode is that the initial response of a slender aircraft to the step application of either ailerons or a side-gust is given by the well-known second order response as illustrated in Fig.3, and characterised by a quasi-steady 'equilibrium' bank angle ϕ_R. The bank angle is obviously determined by the equilibrium condition:

$$\ell_\phi \phi_R = \ell_\xi \xi \tag{6}$$

for an aileron application ξ, or

$$\ell_\phi \phi_R = \ell_v \frac{v}{V} = \ell_v \beta_{gust} \tag{7}$$

for the side-gust case. Hence we can define a gust sensitivity parameter

$$\frac{\phi_R}{\beta_{gust}} = \frac{\ell_v}{\ell_\phi} \tag{8}$$

which describes an important - although not the only - aspect of the roll response of a slender aircraft to a side-gust near the ground.

Taking the value of ℓ_ϕ shown in Fig.2 and assuming that the derivative ℓ_v is reasonably insensitive to ground proximity, i.e. taking the free air values derived earlier as applicable to all heights, we obtain the results for ϕ_R/β_{gust} plotted in Fig.4 against nondimensionalised height h/b. It is clearly seen that the bank angle response of this type of aircraft to lateral gusts is strongly suppressed in flight close to the ground and that any analysis of the lateral control problems during the approach or take-off in turbulence will be grossly in error if it is based on free air values of the rolling moment derivatives. For the particular slender wing under consideration here the bank angle constraint becomes so powerful at touchdown that the aircraft can be seen to be virtually damped to zero bank angle. The same argument also applies to take-off. In Ref.3 it was suggested that the slender aircraft is liable to a violent rolling disturbance after lift-off in cross-winds and that this may lead to wing tip impact with the ground in sufficiently severe conditions. If one now re-analyses this problem by including ground effect on ℓ_ϕ, the hazard indicated by the earlier analysis is practically removed.

Lateral control of turbulence during approach and landing is of course essentially a dynamic problem, only partially covered by the simple and quasi-steady answer given in Fig.4. An appropriate computer study will be discussed in section 4.

However, there is one other likely consequence of the lateral ground effect, which simple quasi-steady considerations will permit us to assess. We have already shown in equation (6) that, if a roll stiffness ℓ_ϕ exists, bank angle can only be held by the permanent application of aileron, the effective bank control power is thus simply given by

$$\frac{\phi_R}{\xi} = \frac{\ell_\xi}{\ell_\phi} \tag{9}$$

This relationship has no equivalent in free flight. In other words if the pilot is obliged for some reason to bank the aircraft during the final portion of a landing approach, this manoeuvre can absorb a substantial amount of aileron. A situation when this may be necessary, both in manual control and in automatic landings, has been indicated in Ref.4. There it was shown that the slender aircraft tends to drift relatively fast across the runway if, after kicking off drift in a cross-wind, touchdown does not immediately occur. The proper reaction to prevent this from happening is to apply an appropriate bank angle and perhaps permit the aircraft to touchdown in this banked attitude. A rough assessment of the magnitude of this lateral control problem is made in the Appendix and it is shown that for the aircraft with the planform of Fig.1 this case poses quite severe demands on aileron power and may dictate the requirement for more control power than would otherwise be necessary. However, this is the only possible penalty which might arise from lateral ground effect; in every other respect it would appear to be beneficial.

4 ANALOGUE COMPUTATIONS OF LATERAL BEHAVIOUR DURING LANDING APPROACHES IN TURBULENCE

Although the benefit of ground effect on the rolling derivatives of the slender wing are already fairly evident from the simple argument presented in section 3, it is nevertheless desirable to consider in more detail the dynamics of the lateral behaviour of an aircraft subject to this phenomenon and for this purpose a study was carried out on an analogue computer to get a more realistic representation of conditions during proper flare manoeuvres and in the presence of more realistic types of gusts.

4.1 The mathematical model

The only relevant aerodynamic information available for the particular slender wing investigated in Ref.1 is that given in Fig.2, i.e. values of $\ell_{\dot{\phi}}$ and ℓ_{ϕ} as a function of height and, by inference, a value of ℓ_v applicable strictly only to free air conditions. As general experience on slender wings suggests that the latter derivative varies only modestly with ground proximity it appeared permissible to assume that this value applies during the whole approach. In the absence of wind tunnel data on the other aerodynamic derivatives relevant to the problem it was necessary either to estimate these or, alternatively, to simplify the equations representing the lateral motion of the aircraft so that it could be satisfactorily approximated. As demonstrated in Ref.2 such an approximation exists in the case of a slender aircraft flying at relatively high incidence, where the lateral motion is reduced to a single-degree-of-freedom roll oscillation about the principal inertia axis. The system is then defined by

$$L_{\phi}\,\phi + L_{\dot{\phi}}\,\dot{\phi} - A_{\ddot{\phi}} = -L_{\beta}\,\frac{v}{V} \qquad (10)$$

when v is lateral gust velocity. To introduce ground effect we must allow L_ϕ and $L_{\dot\phi}$ to become functions of height. Strictly this also applies to L_β, but in view of lack of data we assume this derivative to be constant. Furthermore all these derivatives also vary with incidence but this complication is avoided by simply ignoring the longitudinal motion and assuming that during the landing manoeuvre α, or more precisely C_L, is sensibly constant. In addition speed is assumed constant.

Longitudinal motion is ignored but it is of course necessary to assume a flight path so that the effect of varying height on the lateral derivatives can be realistically introduced.

In addition we must assign scale and mass distribution to the aircraft and assume an approach speed. The relevant data are listed in Fig.1. It will be seen that the aircraft so defined has the general size of Concorde but it should be emphasised that aerodynamically there are major differences, most important perhaps the fact that the wing considered here is significantly more slender than that of Concorde. As a consequence the results of the present study cannot be directly read across to Concorde, but it is believed that they are nevertheless qualitatively representative.

For convenience in the computations it was necessary to express the variation of L_ϕ and $L_{\dot\phi}$ with height by a simple algebraic function. This is illustrated in Fig.5 for the nondimensional values of these aerodynamic terms. It should be noted that the height scale used there, as throughout the computation, is main wheel height and therefore differs by a constant from the height (that of the trailing-edge of the wing) used in the original presentation of Ref.1 and Fig.2.

The differential equation for this simple model of the lateral aircraft motion is now

$$\frac{L_\phi(H)}{A}\phi + \frac{L_{\dot\phi}(H)}{A}\dot\phi - \ddot\phi = -\frac{L_\beta}{A}\frac{v}{V}(t) \quad . \qquad (11)$$

To complete the definition of the problem we must assume a landing flare manoeuvre which most conveniently is expressed as a function of time, i.e. H(t). Once H(t) is defined, equation (11) is transformed into an equation with time-variable coefficients as the left hand side and a time-varying input on the right. The manoeuvre chosen is illustrated in Fig.6. Starting from an initial height of 150 ft, the aircraft is assumed to descend along a straight glide path at an angle γ_A and to commence at an appropriate point a flare with constant normal acceleration Δn. The effect of the consequent change in α on the roll derivatives is ignored. The instant at which the flare is initiated has been chosen so that for each set of values of γ_A and Δn touchdown is tangential to the ground, at which point the computation is terminated.

Equation (11) is a linear differential equation with time-varying coefficients for which an analytical solution is not available. However, in the absence of external excitation, v(t) (i.e. with the right hand side equal to 0) the motion defined by this equation is an oscillation in roll with time-varying period and damping. The instantaneous values of these parameters for the range of heights considered have been calculated with the result given in Fig.7. It is seen that the period shortens and the damping of this simplified dutch-roll improves as the aircraft approaches the ground, the variation becoming most marked during the last ten feet.

It should be noted that although the simple dutch-roll model defined by equation (11) gives a very good approximation to the true dutch-roll with freedom in yaw and sideslip, the suppressions of these two freedoms leads to an overestimate of damping and to restore this to a more plausible value a constant increment $\Delta \ell_{\dot\phi} = +0.097$ has been subtracted from the values of $\ell_{\dot\phi}$ shown in Fig.5. This correction is reflected in the results shown in Fig.7 as well as the results obtained from the analogue studies now to be discussed.

4.2 Analogue computations

The mathematical model representing the simplified aircraft lateral motion and the appropriate glide-path giving the required time history H(t) was mechanised on an analogue computer. The roll behaviour was computed in these approaches in response to three distinct forms of disturbance.

(i) Initial displacement in bank angle at the point (H_0 = 150 ft) when the computation starts. This particular study simply shows the way in which the decay of the dutch-roll is influenced by the ground effect by comparison with the answer one would obtain with conventional analysis based on free-air values for the aerodynamic derivatives.

(ii) Aircraft initially undisturbed meets a pulse type side-gust as it passes through a given height (100 ft or 50 ft). This exercise shows in addition to the effect demonstrated in (i) also the reduction in sensitivity to side-gusts previously illustrated in Fig.4.

(iii) The aircraft is subjected throughout the landing manoeuvre to random turbulence. If a sufficient number of such approaches are computed and the bank angles at the instant of touchdown evaluated one obtains a meaningful statistical assessment of the consequence of the ground effect on the likely touchdown conditions experienced by the aircraft.

It must be noted that throughout this work pilots' control was not represented and that this prevents one from interpreting the results as strictly representative of real flying. It will be appreciated that to introduce a pilot response defined by a mathematical transfer function would require an arbitrary choice of the control gain, which might be even more unrealistic and therefore has not been attempted. In view of the extraordinary degree by which, according to the results of the present study, ground effect constrains bank angle at touchdown it is perhaps permissible to assume that pilots interaction is unlikely to make a significant contribution either to the benefit or to the detriment of the aircraft in this condition. This observation should not, however, be taken to be prejudicial to the value or the desirability of piloted simulation of this phenomenon, which indeed is strongly recommended.

5 RESULTS OF COMPUTER STUDIES

The results of the computer studies defined in section 4 are presented in Figs.8 to 11.

Fig.8 shows the roll response of the aircraft - performing an identical flare manoeuvre in each case to three different disturbances and in each case the result obtained with ground effect represented is compared with that one obtains if the ground effect is ignored, i.e. the result that corresponds to the picture one had so far of the behaviour of the slender aircraft.

(a) Initial displacement in bank angle by 10° at $H_0 = 150$ ft. It is clearly seen that the ground effect improves to a substantial degree the effective damping of the roll oscillation originating from this disturbance. The shortening of the period of this oscillation towards touchdown is also noticed.

(b) Side-gust equivalent to 2° sideslip and of one second duration as the aircraft passes through 100 ft height. Apart from the effect noted previously it is now also apparent that the aerodynamic ground effect reduces the initial bank angle disturbance in response to the lateral gust.

(c) A similar side-gust strikes the aircraft at 50 ft height. The effect of ground proximity in reducing sensitivity to the gust is now even more marked.

In Fig.9 the results of a series of computations is shown which were designed to illustrate how the flight path traversed by the aircraft during the final part of the approach affects the roll response of the aircraft to otherwise identical disturbances, namely a side-gust of 2^{o} magnitude and 1 sec duration met either at 100 ft or 50 height. No comparison is made with the case that ignores ground effect.

The aircraft is approaching in each case,initially,on a 3.2^{o} glide slope, but the flare is started progressively earlier, the normal acceleration for the flare being so adjusted that in each case a tangential touchdown results. Clearly the more gentle the flare, the longer the time the aircraft spends in close proximity to the ground and the more it will therefore benefit from the ground effect. The consequent reduction in the amplitude of the roll oscillation at touchdown is plainly apparent from the traces shown in Fig.9 and needs no further discussion.

To obtain a quantitative assessment a statistical study was made in which the aircraft with and without ground effect represented was 'flown' through lateral turbulence (an actual flight recorded time history was used) for a sufficient number of approaches (approximately 100) to allow statistically significant results to be deduced. Samples of these runs are shown in Fig.10. The values of bank angle recorded in these computations at the instant of touchdown were analysed with the results shown in Fig.11. This diagram shows the probability of exceeding a certain bank angle at touchdown for the aircraft with and without ground effect. As pilot's control was not represented in these computations the absolute values obtained in this study are unrealistic but there can be little doubt about the comparisons; ground effect is seen to reduce touchdown bank angle by a factor of approximately 7, showing a very substantial degree of attenuation.

6 *CONCLUSIONS*

Wind tunnel tests reported in Ref.1 had shown that a slender wing experiences substantial roll stiffness due to aerodynamic ground effect and that in addition roll damping is powerfully amplified by the same phenomenon. In the present Report the consequences of this on lateral control of a slender wing aircraft during the landing approach are investigated, based on the results of Ref.1.

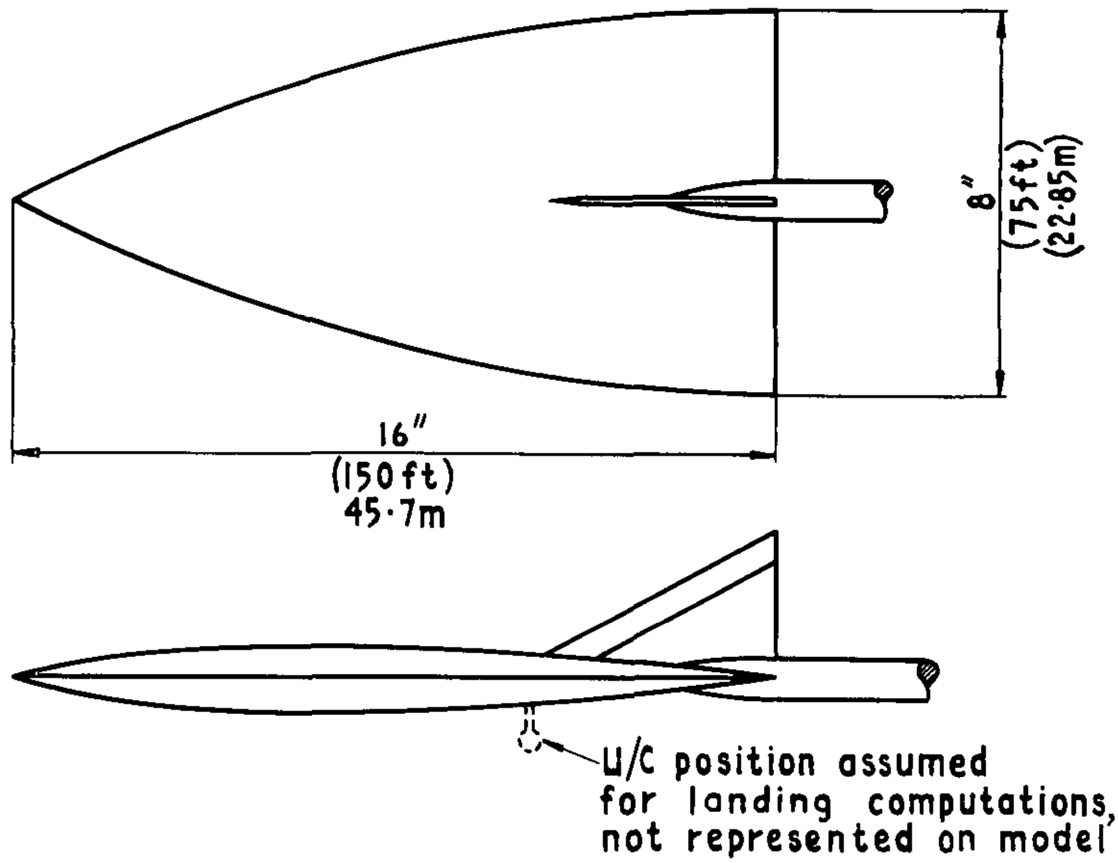
Ground effect is shown to reduce the sensitivity of the aircraft to lateral gusts and at the same time to improve the damping of the dutch-roll excited by such turbulence. The result is a substantial easing of the whole problem of lateral control in the final stages of the landing approach of such aircraft by comparison with previous theoretical and simulator work not representing this effect. Qualitative impressions of flight experience with the HP 115, the BAC 221 and Concorde would seem to support this conclusion. The wind tunnel data on which the present calculations are based were obtained on a model of a gothic wing with an aspect ratio of 3/4. This is a much more slender configuration than any of the aircraft mentioned above. As no theory exists to date by which this ground effect could be scaled to other wing planforms, it is not possible to make quantitative statements applicable directly to these aircraft. However, there is little doubt that the effect discussed here is important even for less extreme slender aircraft and perhaps also for conventional wings. To arrive at a rational assessment of the lateral control problems during landing in cross-wind and turbulence, ground effect must clearly be accounted for and to be in a position to do this it is strongly recommended that wind tunnel tests of the type reported in Ref.1 are made on representative aircraft models. Such data are particularly important for simulator studies of the landing manoeuvre and equally of course for a realistic analysis of automatic landing systems.

ACKNOWLEDGEMENT

The author wishes to express his gratitude to Mr. B. Jepson, a 'sandwich' student from Portsmouth Polytechnic, who carried out the analogue computation and most of the numerical analysis presented in this Report.

REFERENCES

No.	Author	Title, etc
1	T. B. Owen	Low-speed wind tunnel measurements of oscillatory rolling derivatives on a sharp-edged slender wing. Effects of frequency parameter and of ground. ARC R & M 3617 (1968)
2	W. J. G. Pinsker	The lateral motion of aircraft and in particular of inertially slender configurations. ARC R & M 3334 (1961)
3	W. J. G. Pinsker	The dynamics of aircraft rotation and lift-off and its implications for tail clearance requirements, especially with large aircraft. ARC R & M 3560 (1967)
4	W. J. G. Pinsker	Features of large transport aircraft affecting control during approach and landing. AGARD Report 421 (1962)



W = 300000 lb $\begin{cases} m = 136000 \text{ kg} \\ W = 1\cdot33 \text{ MN} \end{cases}$

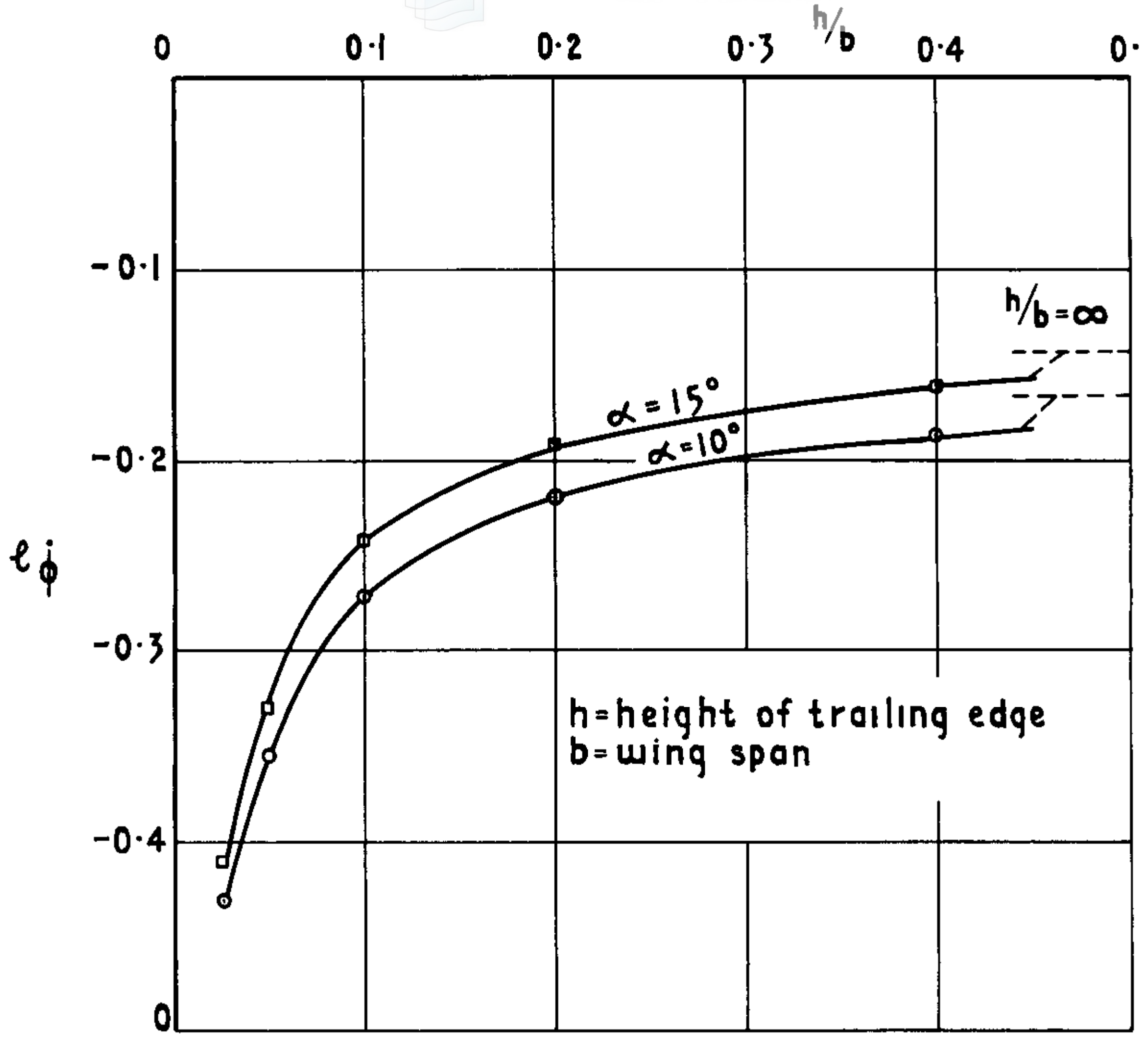
S = 7500 ft^2 ≡ 697 m^2

k_x = 11·4 ft ≡ 3·48 m

A = 39 x 10^6 lb ft^2 ≡ 1·65 10^6 kg m^2

V = 250 ft/sec ≡ 76·2 m/s

Fig.1 Geometry of wind tunnel model used in Ref 1 and full scale aircraft dimensions etc assumed for computer studies



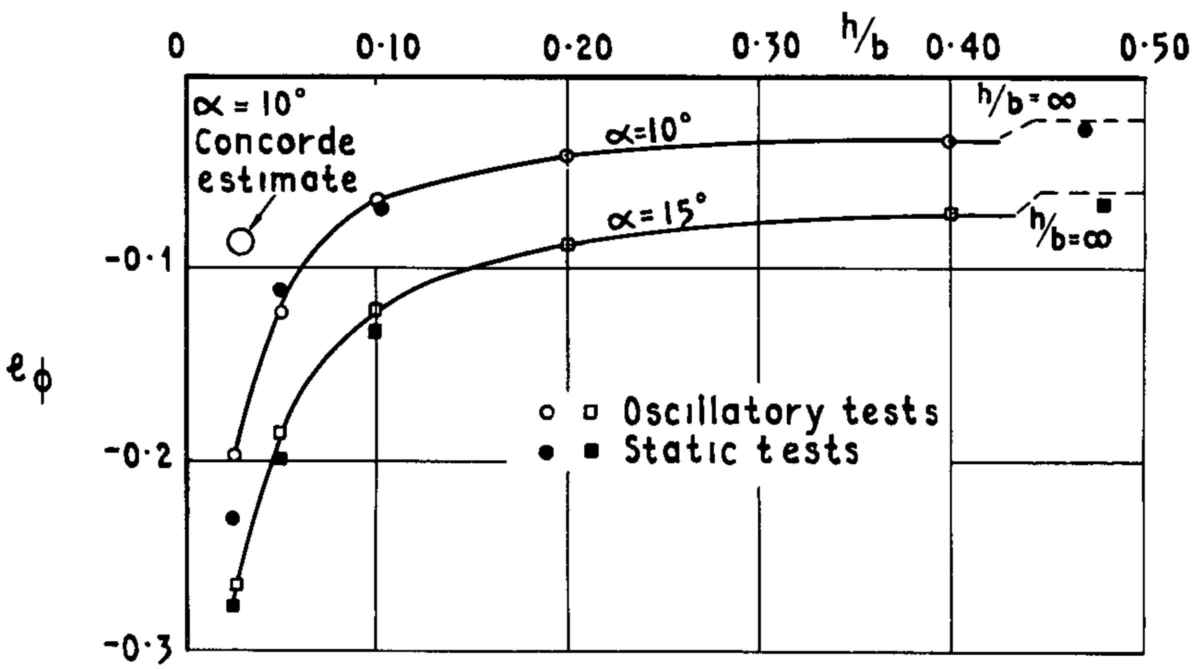


Fig 2 Summary of relevant w.t. results from Ref 1; roll damping and roll stiffness as a function of incidence and height from ground

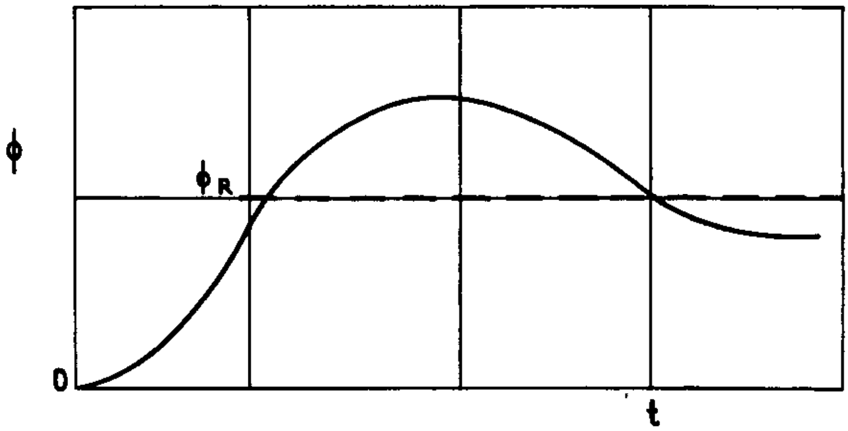


Fig.3 Initial response of slender aircraft to sidegust step function

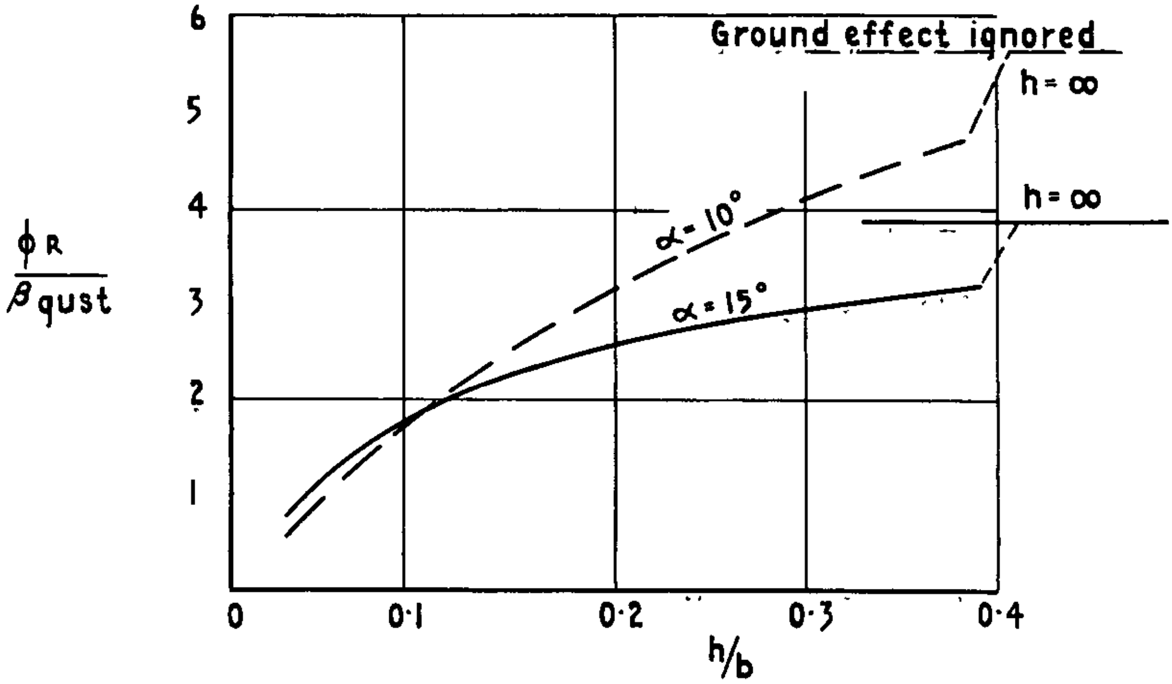


Fig.4 Quasisteady bank angle response to sidegust for Gothic wing tested in Ref 1, as a function of incidence and height above ground

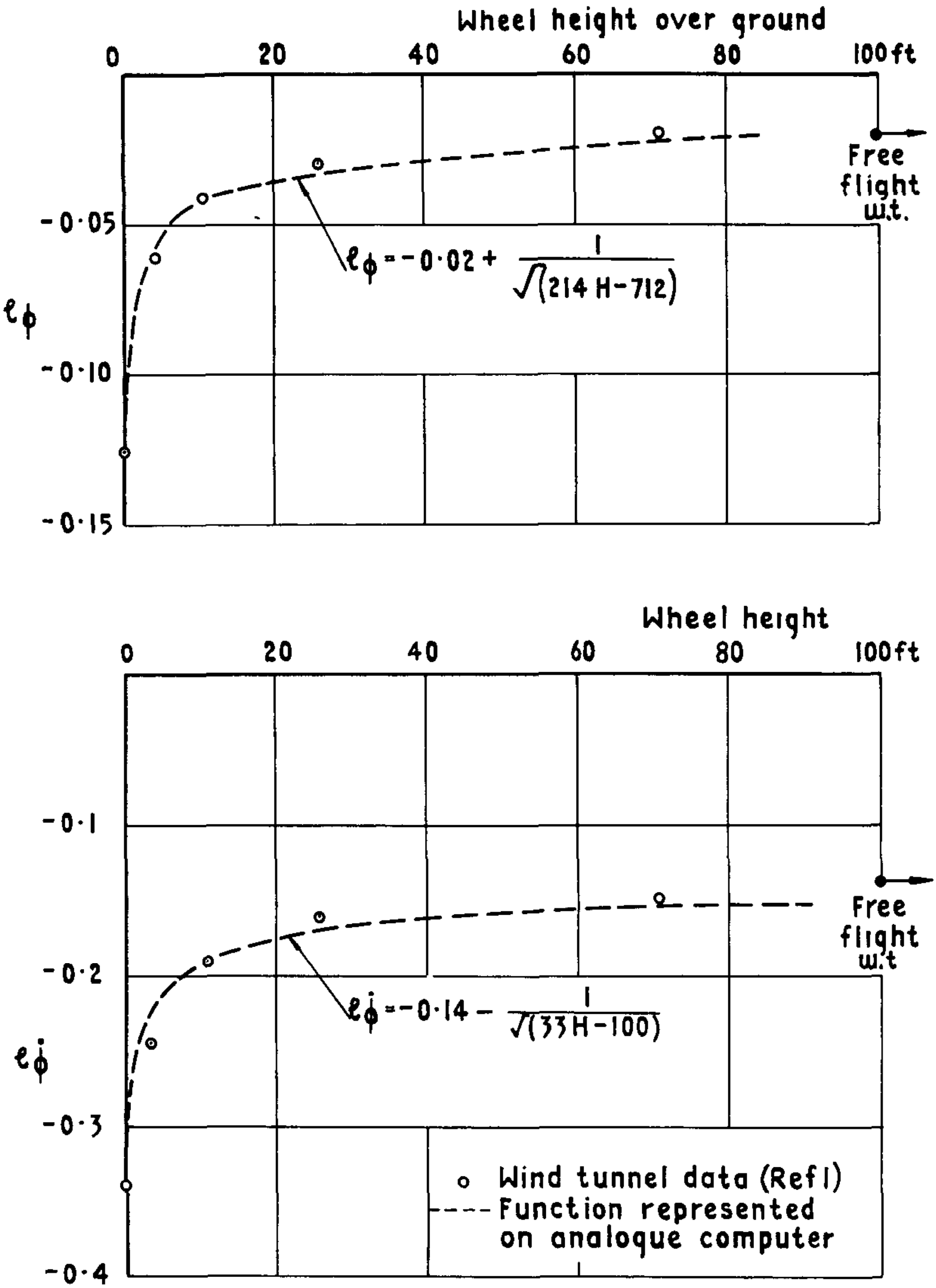


Fig 5 Mathematical representation of rolling derivatives for computer calculations

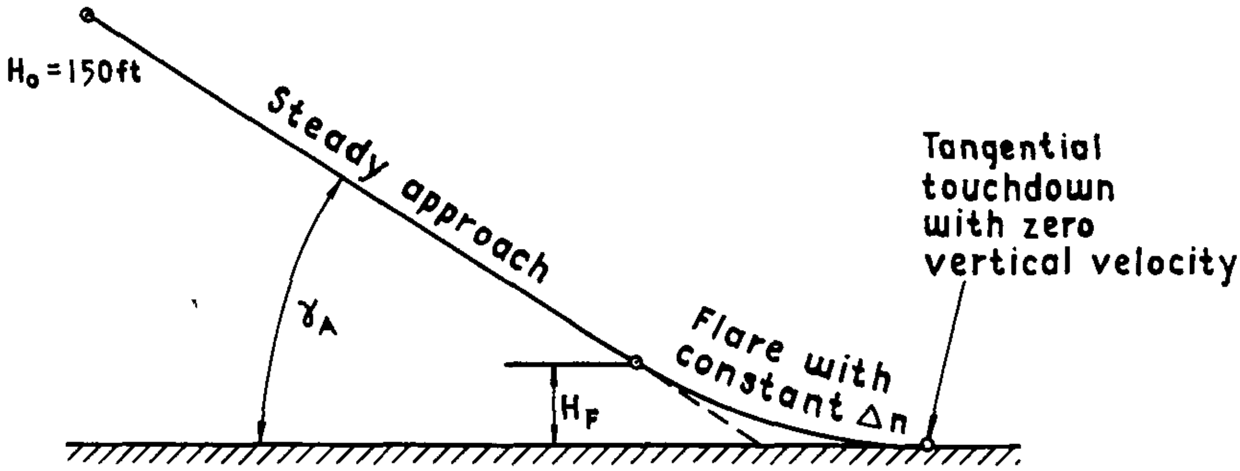


Fig.6 Landing manoeuvre assumed for the analogue computations

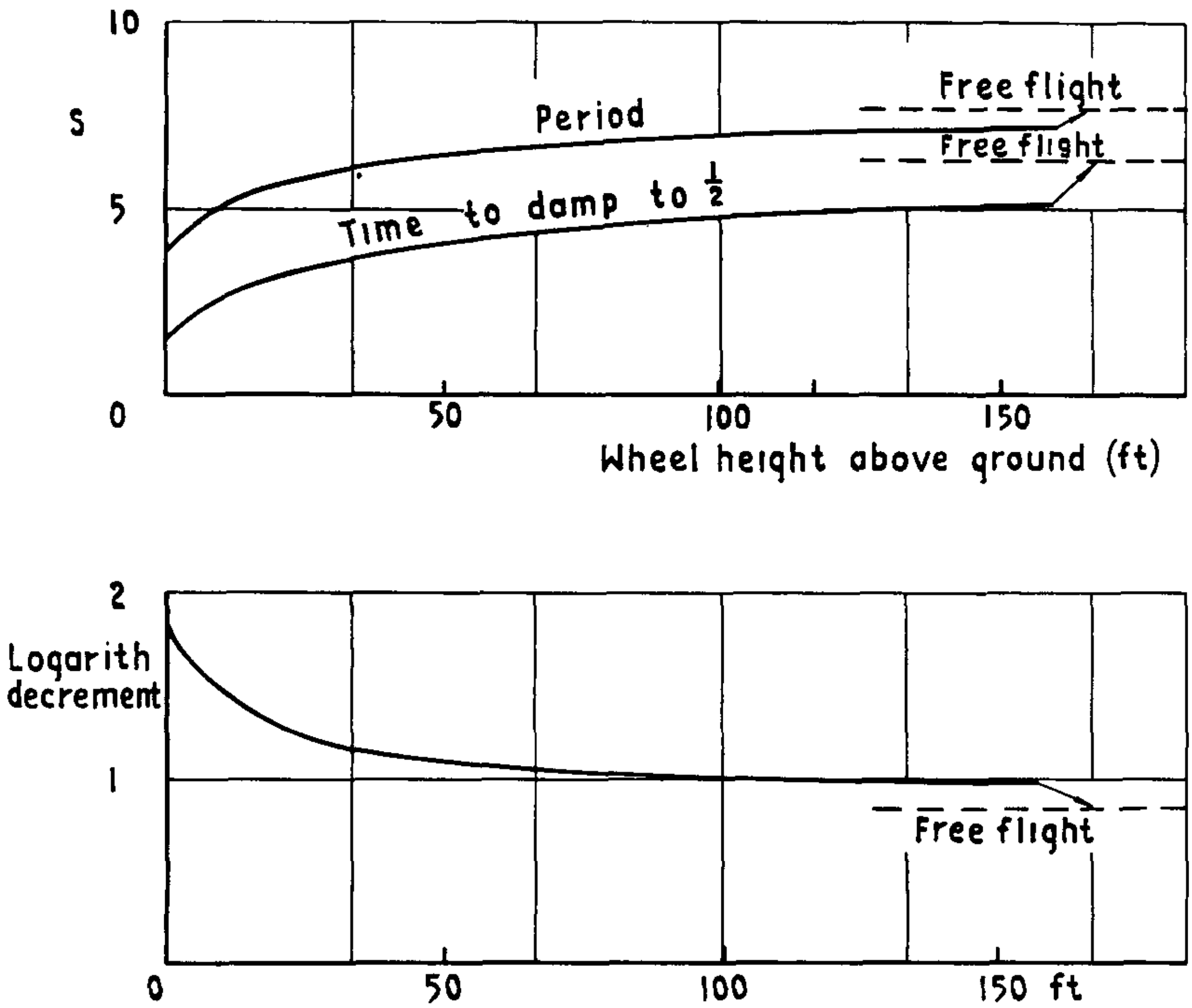
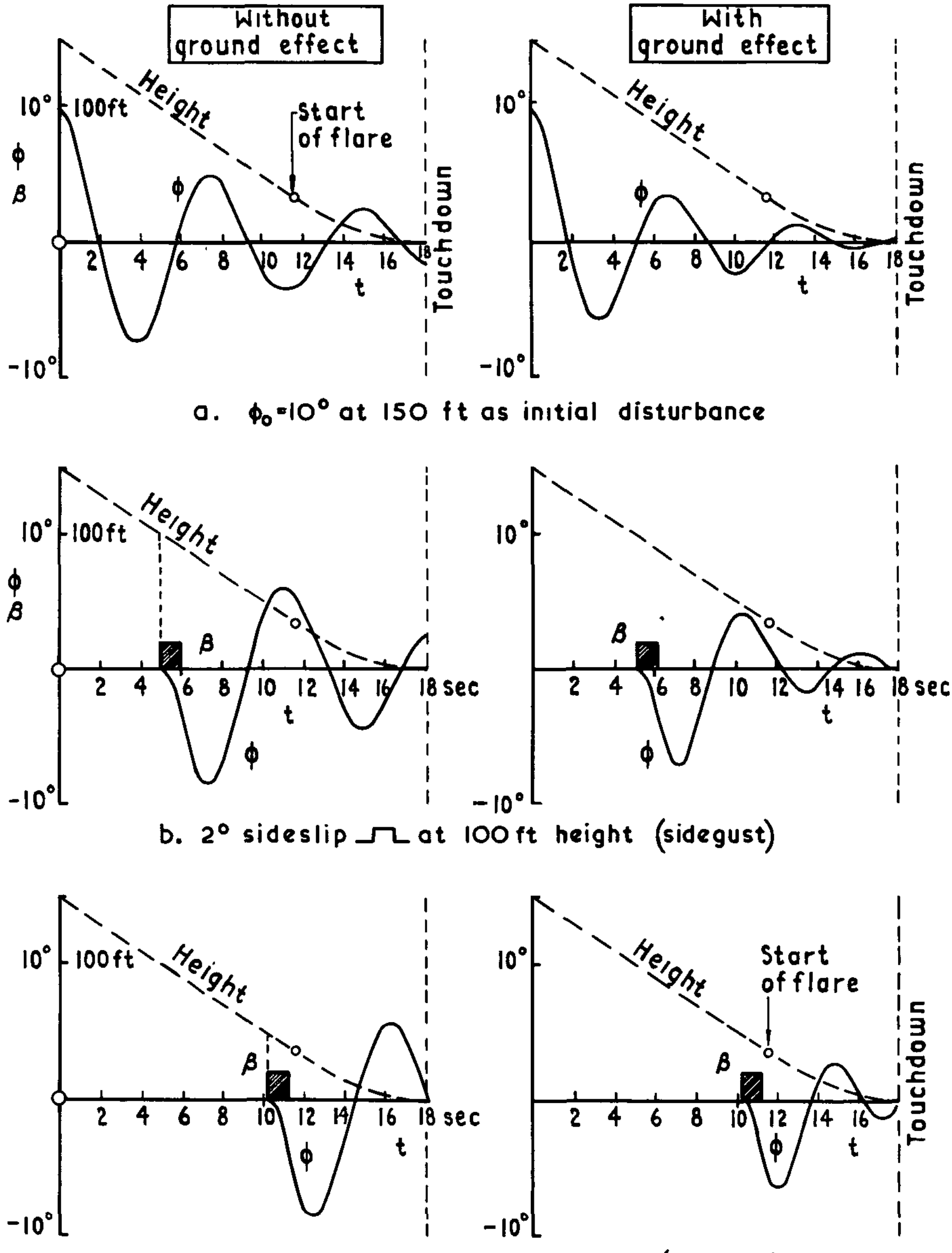


Fig.7 Aerodynamic ground effect on the characteristics of the dutch roll of the slender aircraft defined in Fig.1



a. $\phi_0 = 10°$ at 150 ft as initial disturbance

b. 2° sideslip ⎍ at 100 ft height (sidegust)

c. 2° sideslip ⎍ at 50 ft height (sidegust)

Fig.8 a-c Influence of aerodynamic ground effect on lateral motion during landing for three different disturbances. Approach at $\gamma_A = 2{\cdot}3°$ flare with $\Delta n = 0{\cdot}045g$

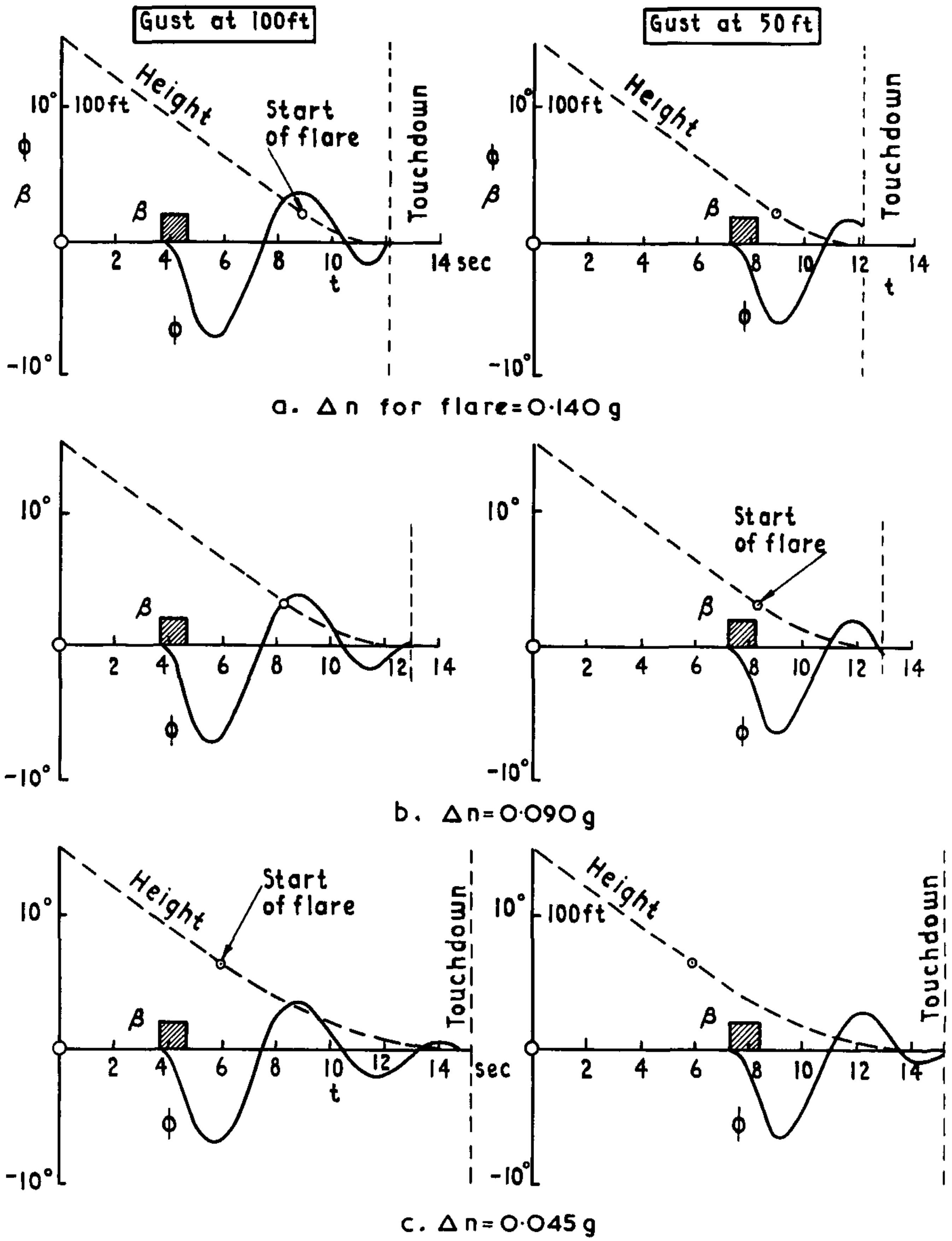


Fig.9 a-c Effect of flare g on decay of lateral disturbance due to ground effect. $\gamma_A = 3{\cdot}2^{\circ}$

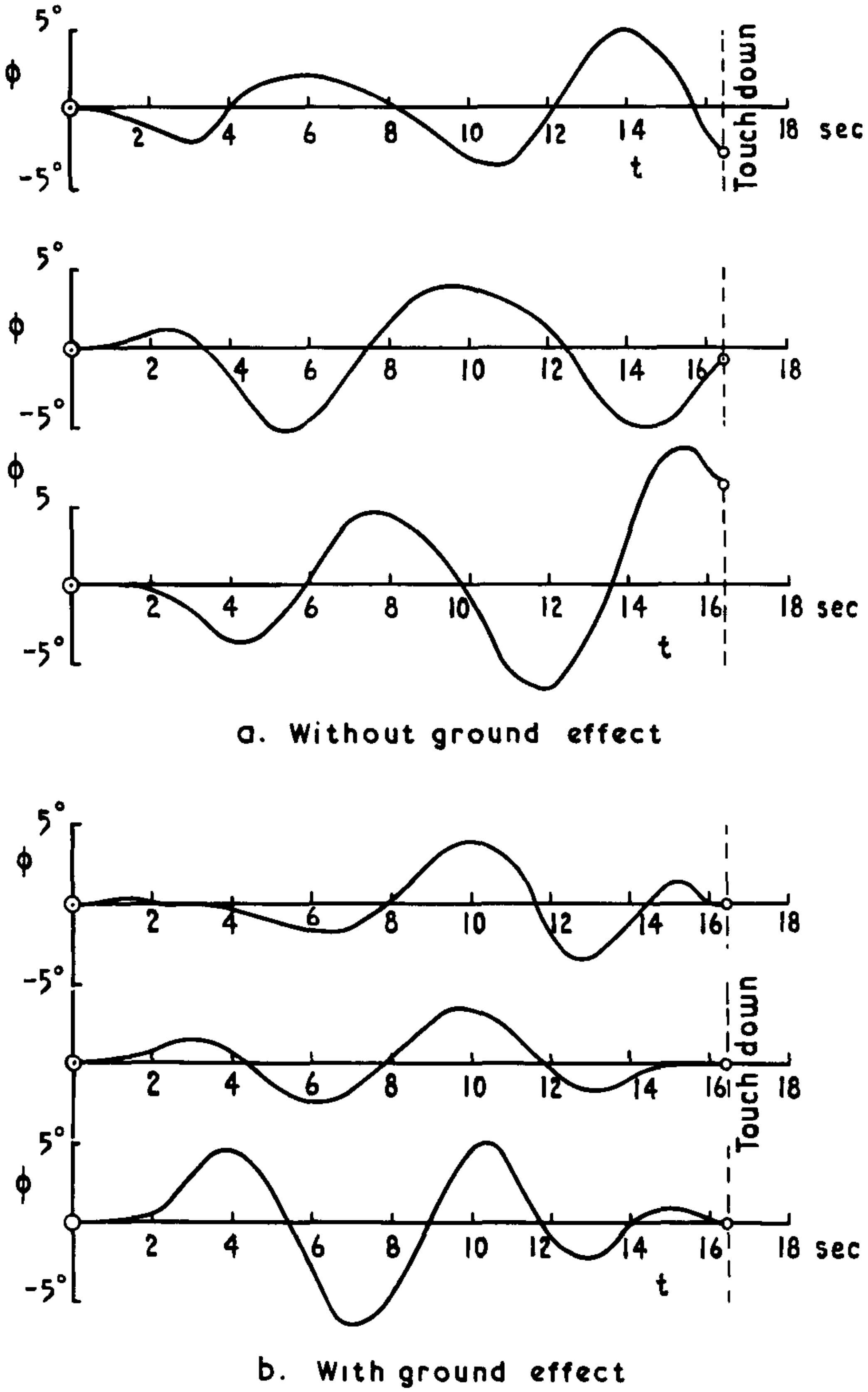


Fig.10a&b Typical examples of computed bank angles during landings in random lateral turbulence with and without ground effect represented

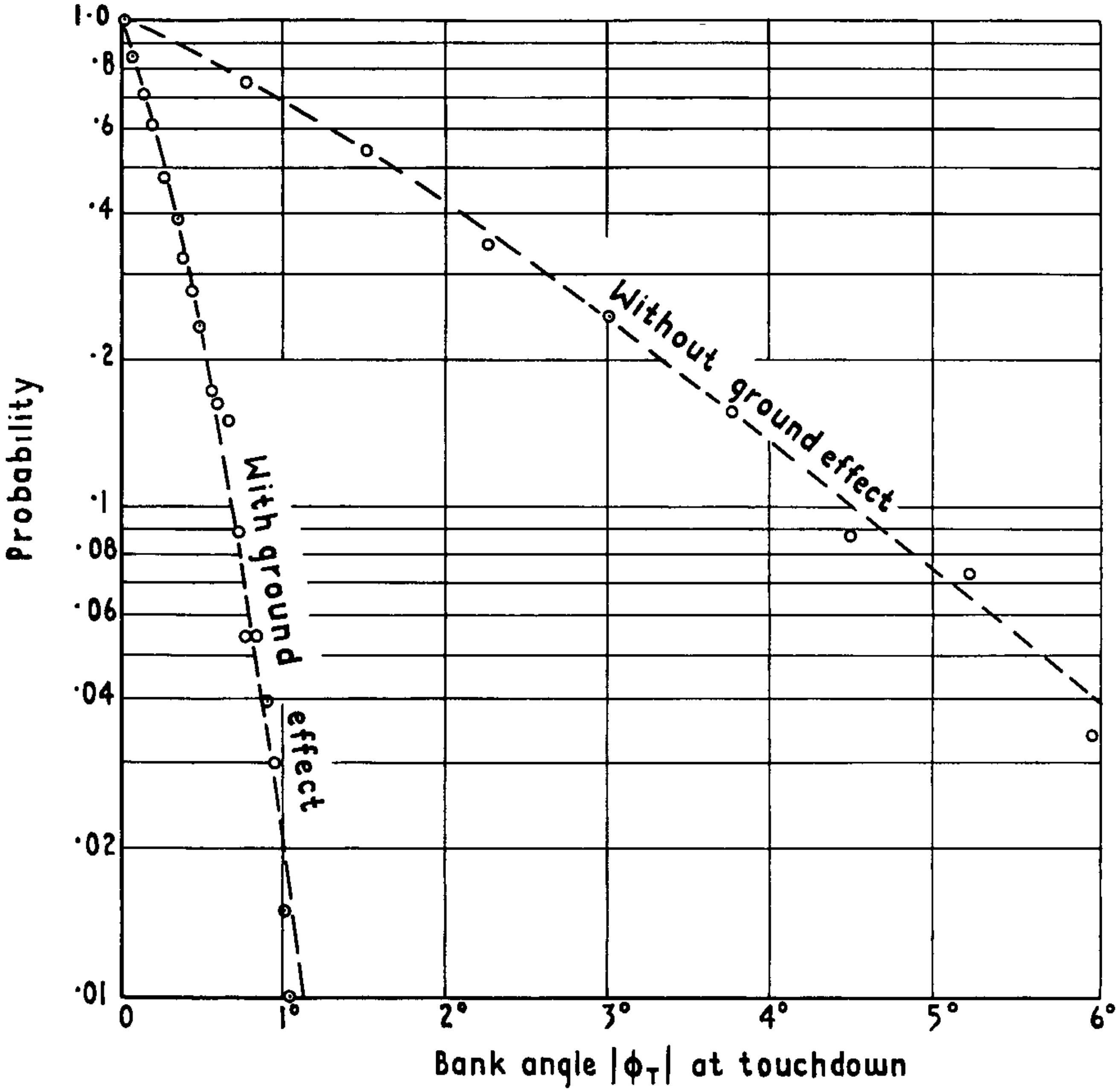


Fig 11 Probability of exceeding given bank angle at touchdown following approach in lateral turbulence with 0·11° rms equivalent sideslip, assuming no pilot control

Printed in England for Her Majesty's Stationery Office by the Royal Aircraft Establishment, Farnborough Dd.501371 K 4

ARC CP No.1152
May 1970

533.682 :
533.693.3 :
533.6.015.2
533.6.013.413
533.6 048.5
533.6.013.153

Pinsker, W. J G.

THE AERODYNAMIC EFFECT OF GROUND PROXIMITY ON LATERAL CONTROL OF *SLENDER AIRCRAFT IN* THE LANDING APPROACH

Recent wind tunnel tests have revealed the existence of a powerful ground effect on the rolling derivatives of a slender wing model. Analogue computer studies have been made which show the consequences of this phenomenon on the lateral behaviour of a large slender aircraft during landing approaches in the presence of side gusts. The ground effect is shown to exert a powerful *constraint on bank angle disturbances for* this class of aircraft, almost eliminating the effects of lateral turbulence as a control problem. Other possible consequences of this ground effect on various lateral control problems are also briefly discussed

ARC CP No.1152
May 1970
533.682 :
533 693 3
533.6 015.2
533.6 013 413 .
533 6 048.5 .
533 6 013.153
Pinsker, W. J. G.
THE AERODYNAMIC EFFECT OF GROUND PROXIMITY ON LATERAL CONTROL OF SLENDER AIRCRAFT IN THE LANDING APPROACH
Recent wind tunnel tests have revealed the existence of a powerful ground effect on the rolling derivatives of a slender wing model. Analogue computer studies have been made which show the consequences of this phenomenon on the lateral behaviour of a large slender aircraft during landing approaches in the presence of side gusts. The ground effect is shown to exert a powerful constraint on bank angle disturbances for this class of aircraft, almost eliminating the effects of lateral turbulence as a control problem. Other possible consequences of this ground effect on various lateral control problems are also briefly discussed

ARC CP No.1152
May 1970
533.682 .
533.693.3 .
533.6.015.2
533.6.013 413
533 6.048.5 .
533 6.013.153
Pinsker, W. J. G.
THE AERODYNAMIC EFFECT OF GROUND PROXIMITY ON LATERAL CONTROL OF SLENDER AIRCRAFT IN THE LANDING APPROACH
Recent wind tunnel tests have revealed the existence of a powerful ground effect on the rolling derivatives of a slender wing model. Analogue computer studies have been made which show the consequences of this phenomenon on the lateral behaviour of a large slender aircraft during landing approaches in the presence of side gusts. The ground effect is shown to exert a powerful constraint on bank angle disturbances for this class of aircraft, almost eliminating the effects of lateral turbulence as a control problem. Other possible consequences of this ground effect on various lateral control problems are also briefly discussed

DETACHABLE ABSTRACT CARD

C.P. No. 1152

Published by
HER MAJESTY'S STATIONERY OFFICE

To be purchased from
49 High Holborn, London WC1 V 6HB
13a Castle Street, Edinburgh EH2 3AR
109 St Mary Street, Cardiff CF1 1JW
Brazennose Street, Manchester M60 8AS
50 Fairfax Street, Bristol BS1 3DE
258 Broad Street, Birmingham B1 2HE
80 Chichester Street, Belfast BT1 4JY
or through booksellers

C.P. No. 1152

SBN 11 470400 7