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# Preliminary Flight Assessment of the Low-Speed Handling of the BAC 221 Ogee-Wing Research Aircraft

*by*

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# PRELIMINARY FLIGHT ASSESSMENT OF THE LOW-SPEED HANDLING OF THE BAC 221 OGEE-WING RESEARCH AIRCRAFT

by

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## SUMMARY

The handling of the BAC 221 slender-ogee-wing research aircraft, at speeds down to 114 knots ias and incidences up to 22°, is described.

Pilots considered the aircraft handling as pleasant, in general. The major problems were of lateral/directional control at high angles of incidence when difficulty was experienced in preventing large sideslip angles from building up. At all angles of incidence in the low-speed range, the response to aileron was oscillatory. Reducing the effective adverse aileron yaw of the aircraft by an interconnect, enabling the ailerons to drive the rudder, lessened the difficulties in sideslip control and the oscillatory response to aileron inputs was reduced.

Longitudinal control was good, but at $\alpha = 22°$ a mild pitch-up occurred. Aerodynamic buffet increased at this incidence and vortex bursting is thought to have reached forward to the rear parts of the wing.

Although approaches were made well below the minimum drag speed, speed control presented no difficulty, provided that it could be given full attention. Cross-wind take-offs and landings presented no problems except during the ground run. Side-step manoeuvres on the approach were made with no difficulty.

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*Replaces R.A.E. Technical Report 67281 - A.R.C. 29913.

CONTENTS

## 1 INTRODUCTION

The fundamental differences between contemporary jet transport aircraft and slender aircraft such as the Concorde, are the very small inertia in roll of the slender aircraft compared with its pitch and yaw inertias[1], and the fully developed wing vortex flow which is present throughout the flight envelope of the slender aircraft. These two features of the slender aircraft lead to handling characteristics at low speeds which are rather different from those of contemporary aircraft. Most of the initial flying of the BAC 221 slender ogee-wing aircraft was therefore devoted to an exploration of these low speed characteristics. Before discussing this flying it is convenient to consider briefly those aspects of the low speed handling of slender aircraft which are relevant to this Report.

It has been shown that due to its extreme inertia configuration, the lateral motion of a slender aircraft is dominated by the powerful constraint imposed by its inertia distribution, so that its Dutch roll and response to aileron are almost completely reduced to a motion about the principal longitudinal inertia axis[2]. At low speeds the aircraft flies at high incidence and it can easily be seen physically, that as the aircraft rolls about its inertia axis, some of this incidence converts to sideslip. A further feature of slender configurations, particularly at high incidence, is the large negative value of the rolling moment due to sideslip derivative, $\ell_v$, which implies a very large aerodynamic restoring moment opposing, for instance, an aileron application once sideslip has built up. The build up of sideslip can be further compounded by large adverse aileron yaw resulting from the large induced drag generated by the aileron surfaces of such a small aspect ratio wing. It may be noted that as distinct from other slender aircraft, such as the HP 115, which employs elevons covering the whole wing trailing edge, the BAC 221 has separate aileron and elevator surfaces, the former occupying the outer portions of the span. With full span elevons, asymmetric control application generates a powerful sidewash at the wing root due to the strong local gradient in lift loading, and this sidewash reacts on the fin in the sense to oppose, or even override, the adverse induced yawing moment. This effect is hardly noticeable with ailerons terminating further outboard, and in this respect the BAC 221 differs substantially from the other two slender aircraft mentioned. At high incidence a further adverse effect on roll response may be caused by a negative yawing moment due to rate of roll derivative, $n_p$ [3]. Data for this derivative are notoriously unreliable and no firm conclusion can be drawn at this stage. The response to aileron application thus tends to be oscillatory unless large co-ordinated rudder inputs are made to keep sideslip to a minimum. Pinsker suggested[1] that an interconnect to enable applied aileron to drive the rudder in phase could provide automatic turn co-ordination, and such a system has proved successful on the BAC 221.

Since $(-\ell_v)$ is large, and the inertia in roll is low, a slender aircraft can be expected to be sensitive to lateral turbulence. Low roll damping, another characteristic of slender aircraft, accentuates this problem.

A further problem which has received some analytical attention[4] is a possible loss of directional stability when a slender aircraft at high incidence is constrained by aileron control to fly wings level. Even though $n_v$ may be positive, but probably small, the destabilising effect of large $(-\ell_v)$ and of large adverse aileron yawing moments as control is applied to keep wings level, can dominate, and produce a directional instability. The controls fixed Dutch roll would still be stable, even with $n_v$ negative, since the Dutch roll is mainly roll and $\ell_v$ supplies the stiffness.

Another feature of some slender delta aircraft at very high incidence is that the usual aperiodic lateral modes, the roll subsidence and spiral modes, are replaced by a single oscillatory mode[1]. This mode is initially stable and of low frequency but as incidence increases, its frequency increases, and the mode eventually goes unstable. Computer studies[5] predict that the BAC 221 should exhibit this behaviour but at incidences outside the normal flight range.

The handling problems mentioned so far relate to lateral motion, but there are also two relevant problems in the longitudinal motion. First, it may be shown that the speed for minimum drag increases as aspect ratio decreases, and slender aircraft on the approach generally operate below the minimum drag speed in a speed-unstable state. This leads to problems of speed control during approach and landing[6]. A second, and related problem, is that, due to the high drag at low speeds, a speed can be reached below which level flight can no longer be maintained but no aerodynamic indication warns the pilot[7]; a conventional aircraft would normally have stalled at a higher speed but a conventional stall does not occur with the permanently separated vortex flow over a slender wing.

Flight research on slender delta aircraft was started at R.A.E. Bedford using the Handley Page HP 115[8,9] low speed research aircraft, having a delta wing with straight leading edges of 75° sweep. This aircraft gave considerable confidence in the performance of a simple slender delta planform at low speeds.

The BAC 221 research aircraft was built to extend this work to cover a greater portion of the potential flight envelope of the slender aircraft and to study the more representative ogee planform as distinct from the simple straight delta shape of the HP 115. The aircraft was converted from the first of the two Fairey Delta 2 supersonic research aircraft, by replacing the original 60° delta wing by an ogee-wing, and increasing the fuselage length by six feet. A longer undercarriage was fitted to satisfy a requirement for approach and landing at very high incidence at speeds lower than the normal approach speed. A clear cockpit canopy, and an eight inch extension to the fin were added later. A photograph of the aircraft and a general arrangement drawing are shown in Figs.1 and 2 respectively and its leading particulars are given in Table 1.

The aircraft was delivered to R.A.E. Bedford in May 1966 and it has been engaged mainly in a programme of low speed flying to investigate the problems discussed earlier. The analysis of the recorded data from this programme is proceeding but it is felt that a preliminary report, based mainly on pilot's reports of the low speed handling characteristics of the aircraft and on a limited assessment of the flight records, is worthwhile.

Computer studies[5] of the expected behaviour of the aircraft and a ground based simulation[10] of the aircraft in the approach configuration were made prior to the first flight of the aircraft and the results of these studies have been of use in assessing the flight tests. The simulation revealed that the handling characteristics of the aircraft, as represented by the simulation, should be satisfactory for its role as a research aircraft.

It should be stressed that the low speed flight tests of the BAC 221 revealed handling problems which were not foreseen. In particular, the occurrence of a directional instability when the pilot was trying to fly the aircraft with wings level at high incidence, stimulated a theoretical investigation of the problem[4].

## 2 WIND-TUNNEL AND THEORETICAL PREDICTIONS

Before considering the tests made on the aircraft it is worthwhile to indicate a few areas in which wind-tunnel results[11], and computer studies[5] using the wind tunnel results, suggested that problems might be experienced.

Fig.3 shows the elevator fixed pitching moment, about the normal flight centre of gravity, as a function of incidence for the clean aircraft and the aircraft in the approach configuration (undercarriage down and nose drooped 8°). The unusually large trim change between the two configurations is due to the unusually long undercarriage of the aircraft. It is seen that at about $\alpha = 20°$ in the approach configuration, and $\alpha = 22°$ clean, there is a region of pitch-up after which the pitching moment becomes stable again. Although the breaks in the pitching moment predicted by these tunnel results appear fairly sharp, the curves do not indicate a superstall. Only 2° of down elevator would be needed to recover the aircraft back to the lower incidence stable regime.

Fig.4 shows expected values of the three lateral stability derivatives, discussed in section 1, as functions of incidence, for the clean aircraft and the aircraft in the approach configuration. The data were obtained from tests at intervals of 4° in incidence and are presented in body axes. The rolling moment due to sideslip derivative $\ell_v$ is negative and relatively large and the corresponding yawing derivative $n_v$ is small and positive up to about $\alpha = 20°$ when it drops fairly rapidly to a large negative value. The yawing moment due to rate of roll derivative, $n_p$, has a small negative value at low incidence, changing progressively in the positive direction until at about 20° incidence this trend is accelerated, leading to large positive values at very high incidence. The major lateral/directional problems which would be expected on this data alone are an oscillatory response to aileron due to large $(-\ell_v)$ and small or negative $n_v$, and the associated problem of directional instability if the aircraft is constrained to zero bank angle. The stick-fixed Dutch roll was expected to be stable up to $\alpha = 30°$ at least, even though $n_v$ was negative at high incidence.

The sideslip derivatives $\ell_v$ and $n_v$ were obtained by drawing the best straight line through plots of rolling and yawing moment coefficients, $C_\ell$ and $C_n$ respectively, versus sideslip for the range $-3° \leq \beta \leq +3°$. However, Figs.5 and 6, which give plots from wind-tunnel results[11] of $C_\ell$ and $C_n$ respectively, in body axes, versus $\beta$ for $\alpha = 18°$ and 22° for both clean and approach configurations show that at the higher incidence the dependence on $\beta$ becomes highly non-linear. For small angles of sideslip the slope of the yawing moment curve implies negative $n_v$ but for $\beta$ greater than about $3°$, the slope, and hence $n_v$, are positive, particularly in the clean configuration. It seemed likely that at high incidence the aircraft would be easier to fly steadily at $|\beta| > 3°$ rather than at zero sideslip.

The predicted aileron and rudder angles, derived from Ref.11, required to hold the aircraft in a steady sideslip are shown in Fig.7. The remarkable feature is that at $\alpha = 22°$ and up to $|\beta| = 4°$, the combination of control and sideslip derivatives requires control deflections in the same sense rather than the normal crossed controls. This indicates a static instability which is shown by Pinsker[4] to be associated with the reversal in sign of the effective directional stability parameter

$$\bar{n}_v = n_v - \ell_v \frac{n_\xi}{\ell_\xi} \qquad (1)$$

where $\ell_\xi$ and $n_\xi$ are respectively the rolling and yawing moment derivatives due to aileron. Beyond $|\beta| = 4°$, changes in sideslip would require changes in control deflection in the normal sideslipping sense, since at large sideslip angles the parameter $\bar{n}_v$ again becomes positive.

A further important effect related to $\bar{n}_v$, is the directional instability which may occur when a slender aircraft is constrained, using aileron, to wings level flight at high incidence[4]. It was shown that the onset of the instability is closely associated with a change in the sign of $\bar{n}_v$ from positive to negative. The variation of $n_v$ and $\bar{n}_v$ with incidence is plotted in Fig.8 for both body and aerodynamic stability axes. As stated in Ref.4, although the values of $n_v$ differ quite considerably in the two axis systems, the corresponding values of $\bar{n}_v$ are about the same. For this aircraft, the influence of the term $\ell_v n_\xi/\ell_\xi$ in equation (1) is thus much greater in aerodynamic stability axes; in body axes, $n_v$ alone would provide an adequate measure of bank angle constrained directional stability.

It was also predicted[5] that the second oscillatory mode, formed by the coincidence of the roll subsidence and spiral modes at $\alpha \simeq 19°$, would become unstable at $\alpha \simeq 24°$, but the latter incidence has not been attained in the flight tests so far and the presence of the mode has not been conclusively established.

Wind-tunnel results suggest that vortex bursting, close to or ahead of the wing trailing edge, and associated aerodynamic buffet, will occur at high incidence, probably in the region of the pitch-up at zero sideslip, but possibly at a lower incidence for larger sideslip angles.

To sum up, it appeared likely that the major problems in flying the aircraft would occur at high incidence. At around $\alpha \approx 20°$, the predicted longitudinal and lateral characteristics both showed features which individually might be expected to increase the demand on the pilot, and in combination could be very demanding indeed.

## 3 CONTROL SYSTEM

Before describing the handling characteristics of the aircraft it is necessary first to describe briefly the flying control system; some characteristics of this system are unsatisfactory and tend to mask or degrade the basic handling characteristics of the aircraft.

The flying controls are fully powered, with a duplicated hydraulic system, and there is no provision for manual reversion. Pitch control is provided by inboard elevators on the trailing edge of the wing, and lateral/directional control by outboard ailerons and a single rudder, (Fig.2). The elevator and aileron circuits have variable gearing; the pilot can select in flight any aileron gearing between 1:1 and 6:1 (full stick movement gives 1/6 maximum control surface movement), and any elevator gearing between 1:1 and 9:1. Lower gearings (higher stick movement per unit control surface movement) are normally selected with increasing speed, but for low speed flying, elevator gearing of 1:1 and aileron gearing between 1:1 and 2:1 were normally used. This was particularly important for the very low speed flying where maximum control surface movement must be available should recovery from a spin be necessary.

A number of deficiencies are apparent in the control system, most of which are related to aircraft or control rod flexibility and are basically due to small control rod movements causing relatively large control surface movements. It should be noted that in converting the original Fairey Delta 2 to the BAC 221, economy required the retention of as much of the original hardware as possible. The somewhat deficient control rods were therefore retained although new aileron and rudder jacks were fitted. The extension of the fuselage by 6 ft increased the possibility of flexibility.

Pilot awareness of flexibility was increased by the fitting of variable rudder pedal stops to prevent application of excessive rudder movements. Due to aircraft flexibility, and possibly also to temperature effects, the pedal stops do not correspond to a fixed rudder position and it is possible, when the permissible rudder movement is small, for all the permissible pedal movement in one direction to be used in trimming the rudder to zero, leaving no rudder control available in that direction and movement beyond the nominal limit set by the stops in the other. Full available rudder movement is permissible at low speeds and this problem is not then significant.

The aileron circuit suffered from a number of related problems. The servo-valves in the powered flying control system required relatively large operating forces and the control linkages were flexible. Lateral stick movement produced control linkage distortion until the valve break-out forces were overcome. There was a very significant lag of control surface movement behind stick movement (a phase lag of as much as 60° in some oscillatory conditions) and differential control surface movement was possible. This made roll control more difficult for the pilot and could lead to a pilot induced 'lateral rock' when very accurate flying was required[12].

Due to aircraft flexibility, and possibly also to temperature effects, the aileron rigged-up angle changed from its ground setting and throughout a flight. Similarly the effect of flexibility meant that a central stick position did not necessarily mean neutral aileron.

The aileron trim system is unsatisfactory in that the control surface continues to move after release of the trim switch. This makes accurate lateral trimming difficult.

After the completion of this first phase of flying, the aileron jack system is now being considerably modified to reduce the operating forces and it is hoped that this will improve the roll control of the aircraft.

An 'auto-stabiliser', having limited authority over both rudder and aileron, and an 'auto-throttle' are fitted to the aircraft. They can be used to vary the stability of the aircraft, both in a stabilising and a destabilising sense. The only part of these systems operative during the low speed flying was the aileron/rudder interconnect mentioned earlier.

The interconnect has variable gearing between the aileron and rudder giving a maximum rudder angle increment equal to the incremental applied aileron angle. The maximum permissible authority is a 5° increment of rudder deflection; a wash-out term is always included so that an aileron-demanded rudder deflection decays with a time constant of 10 seconds if no further aileron movement is made. Although the full range of gearing was checked in flight, only the highest gearing (rudder increment = aileron increment) was used for the low speed flying.

## 4 FLIGHT TESTS MADE

Since delivery at R.A.E. Bedford, the aircraft has made 67 flights, of which 26 investigated specific aspects of the aircraft's low speed handling and a further 12 flights were for pilot familiarisation. The aircraft has been flown by four R.A.E. pilots, who made 30, 21, 15 and 1 flights respectively.

The data for this Report comes from two sources. The first is normal post-flight pilot's reports and debriefings and also two consolidated flight reports written by the pilots with most experience on the aircraft. A report by one of the pilots on handling slender deltas has now been published[13]. The second source is a preliminary assessment of the recorded flight data which enabled the pilots' comments to be related to measured aircraft responses.

It is useful at this point to list those of the parameters recorded on paper trace recorders which are relevant to this exercise:

Incidence
Sideslip
Angle of bank
Accelerations along 3 body-datum axes
Angular rates about 3 body-datum axes
Lateral stick position
Rudder pedal position
All control angles
Throttle position
Free stream static pressure
Pitot pressure
Free stream total temperature

The starboard wing of the aircraft was liberally tufted and a cine-camera mounted on the fin tip was used to photograph the flow patterns shown. Although only a preliminary assessment of the recorded data has so far been made, this list gives an indication of the handling information that will be available when analysis is complete.

The low speed flight tests were designed to obtain a general assessment of the aircraft's handling, as well as to study specific handling problems associated with the slender configuration. The tests involved manoeuvres, within the normal flight envelope, which were expected to be demanding for the pilot, and also an extension of the flight envelope to very low speeds and very high incidence.

Specific manoeuvres investigated were side-step manoeuvres on the approach, cross-wind take-offs, approaches and landings, and recovery from steady flight below the zero rate of climb speed. Normal approach speeds for the aircraft are below the minimum drag speed and some comments can be made on the ease of speed and attitude control under this condition. The extension of the flight envelope to very low speeds was designed to investigate the expected deterioration of handling characteristics, particularly in lateral/directional control, and more generally to obtain some experience of the flight characteristics which might set an ultimate limit to low speed control for this type of configuration not subject to stalling. A limited investigation of the behaviour of the aircraft with the rudder-driven-by-aileron interconnect operative was made up to high incidence.

It was necessary to proceed with caution when extending flight into the very low speed regime and the test technique used is worth describing. The engine intakes had not been tested at values of incidence greater than 18° and it was essential to establish that engine characteristics were acceptable at higher incidence. A ram air turbine to provide hydraulic pressure in the event of engine failure was extended prior to a speed reduction, and the aircraft was positioned suitably for an engine-out landing should this be necessary. The optimum control gearing (between stick and control surface) for spin recovery was selected. An anti-spin parachute was fitted, a chase aircraft was in attendance and a ground safety pilot monitored the pilot's continuous voice transmissions.

Each test was commenced between 30000 and 35000 ft altitude at a stabilised speed of 135 knots ias at 7800 engine rpm without reheat, (maximum power is at 8200 rpm). Speed was then reduced slowly, using elevator, without altering the engine power setting, until an incidence 2° greater than any previously attained was reached, as shown by the pilot's incidence meter. This incidence was held for $\frac{1}{2}$ min during which the pilot endeavoured to hold the aircraft in straight, wings level flight. The incidence was then decreased by 4° and, when the aircraft was stabilised in this condition, the response of the aircraft to rudder kicks and elevator pulses, its trim in steady sideslips, and engine response to throttle movement were investigated. During flight at previously unattained incidence, the engine relight button was continuously pressed, and during the manoeuvering after incidence reduction, limits of +2° on incidence increases and ±5° on sideslip were imposed. It should be noted that during the speed reductions the aircraft was descending rapidly due to the high drag at the low airspeeds. The test was always terminated by 20000 ft using reheat, so that reheat lighting could be investigated at high incidence.

## 5 HANDLING ASSESSMENT

Before delivery to R.A.E. Bedford the aircraft had been cleared for flight down to 135 knots ias (equivalent to $\alpha \simeq 17°$). The initial period of flying at Bedford was concerned mainly with pilot familiarisation and with the measurement of the aircraft pitot-static pressure errors throughout the speed range. During this time the pilots were able to assess the general handling of the aircraft before specific handling investigations, which included extension of the flight envelope to speeds below 135 knots ias, were started.

It is convenient to discuss first the general handling characteristics of the aircraft at low speeds (defined as 135 to say 200 knots ias) and very low speeds below 135 knots ias, including such features as cross-wind take-offs and landings and speed instability on the approach, and finally to describe specific topics such as sidestep manoeuvres on the approach, recovery from flight below the zero rate of climb speed and use of the rudder-driven-by-aileron interconnect.

The choice of 135 knots ias as the boundary between low speed and very low speed flying is not arbitrary as it corresponds to the low speed boundary of the early flight envelope. It was not expected that unsatisfactory aspects of the aircraft handling would appear at speeds above 135 knots ias but that this speed would leave a reasonable incidence margin in hand. The choice of 200 knots ias, $\alpha \simeq 9°$, is more arbitrary, but it is a speed below which Mach number effects are unlikely to be significant at moderate altitudes. A few results at lower incidence have in fact been included in this Report.

During the very low speed flying, indicated airspeeds as low as 114 knots and 116 knots in the clean and approach configurations respectively were reached, corresponding to an incidence of about 22°.

## 5.1 Low speed handling

### 5.1.1 General

The pilots found that their handling evaluation was made difficult by the deficiencies in the control system. The nature of the response of a slender aircraft to control movements is such that it is virtually impossible, and certainly not advisable, to consider stability and control separately, but some aspects of the control system were such that their effects had to be separated out before a meaningful assessment of the 'true' aircraft handling was possible.

In spite of control system deficiencies, the BAC 221 was described as pleasant to handle in all respects. One pilot, some six months after he last flew the aircraft, remembered it as 'an unremarkable aeroplane'. Test pilots are reasonably accustomed to remarkable or demanding research aircraft and possibly their judgement in this respect would be less severe than that of others, but nevertheless such a comment on a radically new aircraft, after flight in it at the limiting extremes of its flight envelope, can almost be regarded as a compliment.

### 5.1.2 Lateral/directional

The lateral/directional aspects of the aircraft handling provoked most comments. This is not surprising,since the slenderness of the aircraft naturally reveals itself more in the lateral/directional handling and it was here also that control deficiencies lay.

The unsatisfactory control system probably prejudiced the aircraft's handling most by the deficiencies in the aileron circuit described in section 3. Small lateral stick movements did not result in corresponding aileron movements because the valve break-out forces first allowed the flexibility in the control circuit to be taken up. Larger stick movements were transmitted to the controls, but again only after the system flexibility was taken up. There was thus a built-in lag of aileron behind stick movement and a relative absence of small aileron movements, a classical situation for over-control by the pilot, which led to a 'pilot induced' lateral-rocking oscillation[12]. In addition lateral trimming was difficult because the ailerons continued to move after the aileron trim switch was released.

Even in calm air it was found very difficult to fly the aircraft wings level. Any small rolling disturbance tended to lead to a bout of 'lateral rock' if the pilot applied aileron corrections. It must be made clear that the lateral rocking oscillation should be distinguished from the fundamental oscillatory response to aileron of a slender aircraft described below. Nevertheless, a less slender aircraft with the same control system deficiencies as the BAC 221 would perhaps be more tolerant to them, as indicated by the Fairey Delta 2, which did not suffer from lateral rock, but which almost certainly had control deficiencies similar to (but probably less marked than) those of the BAC 221.

The change of directional trim due to aircraft flexibility also prejudiced pilot opinion, particularly at high speeds when 3° rudder pedal stops were specified, but more than 3° equivalent pedal movement was needed to centralise the rudder.

Both the aileron and rudder controls are adequately powerful. Due to its slender nature, the aircraft responds rapidly in roll, both in response to control inputs and to lateral gusts. A typical recorded time history of a roll in response to a step aileron input at 150 knots ias is shown in Fig.9. The rudder angle was virtually constant throughout the manoeuvre. The response to aileron is seen to be typical of slender aircraft, in that sideslip builds up due to roll about an axis close to the principal longitudinal inertia axis (and far from the aerodynamic stability axis) and the effect of large $(-\ell_v)$ causes the roll rate to be oscillatory. About 2 seconds after the aileron input, the rate of roll does in fact reverse its sign; the oscillatory nature of the bank angle during the manoeuvre is clearly seen.

The pilot found that it soon became instinctive to apply large rudder movements in co-ordination with aileron during banking manoeuvres. To remove the oscillatory nature of the response shown in Fig.9 it is quite likely that perhaps half the available rudder deflection might be used.

The Dutch roll responses to rudder kicks, after which the controls were held fixed and neutral, at 150 knots ias and 125 knots ias are shown in Fig.10a and 10b respectively. In body axes, the roll/yaw ratio is moderately high at the higher speed but very high at the lower speed where the yaw trace shows virtually no evidence of the Dutch roll motion. The relatively high frequency oscillation shown on the rate of yaw trace is a spurious signal due to an instrumentation fault and should be disregarded. Some measured Dutch roll periods are compared with estimated values[5], derived from wind-tunnel results, in Fig.11 for both the clean and approach configurations of the aircraft. The estimates are seen to be in good agreement with the measured values in the range where data are available. At higher incidence the aircraft could not be flown steadily enough for an assessment of its Dutch roll characteristics to be made and it is not possible to establish whether the rapid predicted increase in period does in fact occur.

Agreement between the predicted[5] and measured Dutch roll damping, expressed as cycles to half amplitude, shown in Fig.12, is reasonable for the clean configuration, but poor for the approach configuration. In the incidence range where flight results are available, the Dutch roll damping is seen to be adequate, but slightly less so in the approach configuration than in the clean configuration, in contrast to the computer predictions. However, at higher incidence, the inability to fly the aircraft sufficiently steadily to make Dutch roll assessments, possibly suggests a reduction in damping in this region, again in contrast to computer predictions, but other factors are probably equally important.

The main problem at very low speeds is lateral/directional control. Pilot technique becomes an even more important factor than usual in flying the aircraft and pilots are perpetually 'on the steep part of the learning curve' as they continually develop their technique to cope with more demanding situations as flight at increasing incidence is attempted.

Fig.13 illustrates a situation which was at first thought to be limiting but further experience showed this not to be the case. The figure shows the elevator and starboard aileron movements during speed reductions to 119 knots and 117 knots ias respectively with the aircraft in the clean configuration. The aileron movements are the prime interest and it is remarkable that such a change in character should appear with a relatively small speed reduction. At both speeds there is evidence of relatively small amplitude, high frequency aileron activity of period about 1·3 sec; the amplitude is perceptibly greater at the lower speed. However, the principal distinction between the two cases is that at the lower speed there is a large amplitude long period (approximately 16 sec) aileron movement, which is practically absent at the higher speed. The short period cycling has rather greater than twice the expected frequency of the Dutch roll mode at an incidence of about 21° but is probably associated with the pilot's response to this mode and with his excitation of lateral rock. The origin of the long period oscillation is not fully understood, but it is likely to be associated with either the second oscillatory mode or the wings level directional oscillation, particularly the latter, since the pilot's primary object was to keep wings level during this record. Both these modes are expected to be of fairly long period at this incidence but insufficient data has been analysed to determine which, if either, is present.

It is seen that nearly full negative aileron was applied at the lower speed. The pilot was concentrating mainly on keeping the wings level, and fairly large sideslip excursions were permitted before large corrective rudder inputs were made. However, it was found that if the pilot concentrated on preventing sideslip from building up, rather than on correcting sideslip once it had built up, or even tolerating it, then the aircraft could be flown much more steadily at a given speed than if bank control was the primary object. Moderate excursions in bank angle were tolerated. The dynamics of the situation are complicated by the non-linearity of yawing moment coefficient with sideslip whereby, at high incidence, the aircraft may be directionally stable at large sideslip, but not within a range of small sideslip angles (Fig.6). It was possibly because of this, albeit unconsciously, that pilots were originally prepared to tolerate large sideslip angles, since the aircraft would then respond in a more conventional manner. It may also explain the asymmetric use of aileron shown in Fig.13b.

5.1.3 Longitudinal

Longitudinal control was good at low speeds (and throughout the speed range) and ample control power was available. Selection of too high an elevator gearing at the higher speeds could lead to pilot induced oscillations but the difficulty disappeared with lower gearings. As speed was reduced, pilots reported a noticeable but gentle nose-up trim change at about 18° or 19° incidence for the aircraft in the clean and the approach configuration respectively. At a somewhat higher incidence, approximately 22°, a smooth pitch-up occurred. The latter appeared to agree quite well with the wind-tunnel predictions, Fig.3, but the earlier trim change was not predicted and was not detectable in flight records. The effect may really be due to a flattening of the curve of elevator angle to trim versus lift coefficient before the true pitch up at 22° is reached.

At high incidence, the response to elevator inputs in the nose-up sense gave the pilot an impression of pitch instability. What at first appeared to the pilot as a steady nose-up pitching response was really the start of the longitudinal short period oscillatory motion which is of relatively long period, about 7 seconds, at high incidence.

Wind-tunnel tests[11] suggest that the pitch-up characteristics of the aircraft are to some extent a function of sideslip and one must be cautious not to over-simplify a comparison between wind-tunnel and flight results since at high incidence the aircraft was inevitably oscillating somewhat in sideslip.

Although the use of rudder to prevent the build up of sideslip made it possible to increase the maximum incidence attained significantly, a divergence in sideslip, defined as $|\beta| > 7°$, on several flights made it necessary to reduce incidence. These divergences were occurring at $\alpha \simeq 22°$ which coincided with the onset of pitch-up. The performance of the pilots was still improving as they gained more experience but it was decided to terminate the programme as further tests were likely to be protracted.

Preliminary analysis of films of the behaviour of tufts on the starboard wing suggests that, at the highest values of incidence, vortex bursting may have been occurring ahead of the trailing edge and there are indications that this coincided with an increase in airframe buffet. Buffet intensity increased slowly with incidence at speeds below 200 knots ias but there seemed to be a sharp increase at the lowest speeds flown.

### 5.2 Cross-wind take-offs, approach and landing

Due to the large value of $(-\ell_v)$ of slender aircraft, approaches at the sideslip angles implied by high cross-wind components can require large aileron and rudder deflections, which will be accentuated by the sensitivity of the aircraft in roll to the level of turbulence associated with such wind speeds. The opportunity was taken, when suitable conditions occurred, to investigate the behaviour of the BAC 221 during cross-wind approaches and landings. Cross-wind take-offs are also of interest, but during these the time spent in the low speed, large sideslip condition is of course less.

Approaches and landings were made with cross-wind components of up to 15 knots and the pilots experienced no difficulty in controlling the aircraft, although they were perhaps more aware than usual of the lateral sensitivity of the aircraft to turbulence. Kicking off drift at the end of a crabbing approach presented no difficulty although if drift was removed too rapidly, roll could build up before touchdown.

During both cross-wind take-offs and landings the pilots commented more on the ground handling than on the airborne phase. While at speed on the ground the aircraft tends to roll out of wind and large aileron deflections are required to minimise the bank angle and to reduce the tendency of the upwind wing to lift. The aircraft has an extremely long undercarriage and it may be that this tends to accentuate the aircraft's rolling behaviour on the ground.

5.3 Speed instability on the approach

Due to the very low aspect ratio of the BAC 221, the normal approach speed of 160 knots ias is below its minimum drag speed and the aircraft operates in a condition of speed instability. This condition was not investigated explicitly during these tests but some comments on speed and attitude control are possible.

In general the pilots found that by using a technique of very positive throttle movements, tight speed control was not difficult. Coarse throttle inputs were used to produce a speed response in the required sense, followed by finer adjustments to maintain the desired speed. Glidepath control was rather more difficult but not excessively so.

One approach and landing was made under radar control at a reduced speed of 140 knots ias in conditions of poor visibility. The pilot felt that speed holding was at least as easy, and perhaps easier, than at the normal approach speed of 160 knots ias, although distractions (poor visibility and another aircraft) in the late stages of the approach led to poorer speed control. An inadvertent increase in speed to 155 knots ias was easily and quickly corrected.

It is perhaps significant that on three approaches during which distractions were known to be present, large speed errors rapidly built up, (see also section 6.1 on side-step manoeuvres). It seems that speed holding is satisfactory, providing that the pilot is able to give it very full attention. The use of the autothrottle should make the pilot's task easier; future tests on the BAC 221 will employ the autothrottle both as a stabilising and a destabilising device.

## 6 SPECIFIC HANDLING INVESTIGATIONS

### 6.1 Side-step manoeuvres on the approach

It is a frequent occurrence for an aircraft making an instrument approach to break cloud laterally displaced from the runway. An approximately sinusoidal bank or side-step manoeuvre to align the aircraft with the runway is necessary. This was thought to be a particularly demanding manoeuvre for a slender aircraft with the potentially oscillatory aileron response described earlier[14,15].

A series of side-step manoeuvres at normal approach speeds was made, commencing at increasing lateral distance from the runway and at various distances from touchdown, that is at various heights above the ground. In addition to the airborne recorders, ground based kinetheodolites were used to photograph continuously the aircraft's approach path so that its position in space at any instant could be defined extremely accurately.

The pilots found that they could perform the side-step manoeuvres adequately using aileron alone but small co-ordinating rudder inputs were usually made. (The aileron/rudder interconnect was not used during this exercise.) The manoeuvres were not considered to be difficult and a maximum selected lateral displacement of over 400 ft from the runway centre-line at an altitude of 300 ft was comfortably corrected in the available time of about 20 sec before touchdown.

Cross-winds on the approach, and turbulence, did not make the manoeuvre significantly more difficult. Speed tended to increase by about 8 to 10 knots ias but this may have been due to excessive precautionary engine power increases by the pilot whilst banking. It is significant, however, that during one manoeuvre the speed fell from 180 to 150 knots ias whilst the pilot searched briefly for an aircraft reported nearby by Air Traffic Control.

The times taken from the initiation of a sidestep manoeuvre to line up with the runway centre-line are plotted against displacement in Fig.14. Included in the figure are predicted limiting curves, derived using the analysis of Perry et al[15], based respectively on the time taken for a side-step manoeuvre with a maximum typical bank angle of 35° for a small aircraft, and on the estimated maximum available rate of roll of 36°/sec for the BAC 221 under these conditions. For lateral displacements greater than about 140 ft a maximum bank angle, acceptable to the pilot, of 35° is seen to be the predicted limiting condition. The earlier work[15] suggested that R.A.E. pilots tended to exceed the minimum theoretically possible manoeuvre time by about 2·5 sec probably because the limiting bank angle or roll rate was attained at only one peak of the sinusoidal manoeuvre. This excess time is broadly in agreement with the limited data available from this exercise, but preliminary analysis of the flight records suggest that the maximum bank angle and rate of roll used by the pilot never attained 35° and 36°/sec respectively.

## 6.2 Zero rate of climb speed

The zero rate of climb speed, the minimum speed at which an aircraft, at a given altitude and power setting, can maintain level flight, is a potential absolute operational lower speed limit for slender delta aircraft, replacing the stalling speed of more conventional aircraft[7]. There are important differences, however; there is no aerodynamic warning associated with the zero rate of climb speed, as there normally is at the stall, and the zero rate of climb speed is not an approximately constant equivalent airspeed but a function of altitude, air temperature, aircraft weight and power setting.

Tests to determine the zero rate of climb speed, and to recover from steady descending flight at lower speeds, were made in the BAC 221 aircraft at a nominal altitude of 25000 ft and at a constant power setting of 7800 rpm. The aircraft, in the clean configuration, was flown in straight flight at a series of constant indicated airspeeds; records were thus obtained over a range of steady climbs at the higher speeds and steady descents at the lower speeds when drag was greater than thrust. The zero rate of climb speed under these conditions was thus established and found to be about 165 knots ias. Recovery to level flight from speeds below 165 knots ias was made by easing the aircraft's nose down, at constant power setting, and pulling out to fly level (when the aircraft would be accelerating) at 175 knots ias. It was found that the height loss during a recovery from 155 knots ias was about 800 ft.

During these tests it was found that if, by climbing, the aircraft's speed was reduced from a speed above the zero rate of climb speed to a speed below that speed, say from 170 to 160 knots ias, it was some time before a rate of descent became apparent and pilots felt[13] that an inadvertent reduction in speed to below the zero rate of climb speed could easily occur, since for a given set of conditions, the pilot is unlikely to know the appropriate zero rate of climb speed. This difficulty is compounded by the very sluggish response of most vertical speed indicators.

### 6.3 Rudder-driven-by-aileron interconnect

Pinsker[1] shows that if the characteristic oscillatory response of a slender aircraft to aileron is to be eliminated by using rudder co-ordination, then the rudder demand is almost in phase with the applied aileron. It is relatively simple to supply an interconnect between aileron and rudder so that the rudder response, $\zeta$, if the rudder pedals are held fixed, is in a fixed ratio to, and in phase with, the applied aileron, $\xi$.

Such a rudder-driven-by-aileron interconnect, henceforth referred to as the interconnect, geared in the sense to provide effective proverse aileron yaw such that

$$\zeta = k\xi \tag{2}$$

is shown in Ref.4 to augment the effective directional stability of an aircraft constrained by aileron control to wings level flight. The effective directional stability $\bar{n}'_v$ is then

$$\bar{n}'_v = n_v - \frac{n_\xi + k\, n_\zeta}{\ell_\xi + k\, \ell_\zeta}\, \ell_v \quad . \tag{3}$$

If $\bar{n}'_v$ is set equal to zero, equation (3) can be solved to give the minimum gearing, $k_{min}$, required to just provide neutral directional stability as

$$k_{min} = \frac{n_v\, \ell_\xi - n_\xi\, \ell_v}{n_\zeta\, \ell_v - n_v\, \ell_\zeta} \tag{4}$$

where $k_{min}$ will be a function of incidence. For values of incidence below which $\bar{n}_v$ is positive, equation (4) is of course irrelevant, in that the solution for $k_{min}$ is negative and a degradation of directional stability is implied (although this might be useful in a variable stability application). The required value of $k$ to restore $\bar{n}_v$ to zero in body axes is plotted for the BAC 221 in Fig.15. It is seen that at high incidence, values of $k$ considerably greater than unity are required, implying the probability of a very large rudder demand which would attempt to drive the rudder beyond the maximum authority to which the interconnect is limited for safety reasons, and thus lose the control law.

For the BAC 221 a maximum value for k of unity was chosen. This value is higher than necessary at low incidence for this purpose, and inadequate at high incidence, but represents a reasonable compromise; lower values of k can be selected by the pilot if desired but for most of the flight tests of the interconnect, k was unity.

The time history of a roll (with rudder pedals held fixed and k = 1) at 150 knots ias is shown in Fig.16. The aileron angle shown is not the mean aileron angle, but the angle of the starboard aileron which drives the rudder via the interconnect. The manoeuvre should be compared with that shown in Fig.9 during which the rudder angle was almost constant and zero. The aileron application shown in Fig.16 is slightly greater than that in Fig.9, but not sufficiently so to account for the much shorter manoeuvre time with the interconnect in operation. The rate of roll is seen to be much less oscillatory and is far from a reversal in sign and the bank angle response is correspondingly less oscillatory. The mean sideslip angle attained is rather less.

At very low speeds the pilots commented favourably on the interconnect. Aileron activity was reduced and it was found possible to fly the aircraft without pilot rudder inputs, a procedure which had led to the build up of large sideslip angles, necessitating large rudder corrections, when the interconnect was not in use. The rudder activity demanded by the interconnect during flight with reduced aileron activity was less than the rudder activity when under manual control.

Experience with the interconnect has thus been very favourable under the conditions so far investigated. A suggested disadvantage[1], is that during a cross-wind approach the rudder deflection required by the interconnect is in the opposite sense to that required for a steady sideslip. The wash-out term prevents a constant rudder application by the interconnect, but in spite of this term, the interconnect could be inconvenient during a transient sideslip, such as during touchdown manoeuvres during a cross-wind landing, when the pilot might have to apply a rather larger rudder input than he would expect. Cross-wind approaches and landings in the BAC 221 with the interconnect in operation have not yet been investigated.

## 7 GROUND BASED SIMULATION OF THE BAC 221

Prior to first flight of the BAC 221 an assessment was made of the controllability of the aircraft, at low speeds in the approach configuration, using the R.A.E. Bedford ground based flight simulator[10]. A series of simulated approaches was made at speeds down to 135 knots ias.

Some of the data used for the simulation have now been superseded but it was recognised at the time that the data then available were unlikely to be completely reliable and the effect of varying a number of important parameters was investigated.

Unfortunately the first opportunity for an R.A.E. pilot to fly the aircraft, after taking part in the simulation, did not occur until 9 months later. This made direct comparison more difficult, but the pilot reported that the simulation gave, broadly speaking, a good impression of the aircraft and that any differences found were in degree rather than in form. This is encouraging support for the value of such simulations.

A further simulation of the BAC 221 is planned shortly at R.A.E. Bedford. More comprehensive low speed wing-tunnel results will soon be available and the results obtained so far from the flight tests will not only provide an excellent guide to the accuracy of the simulation but have also highlighted areas which should be investigated in more detail. The handling of the aircraft at very high incidence is of course the major interest and it is hoped that the simulation will throw light on the aircraft handling at incidences not yet attained in flight.

## 8 CONCLUSIONS

The low speed flight tests of the BAC 221 made so far reveal some interesting aspects of the behaviour of the aircraft at very high incidence. Pilots described the aircraft handling generally as pleasant but certain features, such as difficulty in controlling sideslip in flight at high incidence, were unexpected. However, theoretical analysis, stimulated in consequence, has suggested a probable cause of the latter characteristic.

The major handling problems lay in the field of lateral/directional control, particularly at very high incidence. The response to aileron was oscillatory at all speeds and co-ordinated rudder inputs were needed to prevent the build-up of sideslip.

At very high incidence the best pilot technique was to concentrate on keeping sideslip to a minimum whilst tolerating moderate excursions in bank. If the pilot concentrated on keeping the wings level using aileron, very large sideslip angles occurred and aileron activity was excessive; very large rudder inputs were needed to correct the sideslip.

An interconnect enabling the ailerons to drive the rudder, in order to give effective proverse aileron yaw, reduced the oscillatory nature of the response to aileron. At very high incidence the interconnect restored effective directional stability without the need for pilot rudder inputs.

A pitch-up occurred at very high incidence but longitudinal control was otherwise satisfactory. There was an increase in aerodynamic buffet at an incidence corresponding approximately to that of the pitch-up and this buffet increase seemed to correlate with possible vortex bursting ahead of the wing trailing edge.

Speed control on the approach was relatively easy providing it could be given full attention, but distractions tended to allow speed excursions to build up. Take-offs and landings in cross-wind components of up to 15 knots presented no problems in the air, but control on the runway was difficult. Side-step manoeuvres on the approach with lateral displacements of over 400 ft were easily executed.

A more quantitative assessment of the aerodynamic and dynamic characteristics of the BAC 221, and a detailed comparison with wind-tunnel tests, will be made and reported when the analysis of the recorded data is completed.

Table 1

LEADING PARTICULARS OF THE BAC 221

| | |
|---|---|
| Length | 57·6 ft |
| Span | 25·0 ft |
| Mean aerodynamic chord | 25·0 ft |
| Wing area | 490 $ft^2$ |
| Weight empty of fuel | 16454 lb |
| Weight fully loaded | 19998 lb |

| | |
|---|---|
| Mean centre of gravity position, clean configuration | 161 in forward of datum |
| Mean centre of gravity position, approach configuration | 159 in forward of datum |

Inertia characteristics for weight = 18500 lb:

| | Clean configuration | Approach configuration |
|---|---|---|
| $i_A$ | 0·080 | 0·101 |
| $i_B$ | 0.141 | 0.150 |
| $i_C$ | 0·632 | 0·660 |

Inclination of principal axis to fuselage datum:

| | |
|---|---|
| Approach configuration | 1° 18' nose down |
| Clean configuration | 0° 39' nose down |

Available control angles:

| | |
|---|---|
| Elevator | 26° up, 15·5° down (gearing 1:1) |
| Aileron | 20° up, 22° down (gearing 1:1) |
| Rudder | ±15° |

Aileron rigged-up angle ground setting 2°.

## SYMBOLS

| | | |
|---|---|---|
| $A$ | principal rolling moment of inertia | slug ft$^2$ |
| $B$ | moment of inertia in pitch | slug ft$^2$ |
| $C$ | principal yawing moment of inertia | slug ft$^2$ |
| $\bar{\bar{c}}$ | aerodynamic mean chord | ft |
| $C_\ell$ | rolling moment coefficient | |
| $C_m$ | pitching moment coefficient about centre of gravity | |
| $C_n$ | yawing moment coefficient about centre of gravity | |
| $i_A$ | $A/m\,s^2$ | |
| $i_B$ | $B/m\,\bar{\bar{c}}^2$ | |
| $i_C$ | $C/m\,s^2$ | |
| $k$ | gearing of rudder-driven-by-aileron interconnect | |
| $\ell_v$ | rolling moment due to sideslip derivative | rad$^{-1}$ |
| $\ell_\zeta$ | rolling moment due to rudder derivative | rad$^{-1}$ |
| $\ell_\xi$ | rolling moment due to aileron derivative | rad$^{-1}$ |
| $m$ | aircraft mass | slug |
| $n_p$ | yawing moment due to rate of roll derivative | rad$^{-1}$ |
| $n_v$ | directional stability derivative | rad$^{-1}$ |
| $\bar{n}_v$ | effective directional stability derivative | rad$^{-1}$ |
| $\bar{n}'_v$ | $\bar{n}_v$ augmented by rudder-driven-by-aileron interconnect | rad$^{-1}$ |
| $n_\zeta$ | yawing moment due to rudder derivative | rad$^{-1}$ |
| $n_\xi$ | yawing moment due to aileron derivative | rad$^{-1}$ |
| $p$ | rate of roll | deg sec$^{-1}$ |
| $p_{max}$ | maximum usable rate of roll in a side-step manoeuvre | deg sec$^{-1}$ |
| $r$ | rate of yaw | deg sec$^{-1}$ |
| $s$ | wing semi-span | ft |
| $\alpha$ | angle of incidence | deg |
| $\beta$ | sideslip angle | deg |
| $\zeta$ | rudder angle | deg |
| $\eta$ | elevator angle | deg |
| $\xi$ | aileron angle | deg |
| $\phi_{max}$ | maximum bank angle permitted in a side-step manoeuvre | deg |

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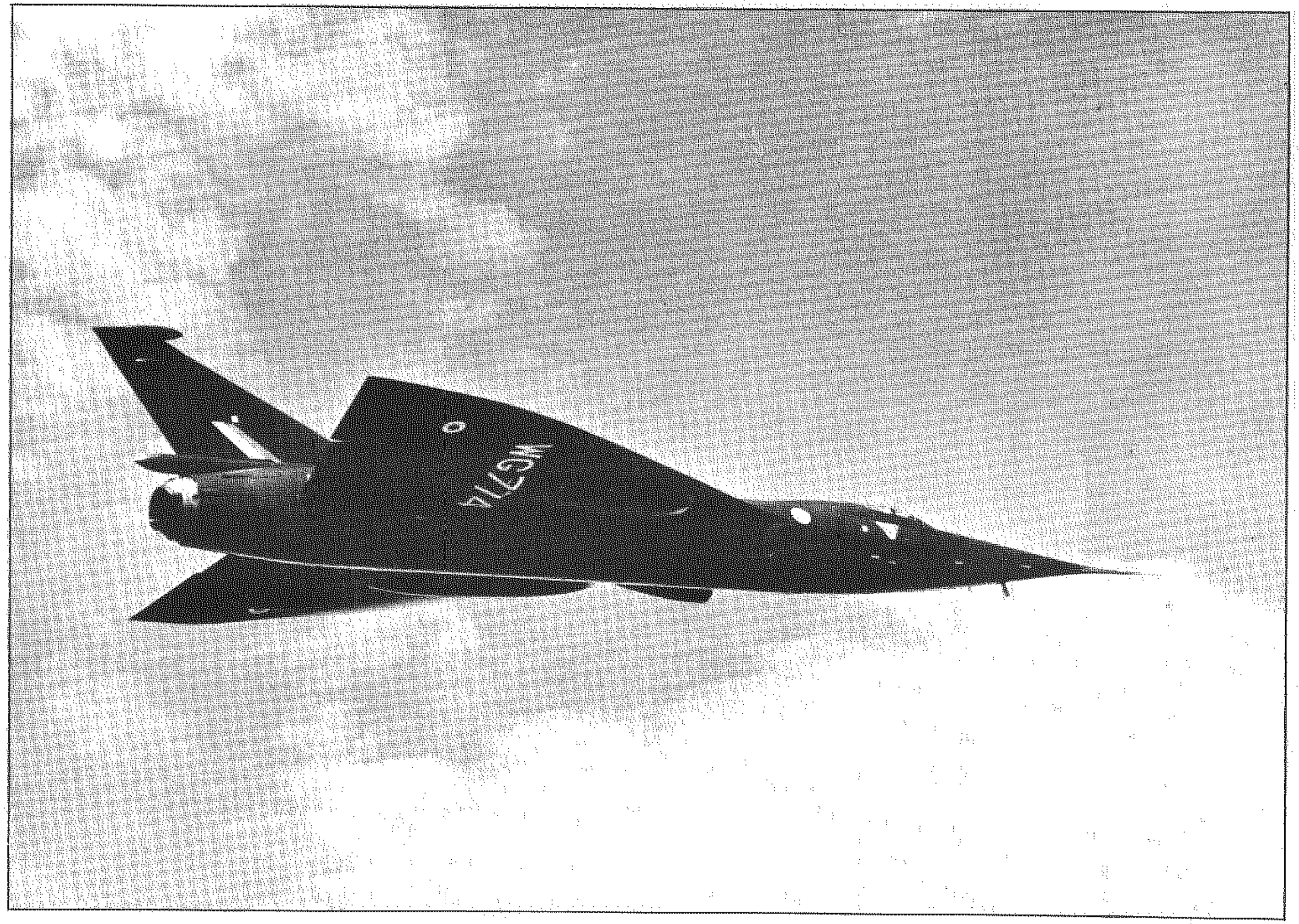



Fig.1 B.A.C. 221

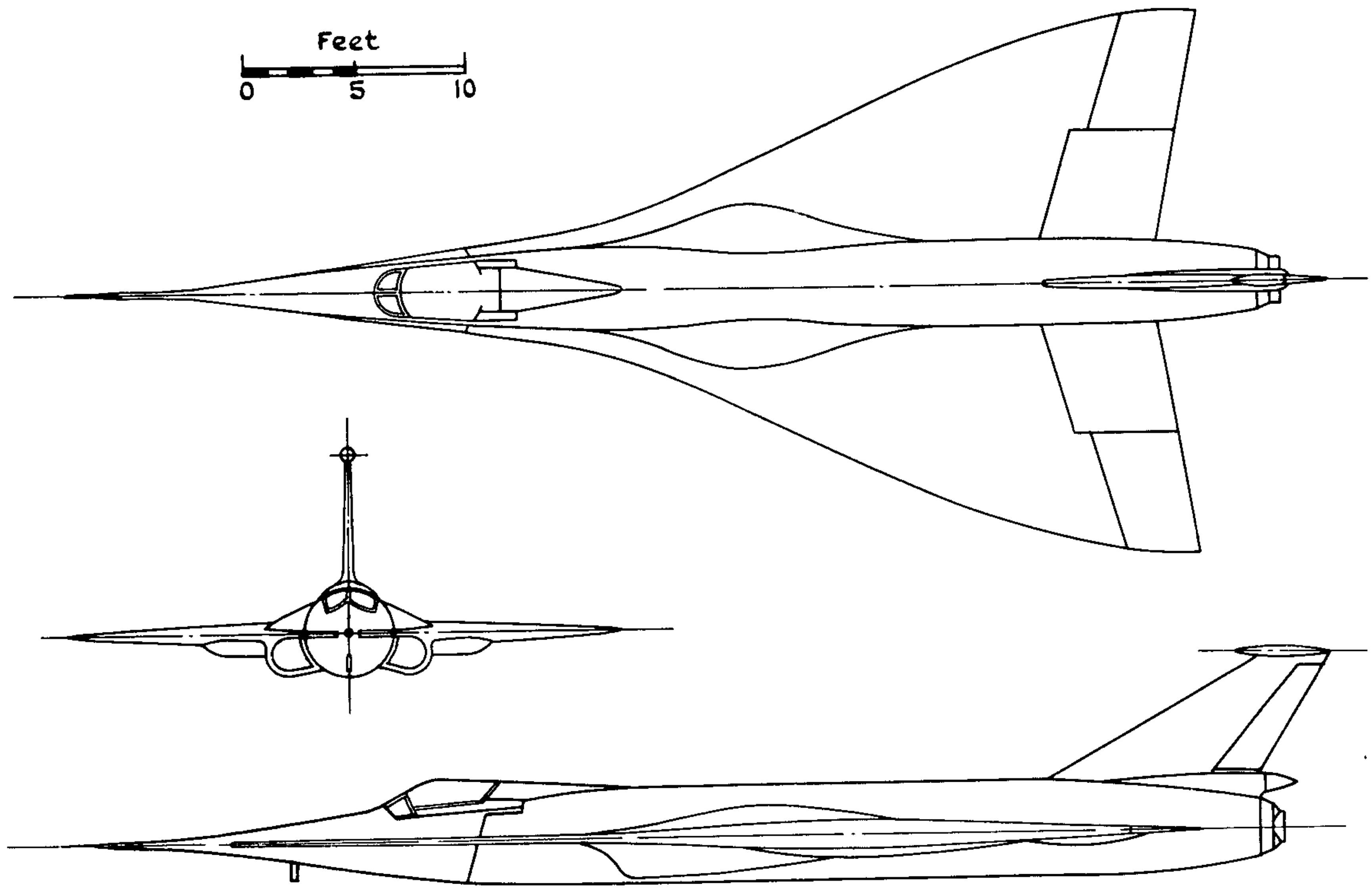



Fig. 2 BAC 221 General arrangement

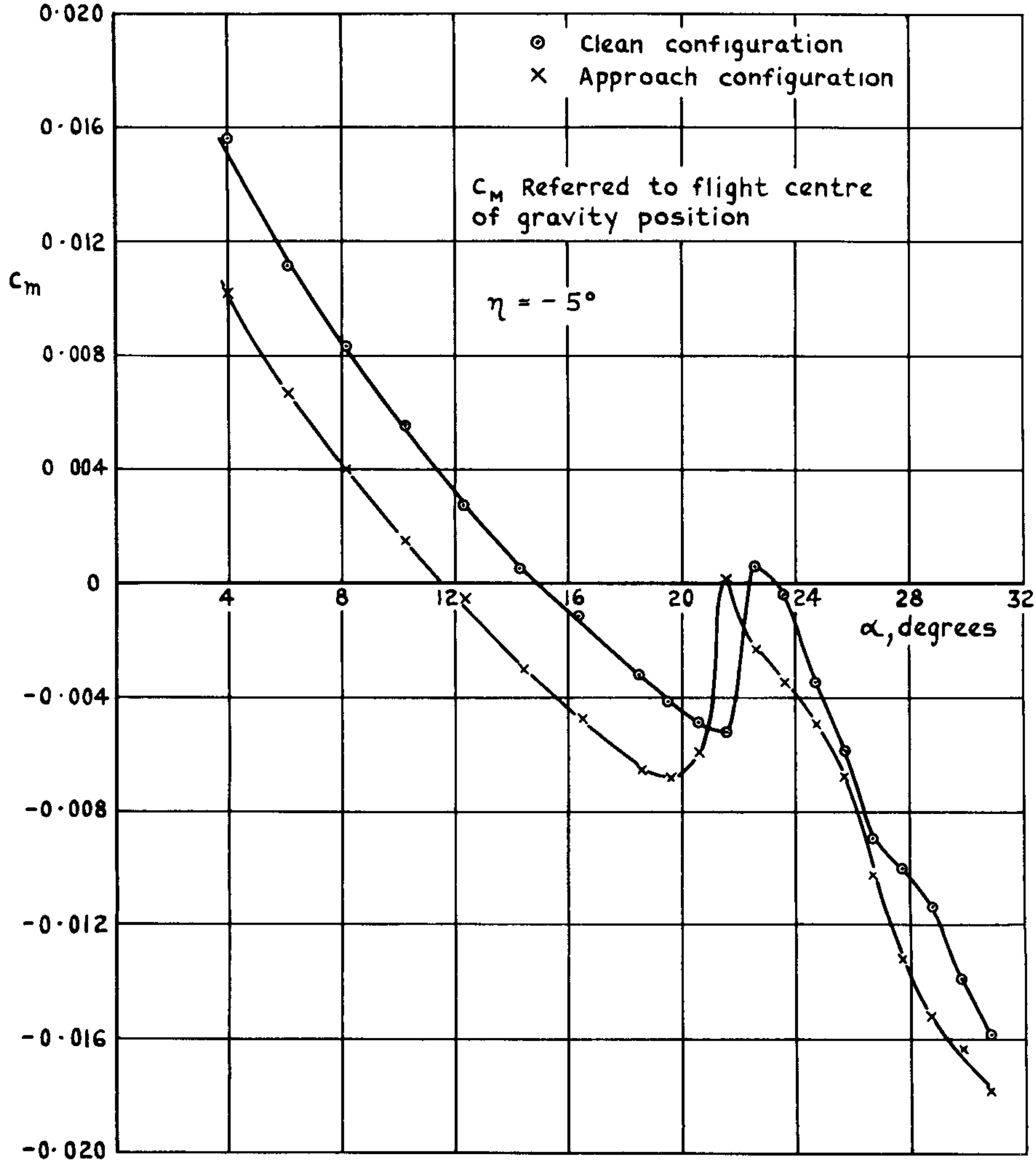
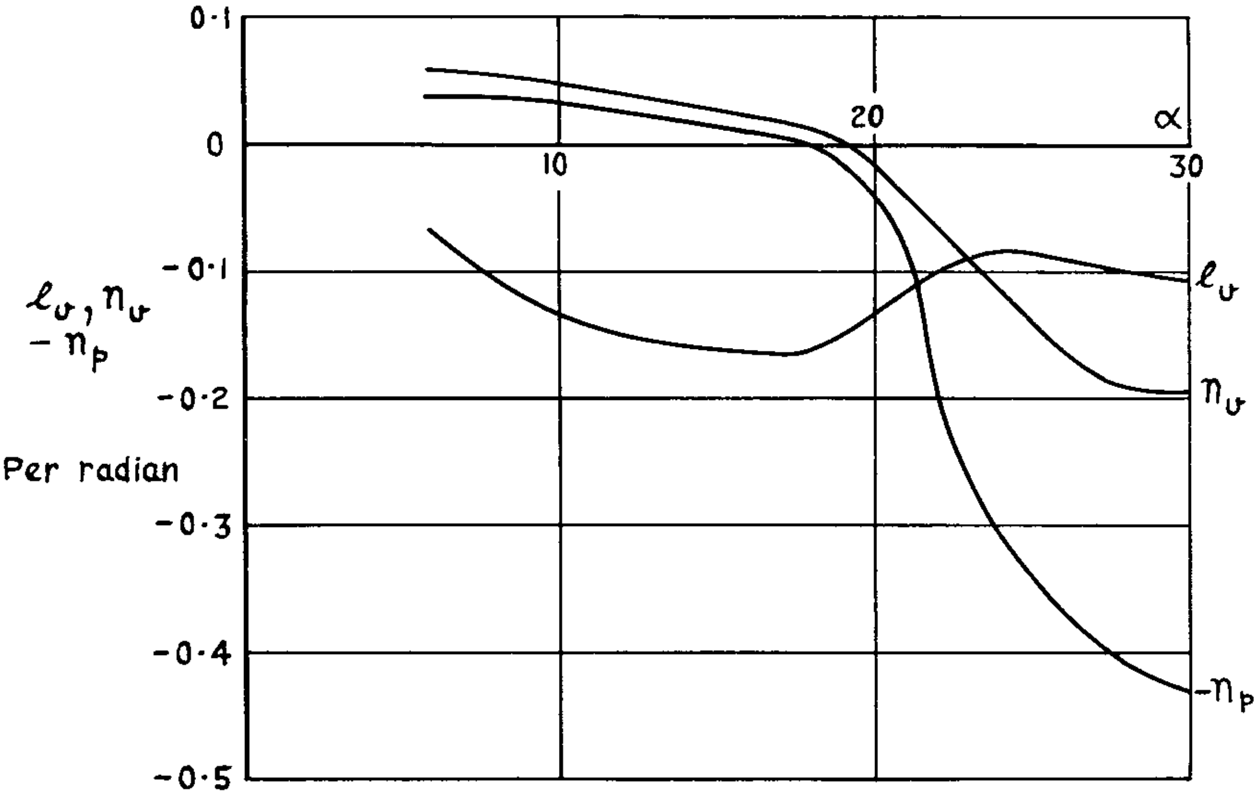
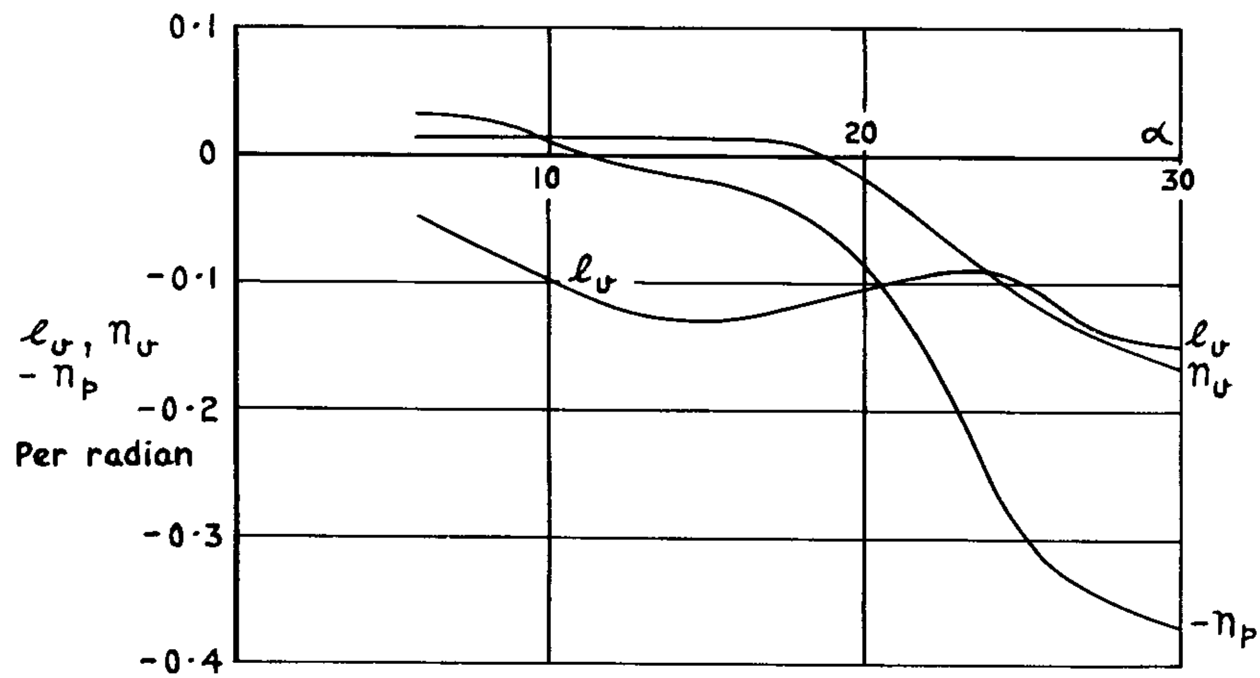



Fig.3 Pitching moment versus incidence, wind tunnel results

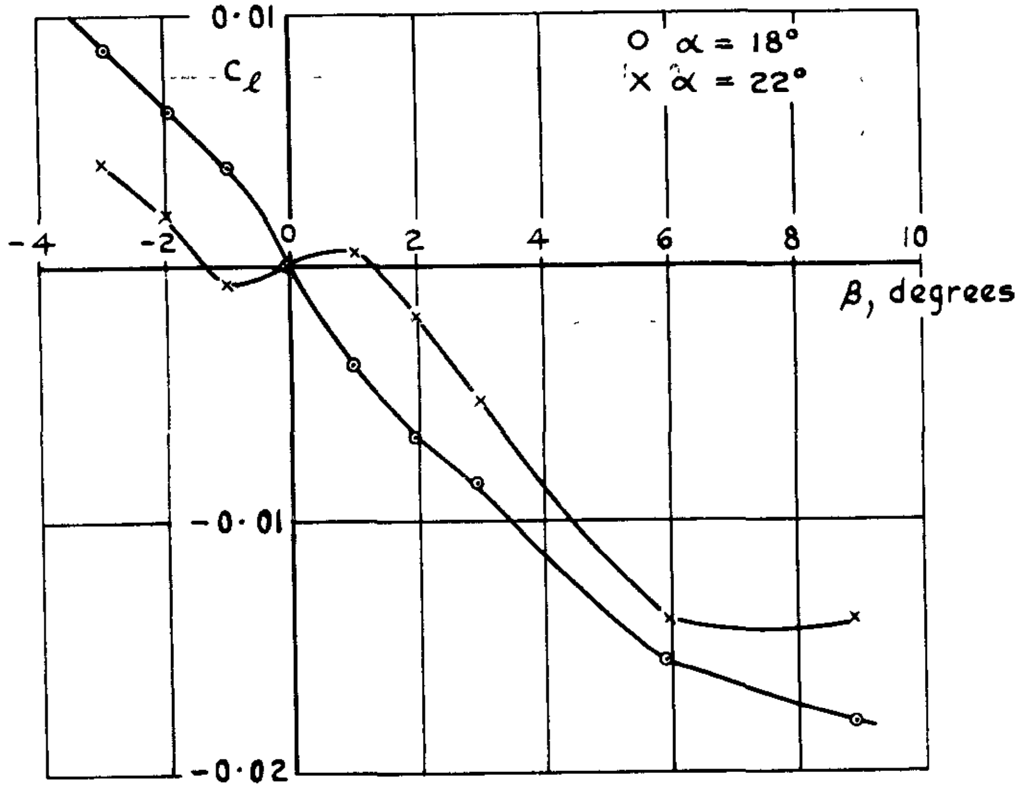



a Clean configuration

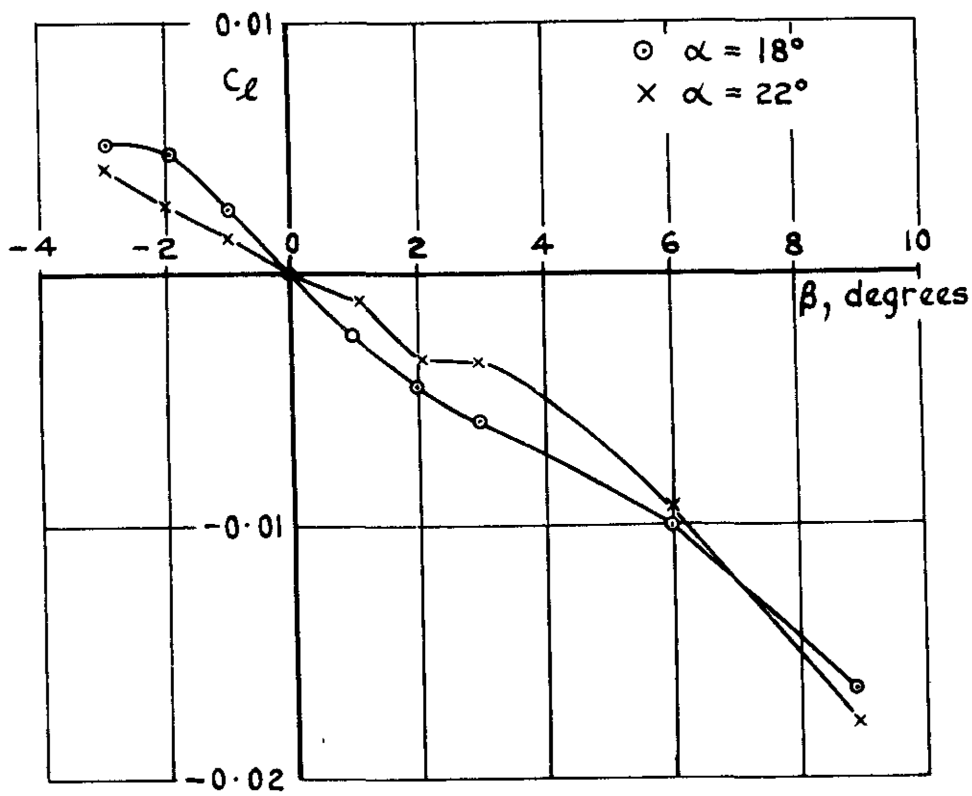



b Approach configuration

Fig. 4a&b Some lateral stability derivatives of the BAC 221 as a function of incidence, body axes, elevator angle to trim for flight cg

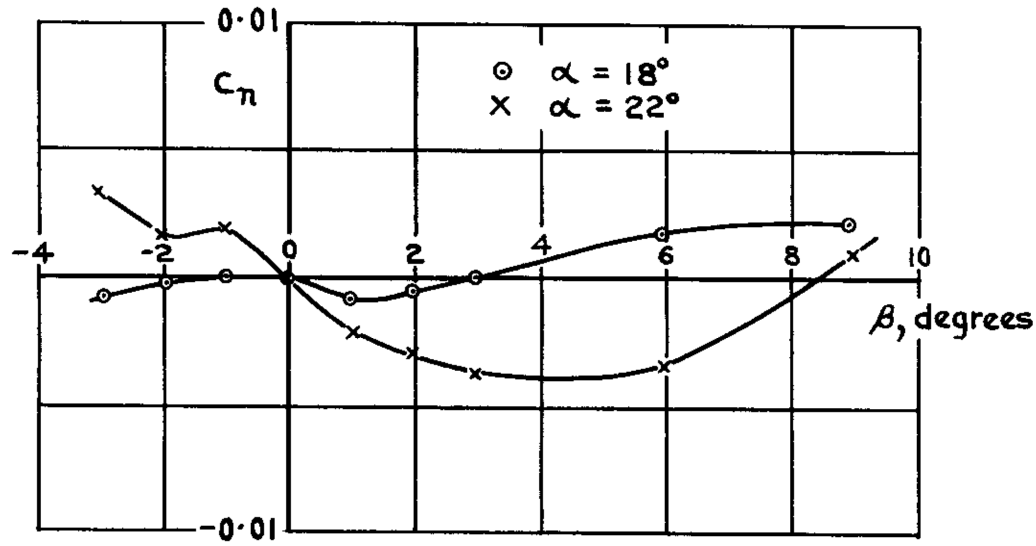



a Clean configuration

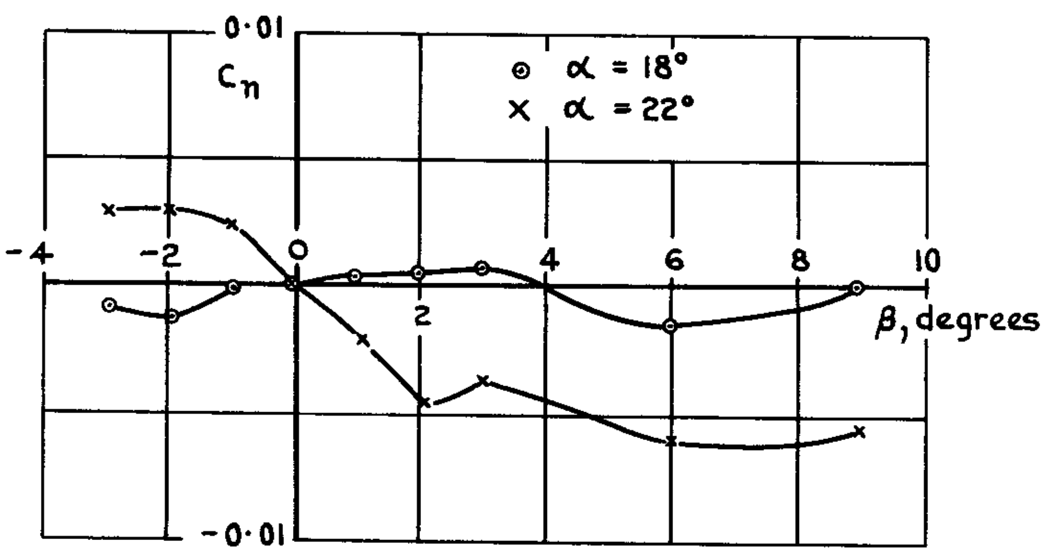



b Approach configuration

Fig. 5a&b Rolling moment coefficients as a function of sideslip, wind tunnel results, body axes, $\eta = -5°$




a Clean configuration




b Approach configuration

Fig.6a&b Yawing moment coefficients as a function of sideslip, wind tunnel results, $\eta = -5^{\circ}$, body axes, flight cg

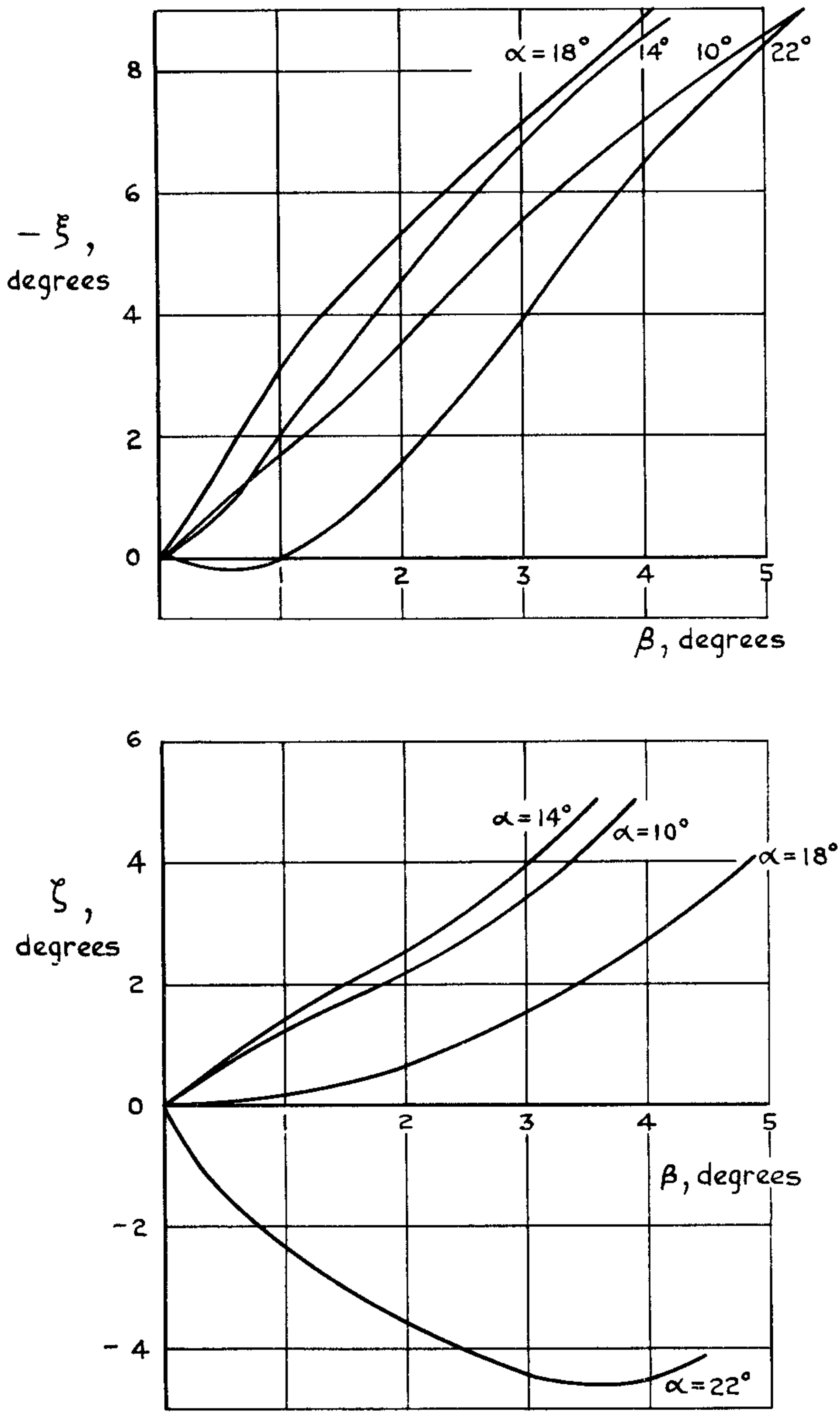
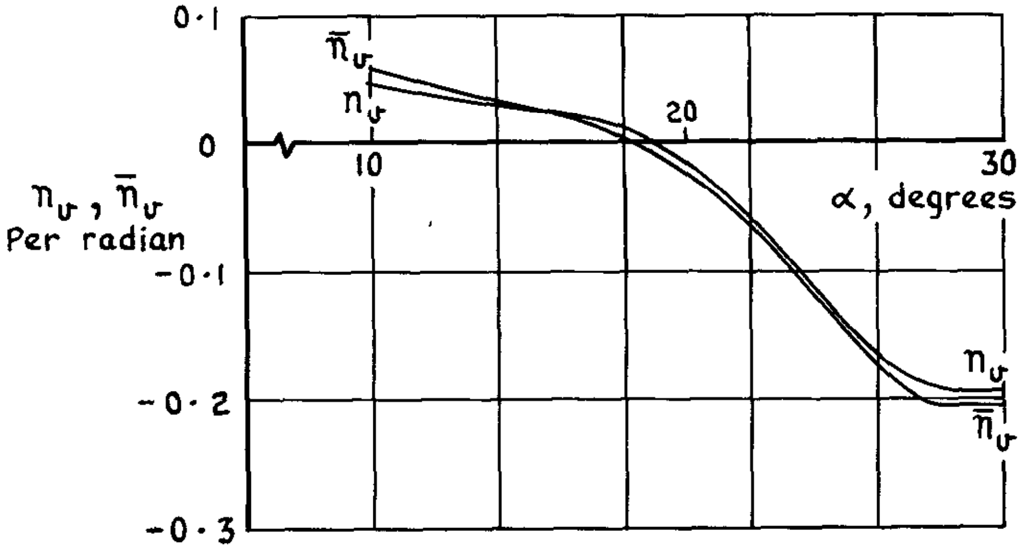
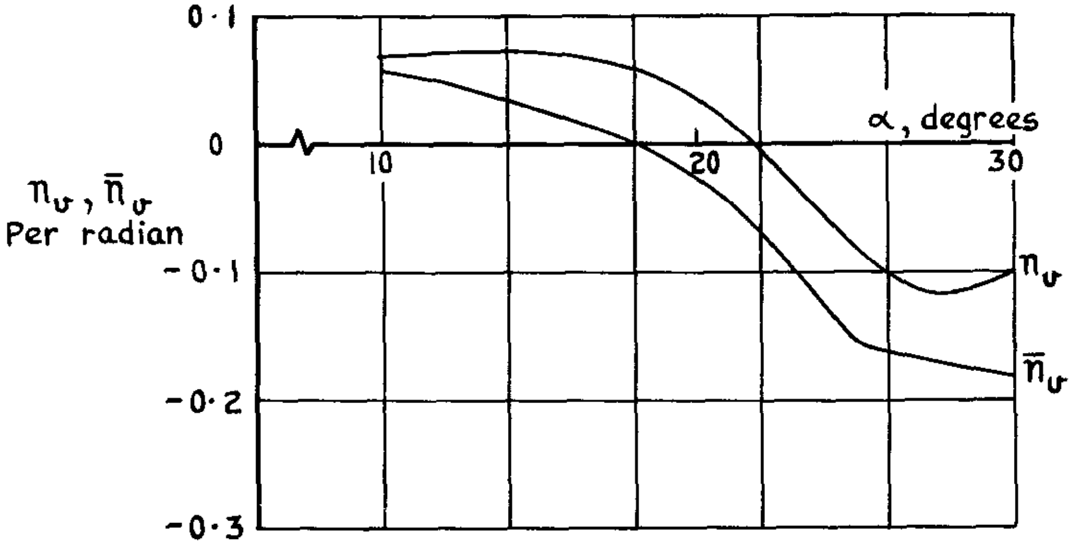



Fig 7 Aileron and rudder angles to trim in steady sideslips, wind tunnel results, clean configuration, $\eta = -5^{\circ}$, flight cg




a Body axes




b Aerodynamic stability axes

Fig.8 a&b Directional stability derivatives in two axis systems, clean configuration, flight cg

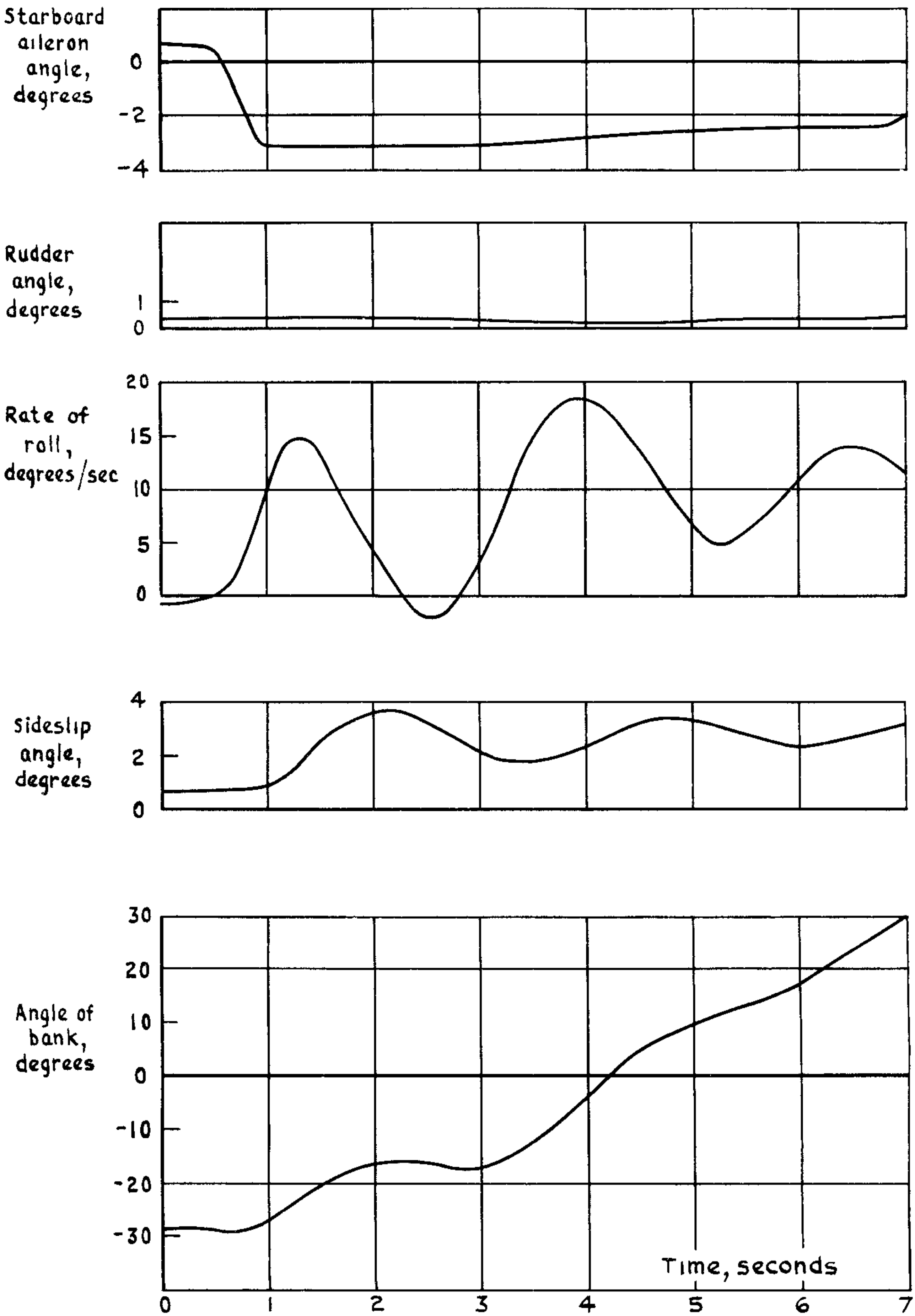
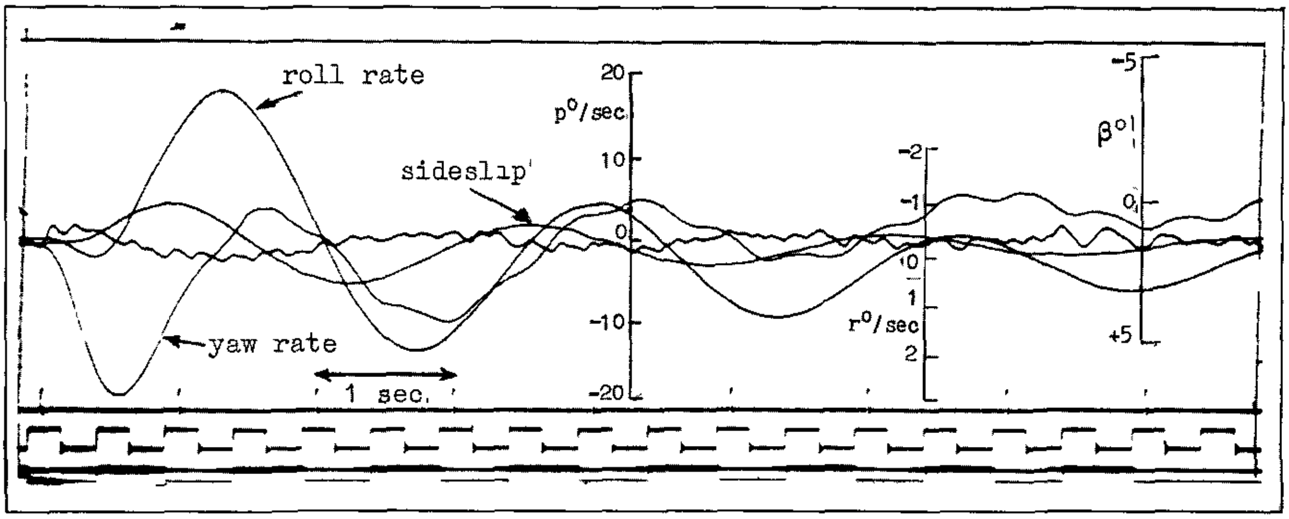
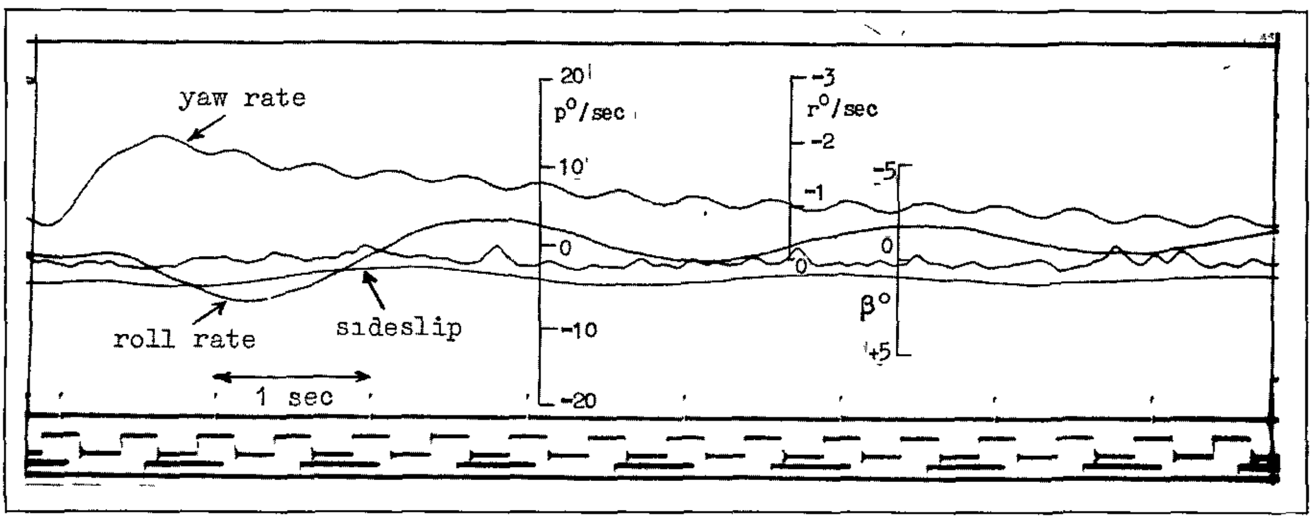



Fig.9 Recorded bank reversal at 150 knts ias, aileron/rudder interconnect not operative, clean configuration, body axes

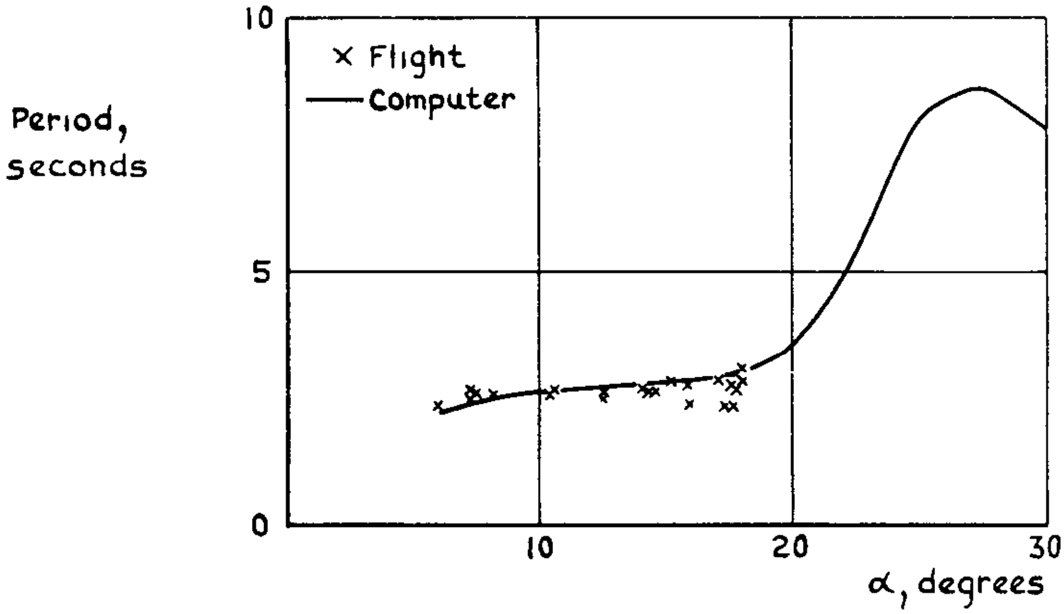



**a 150Kt. I.A.S.**

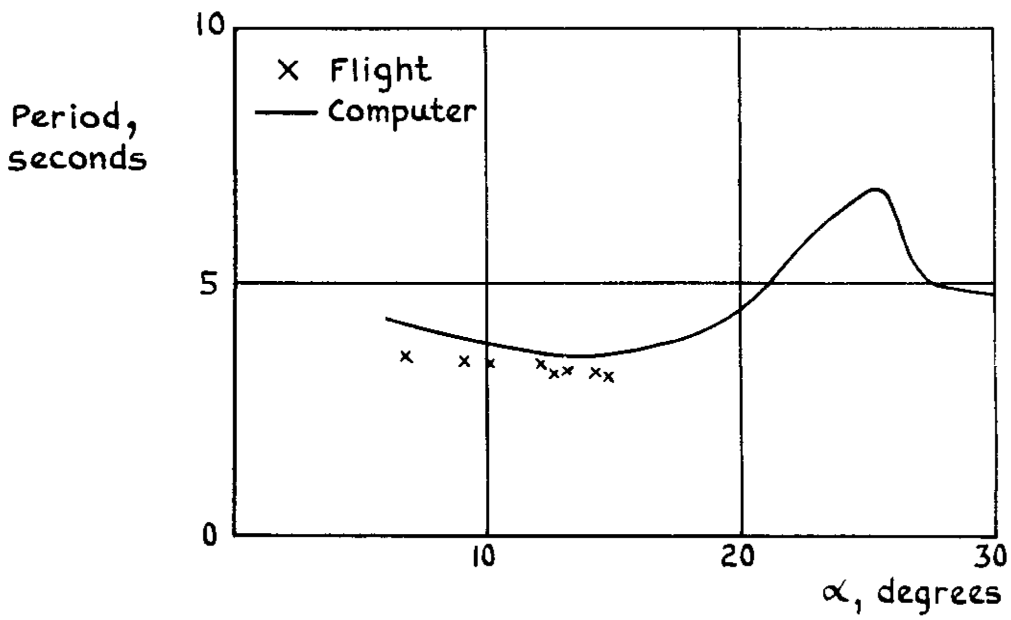



**b 125Kt. I.A.S.**

**Fig.10a&b Aircraft response to rudder kick, clean configuration**

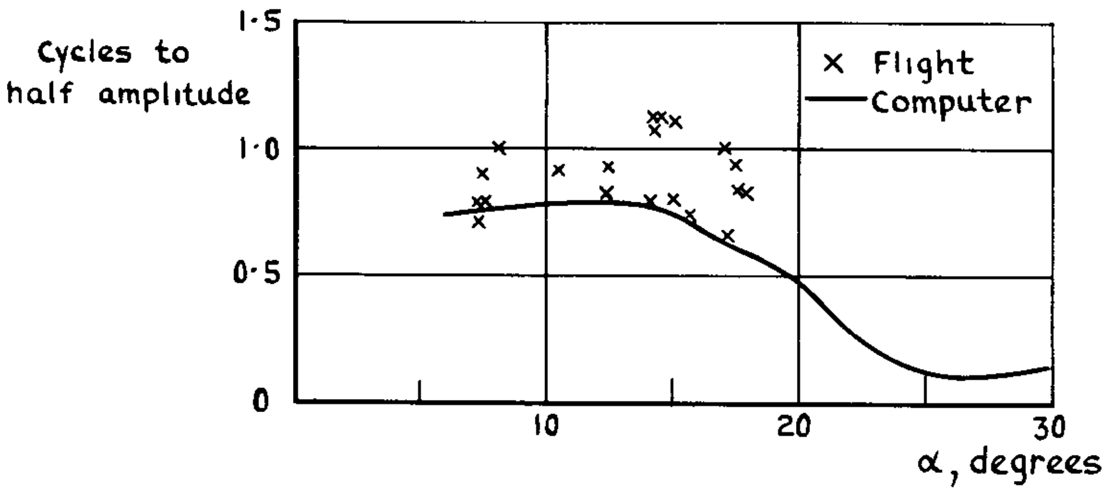



a Clean configuration

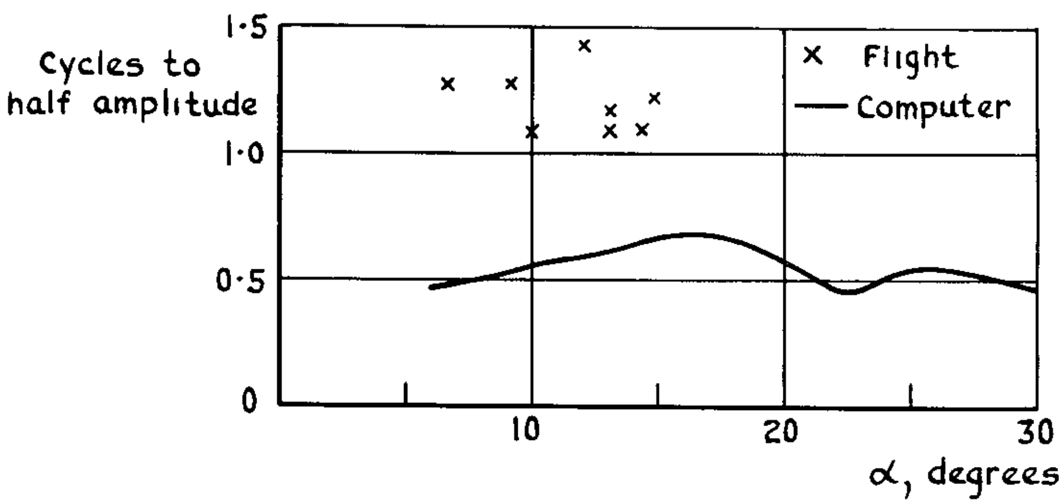



b Approach configuration

Fig.11a&b Comparison between measured and predicted dutch roll periods

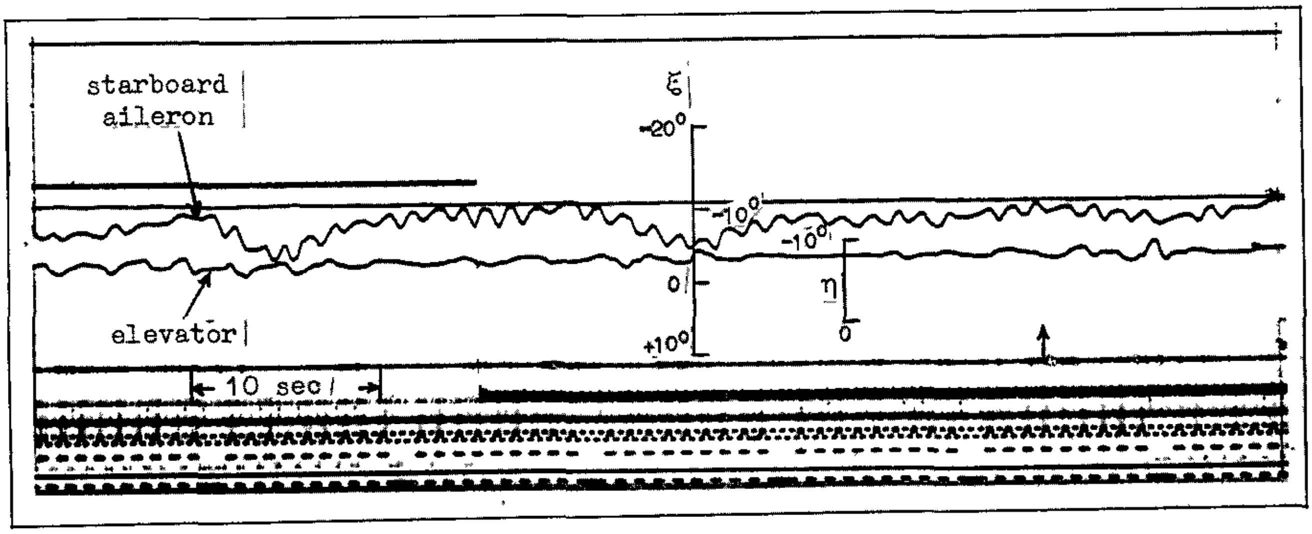



a Clean configuration

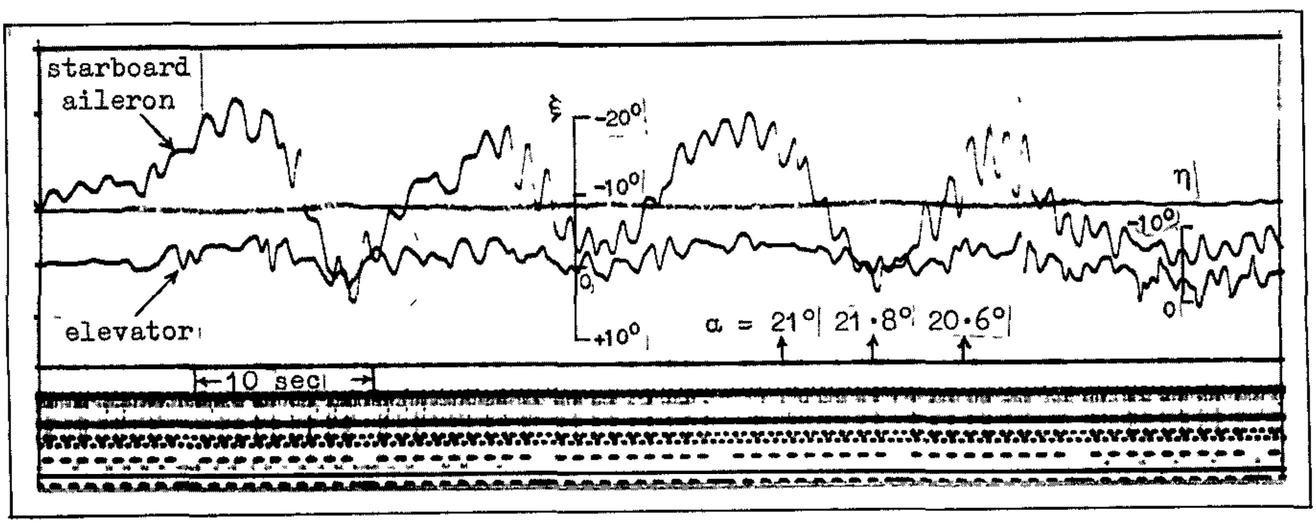



b Approach configuration

Fig.12 a & b Comparison between measured and predicted dutch roll damping




a 119Kt. I.A.S.




b 117Kt. I.A.S.

**Fig.13a&b Aileron activity at low speeds, clean configuration**

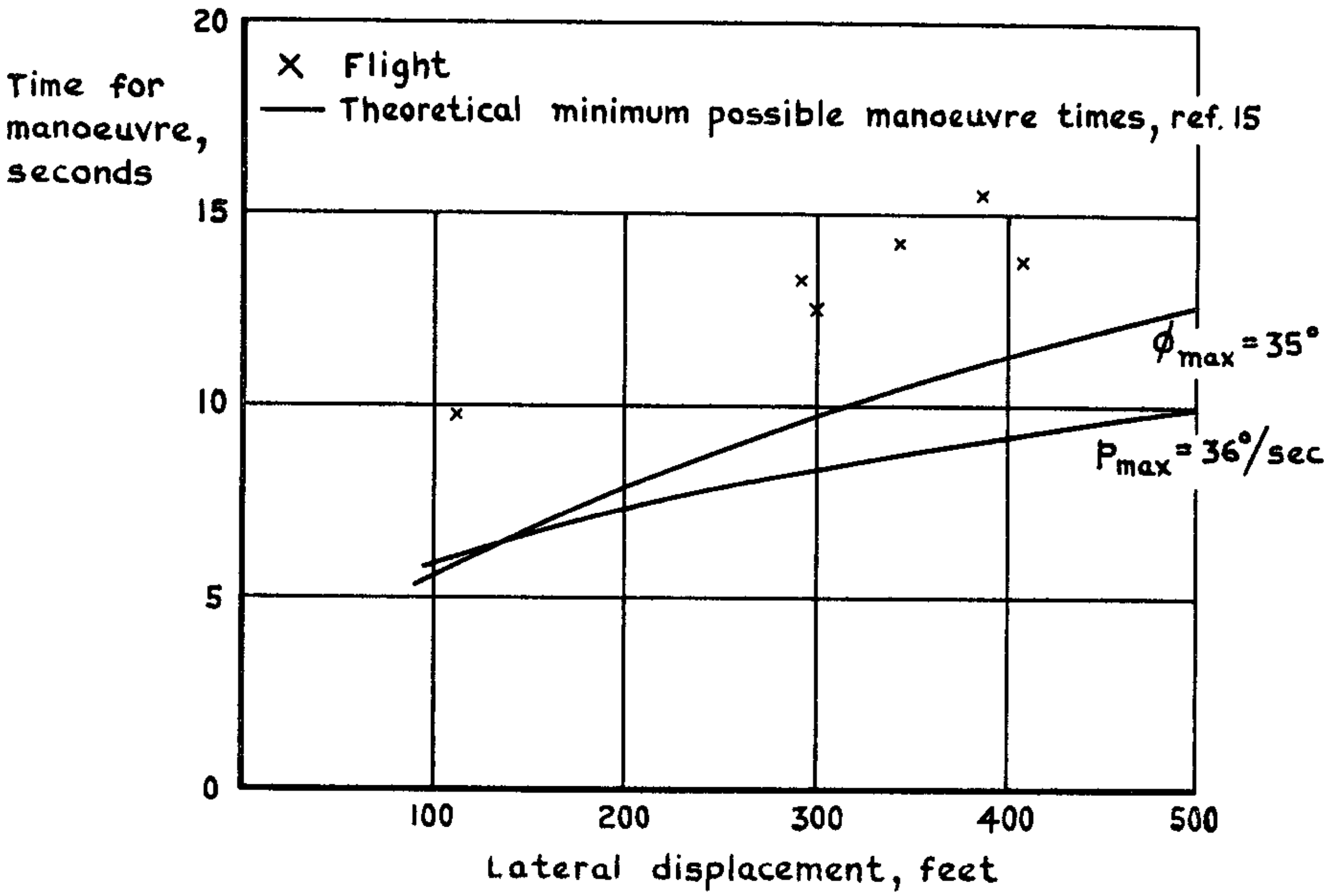



Fig.14 Time to carry out a side-step manoeuvre

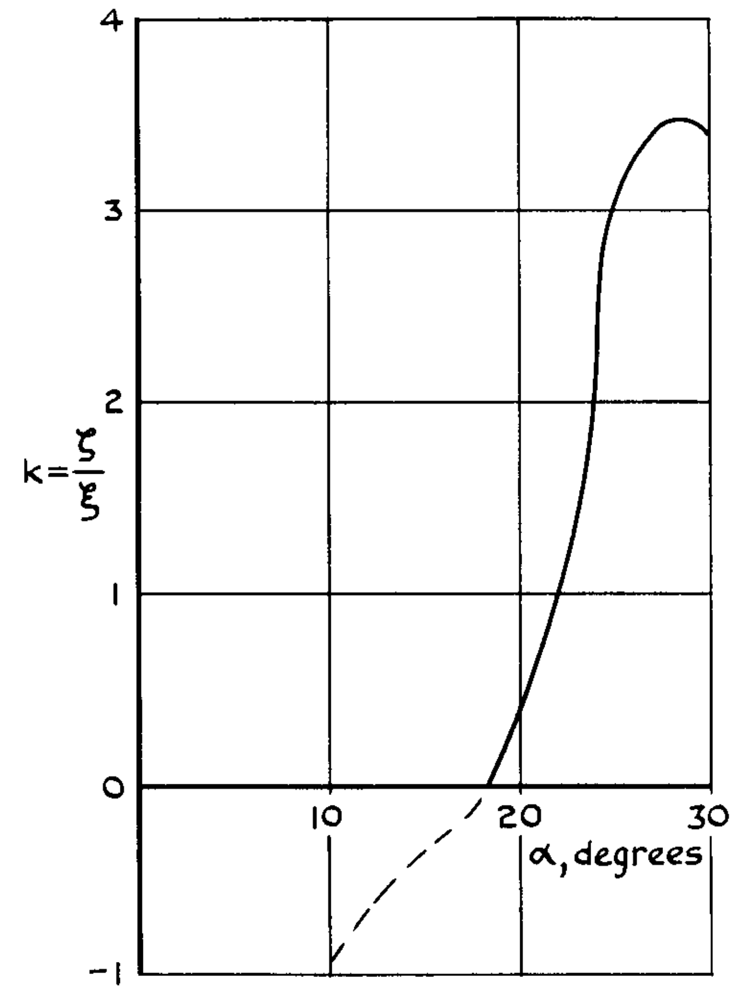



Fig.15 Rudder/aileron gearing required to increase $\bar{n}_v$ to zero for the clean aircraft

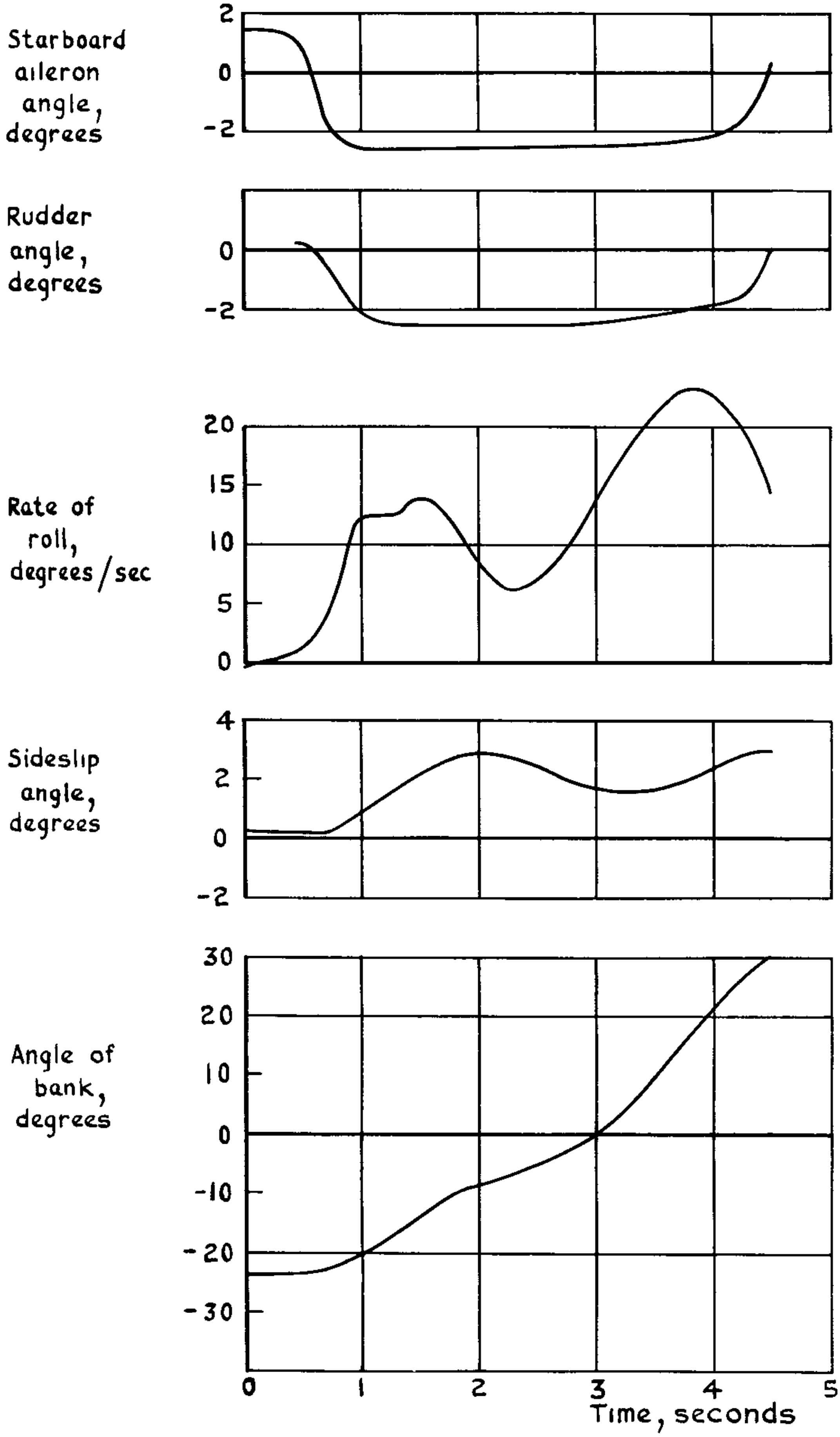



Fig.16 Recorded bank reversal at 150 knts ias, aileron/rudder interconnect operative with k=1, clean configuration

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(Over)

Longitudinal control was good, but at $\alpha = 22^0$ a mild pitch-up occurred Aerodynamic buffet increased at this incidence and vortex bursting is thought to have reached forward to the rear parts of the wing.

Although approaches were made well below the minimum drag speed, speed control presented no difficulty, provided that it could be given full attention. Cross-wind take-offs and landings presented no problems except during the ground run. Side-step manoeuvres on the approach were made with no difficulty.

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