STABILITY AND CONTROL OF SUPERSONIC AIRCRAFT AT LOW SPEEDS

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ABSTRACT

The paper gives a general discussion of the low-speed problems of large, slender, supersonic aircraft. The first part contains a descriptive outline of the general handling characteristics, with particular emphasis on those aspects where the behaviour is significantly different from that of conventional aircraft. The second applies the results of the previous discussion to the particular problems of takeoff and landing.

It is shown that there are some basic differences in behaviour, but that the effect of these differences can be reduced by suitable design so that no radically new piloting techniques should be necessary.

INTRODUCTION

The common property of being able to travel faster than sound does not in general confer on aircraft any other similarities of shape or form. Thus supersonic aircraft have no great body of low-speed behaviour in common, and in order to limit my discussion I shall have to choose a particular type of supersonic aircraft. In view of the work I am at present engaged upon it will come as no surprise that I intend to deal with large transport aircraft of slender form, a type exemplified by the Concord. However, I shall try to cover a reasonably wide field and my remarks will not be related specifically to that aircraft.

In many respects the characteristics of such machines are very similar to those of conventional aircraft, and I shall not dwell on these similarities but rather try to evaluate the significance of those aspects which are markedly different. This similarity is particularly true of the mathematical formulation of the equations of motion, and I shall therefore deal with the subject largely from a phenomenological point of view.

I shall first discuss the basic stability and control differences between slender and conventional aircraft, and then show how these affect the handling and performance in particular phases of low-speed flight.

BASIC CHARACTERISTICS

I have already referred to "slender" and "conventional" aircraft, and I must now say what I mean by these terms. Fundamentally, by "conventional aircraft" I mean those types which have contributed the bulk of the experience on which our ideas of "good" and "bad" flying qualities are based. In the civil aircraft field this inevitably implies a high aspect ratio wing of low sweepback, a spanwise distribution of engines and a tailplane. By this standard the current generation of big jets are only nearly conventional, while the newer rear engined generation (Boeing 727, VC. 10, etc.) are significantly unconventional.

By slender aircraft I mean aircraft with wings having low aspect ratio and high leading-edge sweep and a concentration of mass towards the centre line. In general I shall also assume that the aircraft is tailless (Fig. 1).

THE LONGITUDINAL MOTIONS

Let us now consider the longitudinal motion. The most important characteristics of slender aircraft are:

(a) The low-lift curve slope (a_1).
(b) The large elevator lift effect (Z_η).
(c) The high induced drag.

Of secondary importance are:

(d) The high-pitch inertia.
(e) The low-pitch damping.

In addition, the static stability will normally be kept as low as possible, for two reasons:

1. A more aft centre of gravity minimises supersonic trim problems.
2. The large Z_η term means that the lift loss due to trimming is significantly large (Fig. 2).

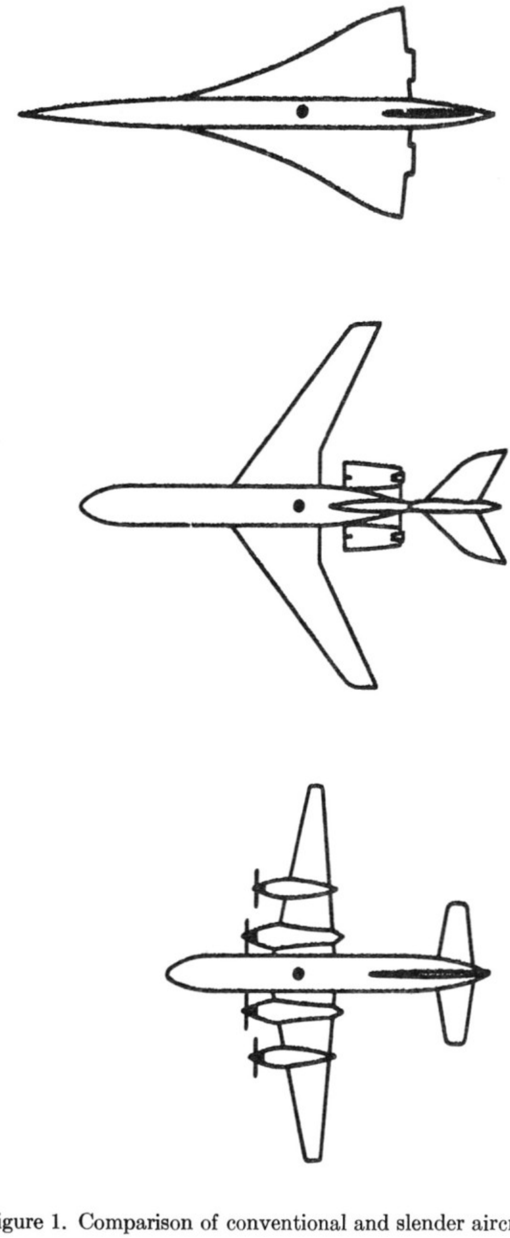

Figure 1. Comparison of conventional and slender aircraft.

Combinations of these effects give rise to some rather unconventional handling characteristics as follows:

(a) The aircraft flies at a markedly nose-up attitude. This is not, as has often been said, due to the low-lift curve slope, but rather to the absence of flaps, which in turn is due to the absence of a trimmable horizontal stabiliser. The effect of the low-lift curve slope is cancelled by the relatively low wing loading, which leads to unusually low values of C_L. This can be seen in Table 1.

(b) Much of the normal low-speed flight regime lies below minimum drag speed. This arises directly from the high induced drag and is probably the most well-marked difference between slender and conventional aircraft. The behaviour of the aircraft in this respect can of course be made quite conventional by the use of an automatic throttle.

(c) The flight-path response of the aircraft to an elevator input corresponding to a given increment in normal acceleration is relatively slow (Fig. 3). This is due to two factors.

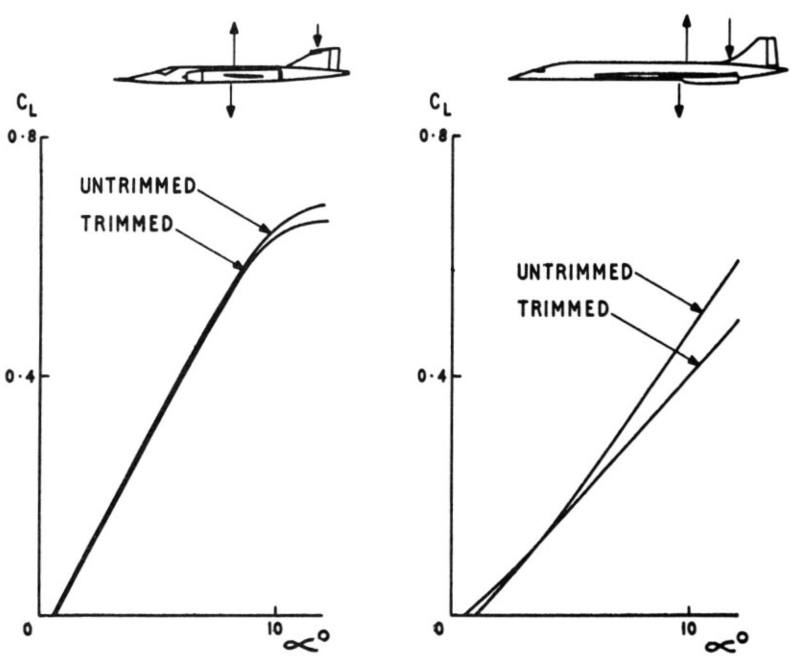

Figure 2. Trim effect on lift.

TABLE 1

Characteristics	Turbo-prop	Big jet	Slender SST
Wing loading, lb/sq ft	63.4	65.5	45
Speed, knots	114	140	142
C_L	1.44	0.98	0.65
a_1	4.8	4.3	Nonlinear (Approx. 2.75)
Aerodynamic incidence, degrees	12.5	13.0	13.5
No lift angle with full flap, degrees	−10	−9	Flapless
Attitude, degrees (3° glide path)	−0.5	1.0	10.5

First, there is the combination of low static stability (and low pitch damping) and high-pitch inertia. The former means that the pitching moment per "g" is small, and this combined with the high-pitch inertia gives a low pitching acceleration and hence a long time to reach steady static conditions. (This is consistent with the normal criteria which says that the frequency of the short-period oscillation should not be too low.) The second factor is the Z_η effect, which gives an initial lift increment of opposite sign to the final steady static one, so that a finite time must elapse before there is a net gain in lift, and an even longer time before there is a net favourable change in the flight path. It is of interest to note that the low-lift curve slope has very little to do with this phenomenon, since, as

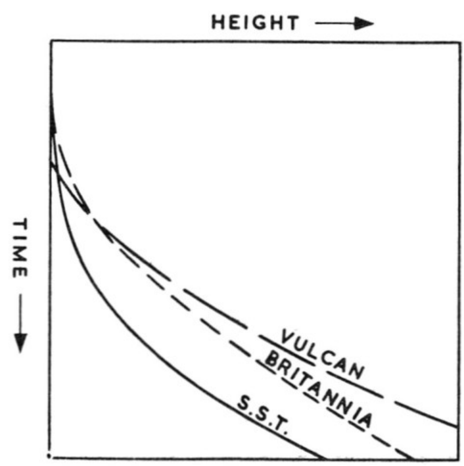

Figure 3. Height response to elevator.

Table 1 shows, the aerodynamic incidence, and hence incremental incidence per "g," is about the same for slender and conventional aircraft.

The method of improving this response is to attack the first cause (the low pitching acceleration), since there is nothing that can be done about the Z_η effect without changing the whole aerodynamic form of the aircraft. In order to get this increase in pitching acceleration we must initially apply much more elevator than is required for the steady state condition. The simplest way to do this is to ask the pilot to do it! To some extent this is acceptable, and in fact even on present aircraft most pilots apply somewhat more elevator to initiate a pull-up than is required for the steady state, but there is clearly a limit to what it is reasonable to demand in this respect. However, as we see from Fig. 4, a simple pitch damper has just the same effect, provided that the gain is high enough. The disadvantage here is that in order to get good flight-path response we may produce a very "dead-beat" aircraft.

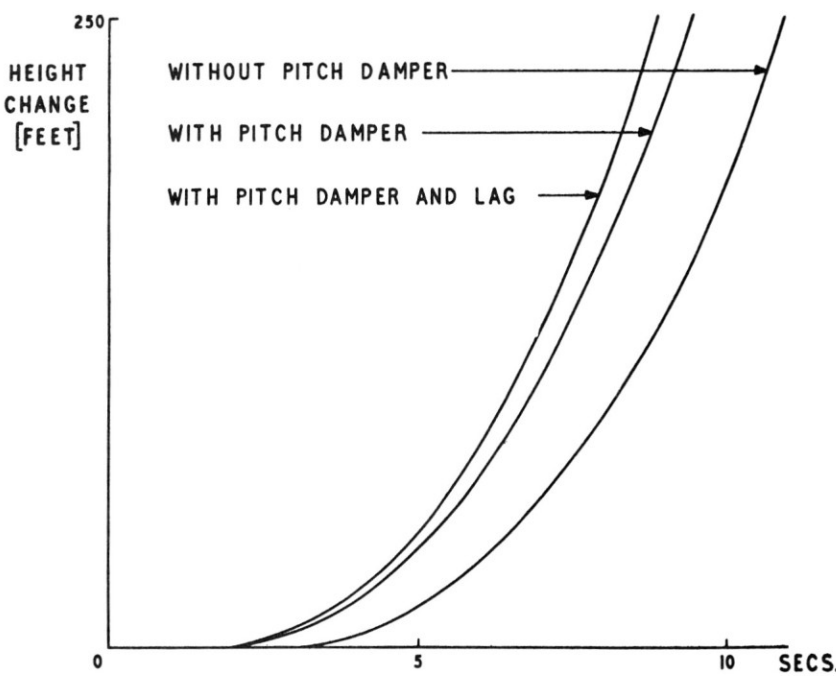

Figure 4. Effect of pitch damper on height response.

If, however, we introduce a lag term into the damper system we can get a large improvement in flight-path response by using a high gain without the corresponding excessive increase in damping ratio. Thus it is possible to get the best of both worlds in this case.

(d) At extreme aft centre of gravity the normal distinction between the phugoid and short-period oscillation becomes lost (Fig. 5). It is unlikely that these conditions will be encountered in normal flight, but they may become of interest in extreme conditions (see above).

(e) The large Z_η effect may result in difficulties for some automatic control systems.

Ground Effect. Slender aircraft undergo large changes in both lift and pitching moments as they approach the ground. Figure 6 shows these effects, and it will be seen that both the lift and stability increase. These effects will be discussed in more detail when we come to the question of flare and touchdown.

THE LATERAL MOTIONS

I now turn to the characteristics of the lateral motion. The peculiarities of the slender aircraft here arise partly from aerodynamic and partly from

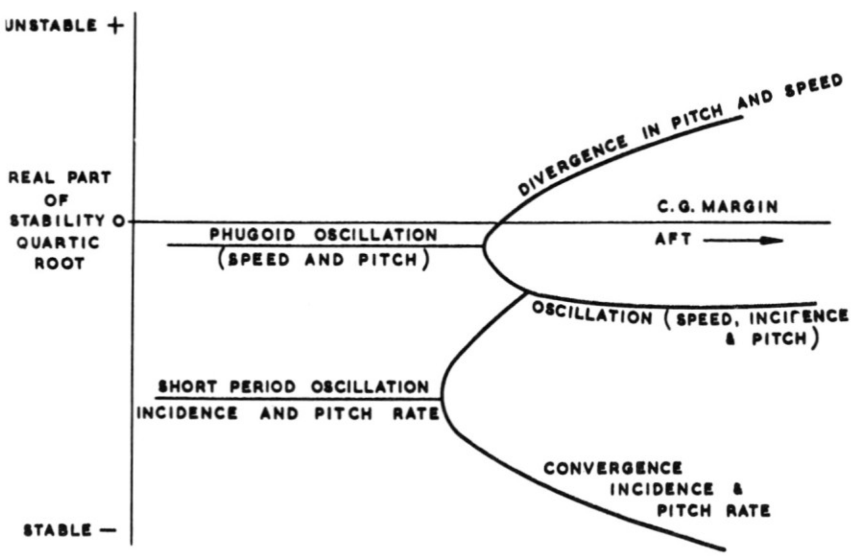

Figure 5. Effect of c.g. position on longitudinal dynamic characteristics.

TABLE 2

	Conventional	Big jet	Supersonic transport
Roll (A)	1	1	1
Pitch (B)	1	3.5	7
Yaw (C)	2	4.5	8

purely dynamic causes. Considering the dynamic aspects first, Table 2 shows the moments of inertia about the principal axes of pitch, roll, and yaw for three types of aircraft. I have taken the roll inertia to be unity in each case.

It can be seen that for the conventional aircraft the inertias are all of the same general order (with the yaw inertia somewhat higher), while for the slender aircraft the yaw inertia is eight times the roll. The effect of this disparity on the aircraft motions is considerable, the general tendency being for the aircraft to try to roll about its principal axis of inertia rather

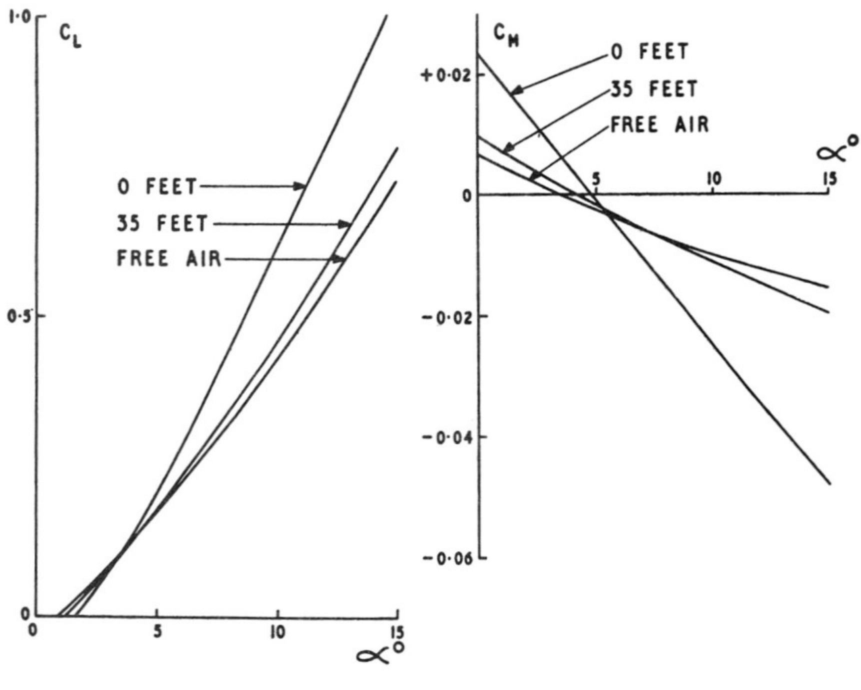

Figure 6. Effect of ground proximity.

than the wind axis. This phenomenon is well known and can easily be shown mathematically to arise from the cross-product terms in the equations of motion. However, I have found it helpful to try to get a feel for its physical basis, and the following very elementary analysis may help in this—although it makes no pretense to rigor.

Consider a rolling moment L applied about the wind axis of an aircraft flying with its principal axis at an incidence α (Fig. 7). This moment can be resolved along the principal axes of roll and yaw, and the resulting angular accelerations of $(L \cos \alpha)/A$ and $(L \sin \alpha)/B$ can be recombined to give a resultant inclined downwards from the roll principal axis at an angle of

$$\theta = \tan^{-1} \frac{A}{C} \tan \alpha$$

Hence, if $A \simeq C$, then $\theta \simeq \alpha$ and the aircraft starts to roll more or less about the wind axis. As A becomes small with respect to C, however, θ tends towards zero and the aircraft starts to roll more nearly about the inertia axis. Clearly, this simple reasoning only applies to the initial motion, and things become more complicated when there are large angular rates present, but the argument does seem to indicate the basic physics of the phenomenon.

The effect of this strong tendency to roll about the principal axis is illustrated in Fig. 8, where it can be seen that the final result is to convert incidence into yaw (or sideslip). Since, as we have already seen, the slender aircraft flies at high geometrical incidences at low speed this effect is very significant. In fact it is probably the dominant characteristic of the lateral handling characteristics of these aircraft.

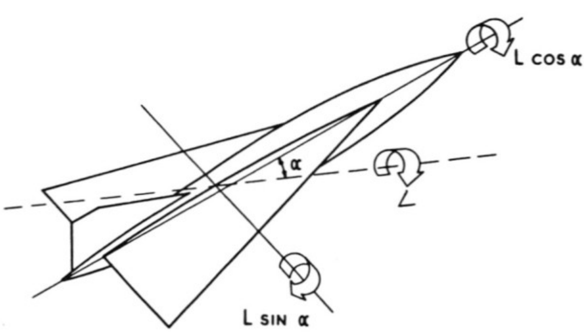

Figure 7. Resolution of rolling moment.

The major aerodynamic factors are

1. A high value of $l_v(C_{l\beta})$ at high incidences, caused by the high sweep-back.
2. A relatively poor damping in roll due to the highly tapered short span wing.

In spite of all these differences, the solutions of the lateral stability quartic in general take the same form as for conventional aircraft, and we

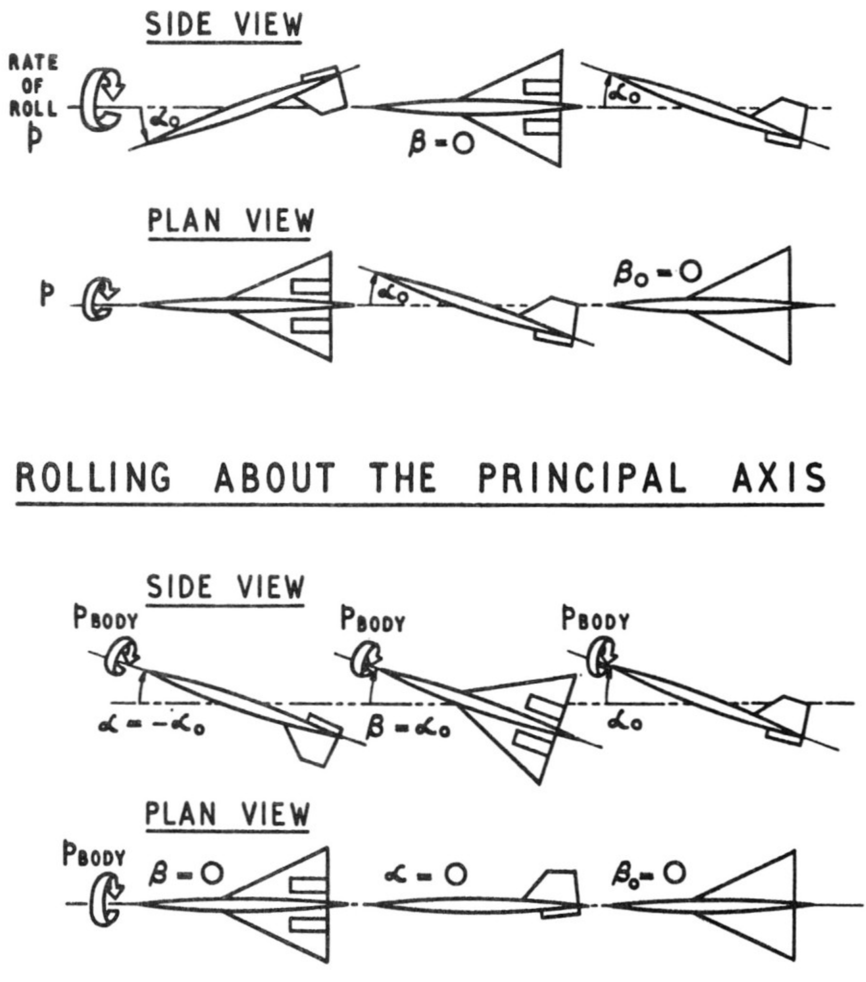

Figure 8. Rolling about the wind-stability axis.

can legitimately speak of the spiral and rolling modes and of the Dutch roll oscillatory mode. (Under some circumstances at very high incidence the spiral and roll modes combine to form an oscillatory mode, the so-called "lateral phugoid." This mode is normally of long period and highly damped and hence does not make itself felt to the pilot to any significant extent.)

Spiral Stability. The classic spiral stability criterion is

$$L_v N_r - N_v L_r > 0$$

As incidence increases both L_v and N_r increase numerically, L_v approximately as α and N_r as α^2. N_v and L_r, on the other hand, vary relatively little—in general N_v will probably tend to decrease. Hence spiral stability increases as incidence increases, and slender aircraft usually exhibit high spiral stability at low speeds. As a result there is unlikely to be any marked wing dropping or spinning tendency.

(There is not sufficient data on the spinning characteristics of slender aircraft to generalise about them. It is usually difficult to get them to spin, but when this is done it appears that three forms may develop.

1. A relatively steep, slow spin with easy recovery. This is the most common and usually starts from 1-g flight.
2. A flat, fast spin.
3. A steep, violently oscillatory spin.

These latter are rare and usually start from accelerated flight. Recovery from them is often difficult.)

The Roll Mode. This mode is usually only excited to any significant extent by control application, and I shall discuss it later under that heading.

The Dutch Roll. Pinsker [1] has given an excellent account of the development of the Dutch roll from the almost pure directional oscillation of an aircraft with very low l_v through the conventional combined rolling and yawing motion to the slender aircraft Dutch roll which is more nearly a pure rolling oscillation. This progression is illustrated in Figs. 9 and 10. Figure 9 is plotted for a constant value of incidence and shows the general effect of the l_v/n_v ratio and the roll/yaw inertia ratio. Figure 10 is drawn for a typical slender SST and illustrates the fact that the typical "slender" Dutch roll only occurs at high incidences. In the paper referred to above Pinsker shows that if the aircraft satisfies a criterion of "inertial slenderness,"

$$\sin^{-1} \frac{n_v A}{1_v C} < \alpha$$

then the Dutch-roll frequency becomes a function of L_v and incidence only

$$W_d = \frac{1}{2\pi} \sqrt{L_v \sin \alpha}\, \alpha$$

while the roll/slip ratio ϕ/β is equal to $1/\sin\alpha$. However, while ϕ/β reduces with increasing incidence ϕ/ψ, the roll/yaw ratio as it appears to the pilot,

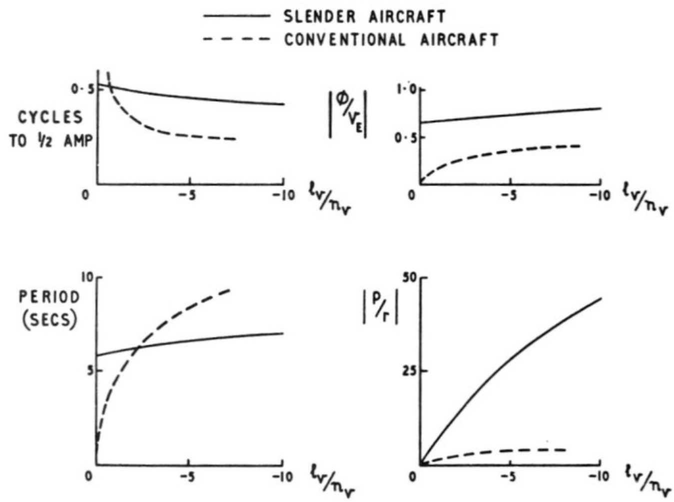

Figure 9. Effect of l_v/n_v on Dutch-roll characteristics.

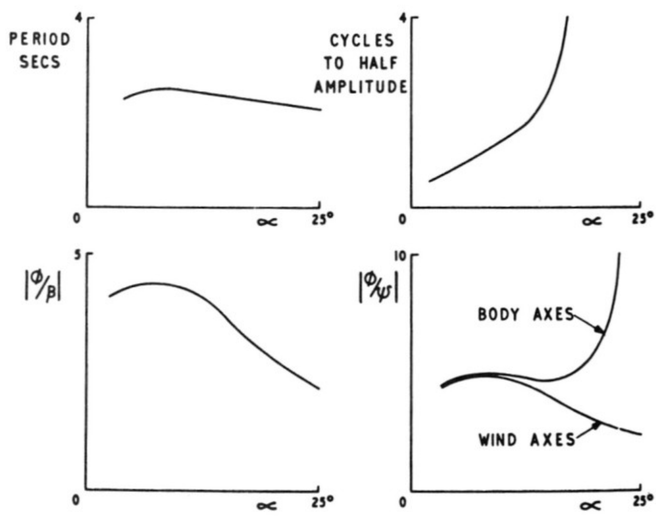

Figure 10. Effect of incidence on Dutch-roll characteristics of slender aircraft.

increases very rapidly. This difference arises because of the interchange of α and β at high incidences, which means that sideslip can be generated with very little actual motion of the longitudinal axis. Thus to the pilot it appears that the motion is almost purely an oscillation in roll.

Lateral Control and Response. I shall discuss the control power situation in the sections dealing with specific flight regimes. In this section I wish to deal with the form of the aircraft response to control application.

First let us consider the ailerons. As I shall show later, in order to have sufficient roll control it is necessary to use the greater part of the trailing edge controls on ailerons. The effect of this on an aircraft where the fin lies close to the trailing edge is to produce large "favourable" (i.e., pro-turn) yawing moments, as can be seen from Fig. 11. As we saw in Fig. 8, when a slender aircraft is rolled it tends to generate sideslip, and this sideslip is adverse in the sense that the rolling moment due to l_v tends to oppose the motion. The overall result of this and the resulting disturbance of the Dutch roll mode is an oscillatory roll of the form shown in Fig. 12. If this oscillatory tendency is large it can be most disconcerting to the pilot and make the performance of coordinated turns most difficult. Clearly, the simple way out of this problem is to suppress (or partially suppress) the inertially induced sideslip by aerodynamic means. The aileron-fin-induced yawing moments help in this, but they may not be sufficiently powerful.

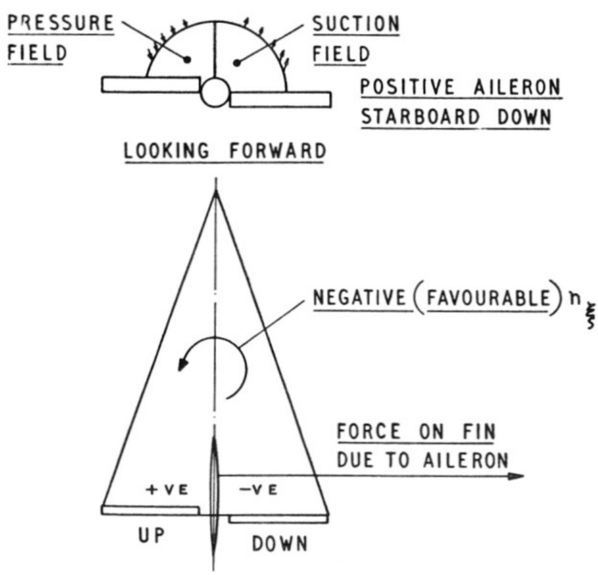

Figure 11. Aileron-fin interaction.

The magnitude of the yawing moment accompanying aileron application can be increased by feeding the aileron demand signals into the rudder circuit.

This can be mechanically simple and reliable and will certainly suppress the sideslip giving rise to the oscillatory roll. However, it does this at the expense of introducing a true yawing motion in space axes, which would not be present in a conventional aircraft. This can be disturbing to the pilot in large manoeuvres. Thus the extent to which this device can be successfully used is limited, but flight-simulator experience suggests that a moderate rudder-aileron gearing combined with adequate damping of the Dutch roll mode gives good results.

It can be shown [1] that at high incidences the rudder can become a more powerful roll control than the aileron. However, such a use of the rudder is liable to give much larger Dutch-roll excitation than would the ailerons, and the evidence at the moment is that the rudder will be used primarily to deal with engine failures and cross wind conditions.

The combination of high l_v, low roll damping and low roll inertia inevitably leads to a high level of response to lateral gusts, as can be seen in Fig. 13. However, artificial roll damping of an acceptable order of magni-

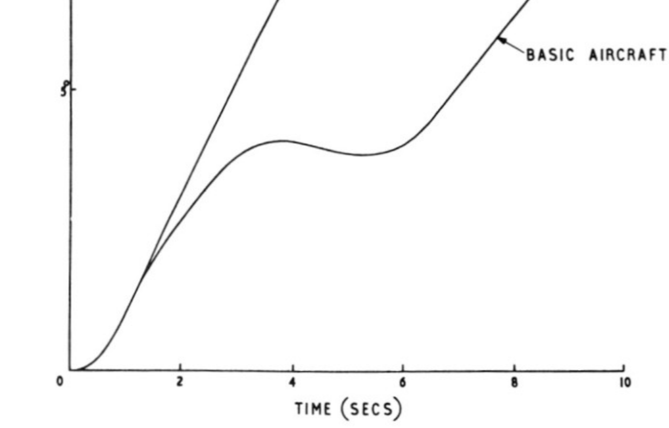

Figure 12. Roll response of slender aircraft.

tude can make a considerable improvement, while other forms of input to the autostabiliser, such as roll acceleration or roll rate phase advance can make further contributions.

LIMITING CONDITIONS

The bulk of the remarks in the foregoing sections apply to the normal low-speed flight regime—i.e., down to speeds a moderate amount below the nominal approach speeds. As the speed is further reduced, new phenomena start to appear, one or more of which ultimately form a barrier (albeit a rather hazy one) to further speed reduction. These phenomena are of two broad classes:

(a) Flow breakdown
(b) Aircraft dynamic phenomena

Flow Breakdown Phenomena. At moderately high incidences the flow on a slender aircraft is essentially separated, with large, rolled-up leading-edge vortices (Fig. 14). As the incidence increases the stability of this flow pattern decreases, and any or all of three types of breakdown can occur:

(a) The vortices from the forebody no longer join with the wing vortices but continue straight back past the fin. At still higher incidences the

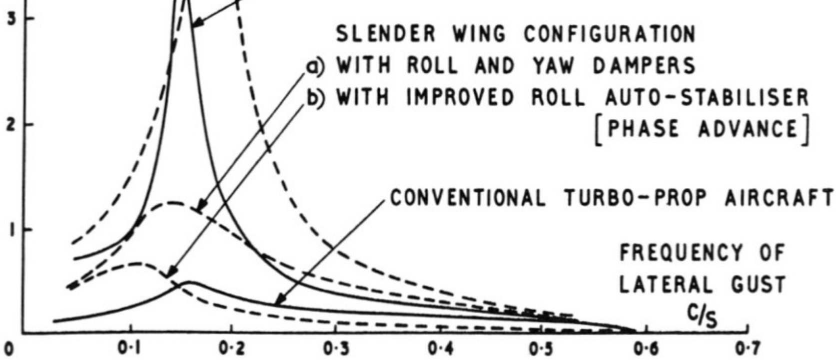

Figure. 13. Frequency response of bank angle to side-gust landing-approach conditions.

symmetry of this pair of vortices becomes unstable and they cross or leapfrog each other.

(b) The main wing vortex leaves the leading edge at part span and trails aft, allowing a new leading-edge vortex to start just outboard of it.

(c) The main wing vortex remains essentially in one piece but becomes internally unstable and "bursts" as it nears the trailing edge.

Case (a) can cause directional problems, giving low or negative directional stability over small sideslip ranges; or, in a more severe form, causing more-or-less random yawing moments of significant magnitude at very nearly zero sideslip.

Case (b) can have a variety of effects. When it first occurs it may have no measurable effect on the derivatives, but as it develops it is very often associated with a loss of pitch stability; not necessarily a sudden pitch-up, but a relatively gentle curving up of the C_m-C_L curve. It can also give rise to sudden changes in the lateral derivatives, particularly l_v.

Case (c) is usually associated with some form of pitch-up, and there are some signs that in a well-developed form it might give rise to buffet.

Thus two of the possible forms of flow breakdown can lead to a loss of longitudinal stability, and in fact, even when no specific flow breakdown can be detected, slender aircraft designs often show a steady reduction in stability in the higher C_L ranges. It is of interest to note therefore that flight-simulator experiments have shown the deterioration of handling characteristics with reducing stability to be quite slow, and that instabilities of several per cent of the root chord are quite acceptable (Fig. 15).

Dynamic Phenomena. Clearly, any form of flow breakdown, can, in principle, couple with the aircraft motions to form a dynamic phenomenon. However, such phenomena are very sensitive to the fine details of the flow, and there appears to be no reasonable way of either classifying or predicting them.

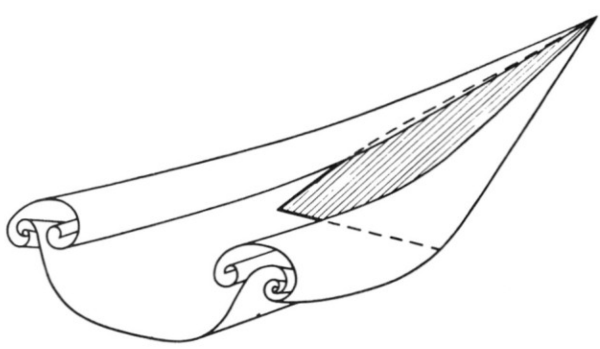

Figure 14. Flow past a lifting slender wing, sharp leading edges.

There is, however, one high-incidence dynamic effect which does not appear to depend in essence on flow breakdown. This is the large-amplitude roll oscillation sometimes known in England as Gray's oscillation. A basic cause of this oscillation is a simple linear instability in the Dutch-roll mode. This sets up a divergent oscillation, almost entirely in roll, which is then fixed at some finite amplitude by some nonlinearities in the derivatives. By using small-scale free-flight models, Gray was able to establish a curve giving the incidence for the onset of this oscillation in terms of the sweepback of the leading edge. That such a generalisation is possible is not altogether surprising in view of the extreme simplicity of the formulas given under "*The Dutch Roll*" section above.

Flight tests on the HP-115 research aircraft have confirmed the existence of this oscillation, which starts at about the expected incidence and increases in amplitude as the incidence increases. Pilots have reported that they have no difficulty in checking and damping out the oscillation in two or three cycles.

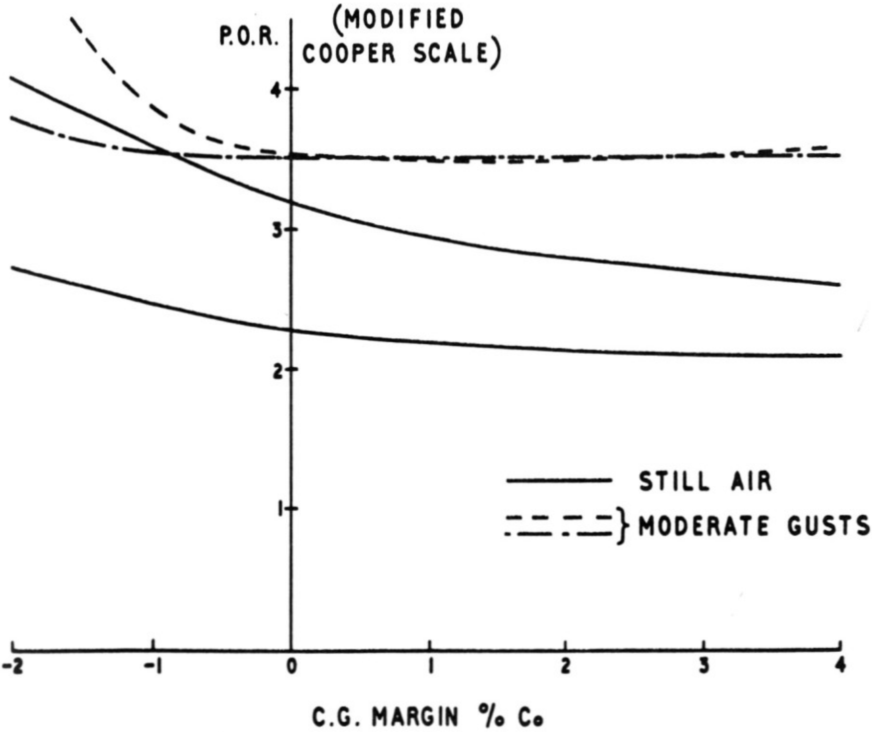

Figure 15. Effect of c.g. position on pilot-opinion rating.

Figure 16 shows the generalised curve together with the calculated zero stability point for the HP-115.

I have now completed this brief résumé of the basic handling peculiarities of slender aircraft, and I must turn to considering how these affect the task the pilot has to perform in different phases of flight. Before doing this, however, I should like to look at one or two general points which seem to come out of the previous sections. The first is that many of the longitudinal peculiarities arise from the fact that the aircraft I have considered is tailless, and many of you will wonder why one does not fit a foreplane and be done with it. This is a perennial subject for discussion and would merit a whole paper in its own right.

Very briefly I would only say:

(a) The desirability or not of a foreplane at high speed depends primarily on the choice of cruise Mach number, and that at around Mach 2 the balance is against one; and

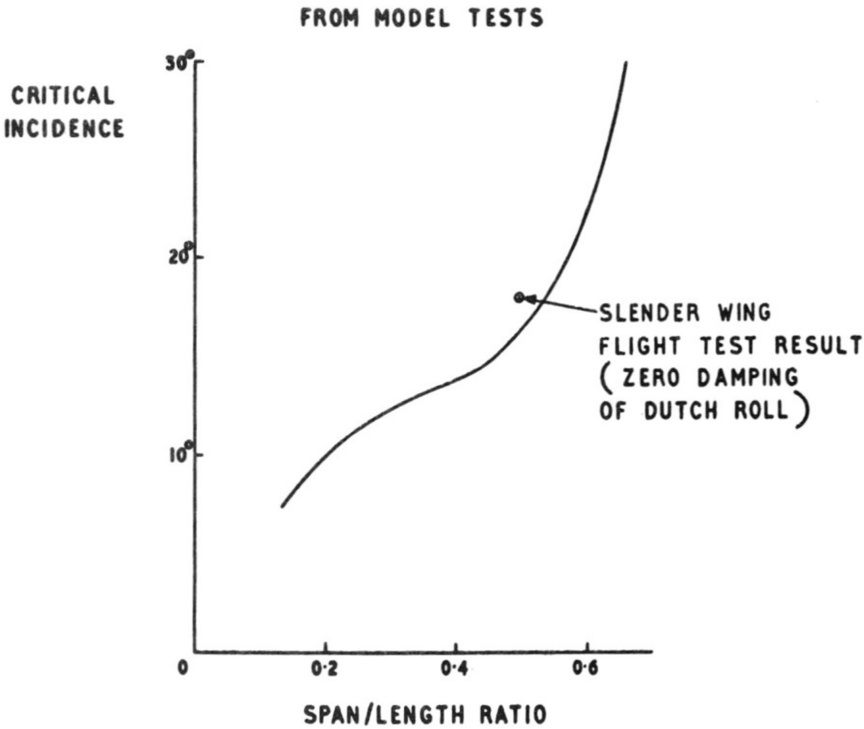

Figure 16. Incidence for start of lateral oscillation of slender aircraft.

(b) Both flight simulator studies at low speed and flight tests—the HP-115—have demonstrated that the piloting problems do not in fact loom so large as one might have supposed.

The second is that many of the lateral problems are associated with high values of l_v. It would therefore appear logical to incorporate negative dihedral to reduce these effects. This is indeed a possible course of action, but it has several subsidiary disadvantages:

(a) The spiral and/or Dutch-roll stabilities at high speed are adversely affected, and in particular the rolling pullout cases at less than 1 g are worsened.
(b) Simple anhedral from the root has severe layout disadvantages, particularly from the point of view of ground clearance.
(c) Some form of outboard anhedral avoids the worst problem of (b), but there is a possibility that the kink will adversely affect the vortex flow stability.

LOW-SPEED FLIGHT

In this section I shall consider the overall handling characteristics of slender aircraft—in particular, low-speed flight regimes. I shall start with the approach and landing phase, since it is in this phase that the pure handling problems are most clearly exemplified. In the takeoff phase the handling and performance aspects are more closely interwoven, and I shall deal with them last.

APPROACH

From the preceding section it would appear that it should be possible, using only unsophisticated autostabilisation, to make a slender aircraft comfortable and conventional to fly at normal approach speeds. This supposition has been borne out by a number of flight simulator studies which have been carried out during the development of the Concord, the results of which have been summarised in Figure 15. Although the fact that these studies were made on different sets of equipment, both fixed-base and moving-base, and at different stages of the design has led to some scatter, the general result is to show that very satisfactory handling levels can be achieved, even at centre-of-gravity positions where the aircraft is statically unstable. The two main problems which were commented on by the pilots were a certain difficulty in achieving the trimmed state after intersecting the glide slope, and a rather greater than usual sensitivity to

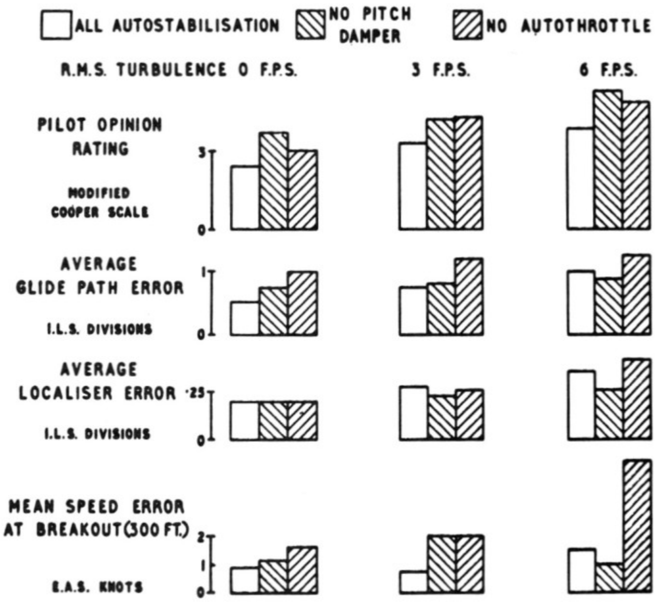

Figure 17*a*. Effect of autostabiliser and autothrottle failures on approach characteristics.

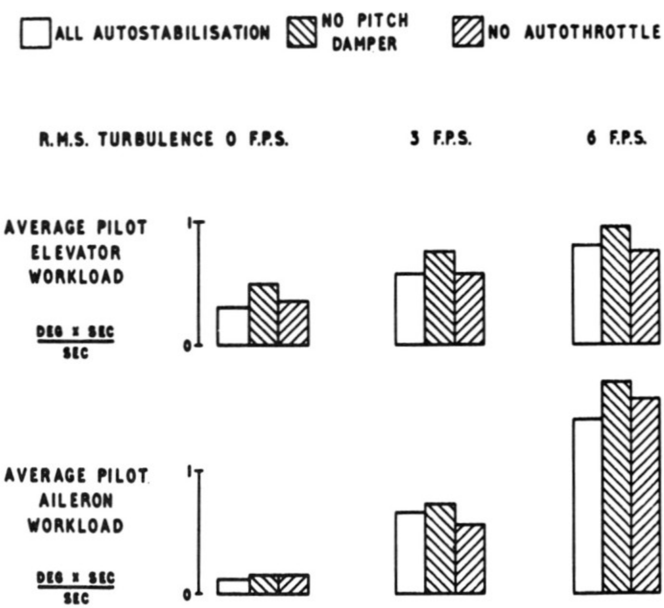

Figure 17*b*. Effect of autostabiliser and autothrottle failures on approach characteristics.

gusts (this was for simple dampers with no phase advance in the roll circuit). In these exercises the pilot was asked to perform a normal ILS approach, with an initial lateral offset, and to carry out a number of standardised manoeuvres, such as S-turns.

However, unless we resort to extreme complexity we must assume that automatic devices will fail on occasion and investigations into the effects of various failures have been made (Fig. 17). These show that while the Pilot Opinion Rating is worsened by the loss of either pitch damper or auto throttle, there is relatively little decrease in the accuracy of holding the flight path, particularly in rough air. There is, naturally, a significant increase in the speed error at break off height. It is to be presumed that the change in POR is due to the increased concentration required and the increased work load, either in terms of control or throttle movements.

The results I have quoted here are for an early version of the Concord, and using simple pitch and roll dampers. Work on later configurations and with more sophisticated damper laws has shown that significant improvements of up to one point on the POR scale can be obtained, particularly in rough air.

FLARE AND LANDING

Longitudinal Aspects. The basic flare itself does not appear to have any new problems with this type of aircraft, particularly with the pitch autostabiliser in operation. Analytical studies, using both arbitrary elevator inputs and pilot-transfer-function techniques, have shown that satisfactory flares can be made from normal heights using conventional types of stick movement; and that the touchdown conditions are not unduly sensitive to the exact form of the stick movement (Fig. 18).

These general conclusions have been confirmed by the flight experience on the HP-115, where no difficulty in carrying out the flare has been reported. However, there is one major difference between an SST and a research aircraft such as the HP-115. This is sheer size. The pilot on the Concord, for instance, will be some 90 ft ahead of the main wheels, and at touchdown he will be about 35 ft above the ground. Some fears have been expressed that this will make the judgement of touchdown unduly difficult. This may be a problem, but it must be remembered that this situation is not all that different from that on current aircraft; the corresponding figures for the Boeing 707 are 55 ft and 22 ft respectively, and for the Super VC-10, 80 ft and 25 ft.

Having got the main wheels on the ground, we must now lower the nose of the aircraft since the touchdown altitude is some 10° nose up. If the touchdown is made with a finite velocity of descent, the nose will start to drop automatically and analytic studies have shown that there is then no problem in obtaining a well-controlled lowering of the nose. If a very soft landing is made with a nearly zero rate of descent, and the aircraft in trim with zero rate of ptich, then the nose will only start to fall very slowly as the speed falls off. An attempt to hasten this process by pushing the stick forward could lead to the aircraft ballooning off due to the elevon lift effect. This problem is eased by the pitching effect of wheel spin-up, and should it prove to be a real problem it has been suggested that the brakes could be used to give a further nose-down pitching moment. (This pitching moment would be quite weak because of the small weight on the wheels at this point, and it is only required to initiate the motion—once the nose starts to drop the whole process can be controlled by the elevators.) However, all this is conjectural, since although this could theoretically be a problem it has not so far been experienced in flight.

Lateral Aspects. The problem of crosswind landing gives rise to one of the major design cases for the aerodynamic controls on slender aircraft.

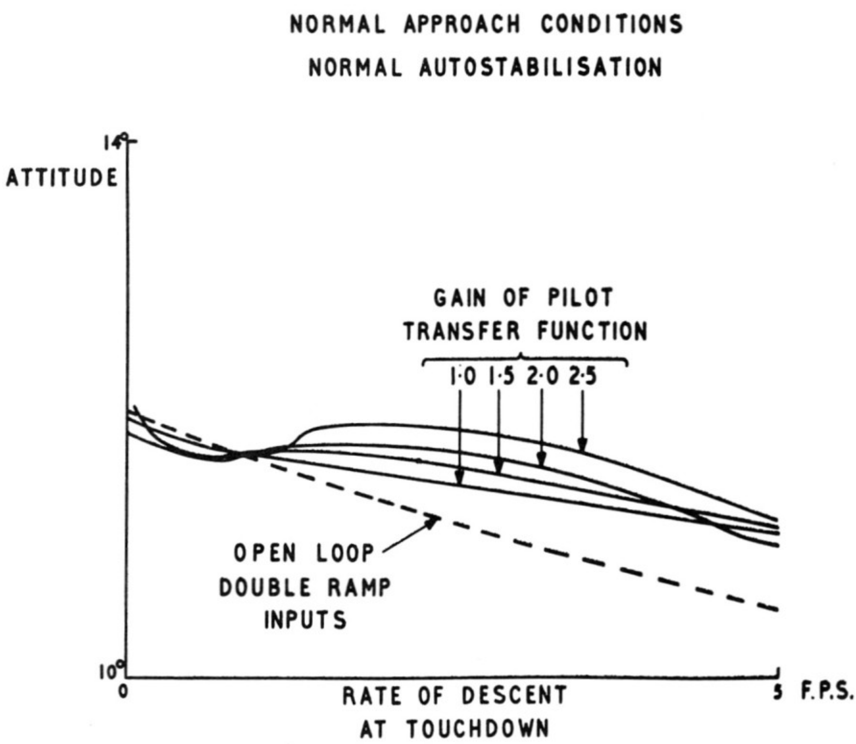

Figure 18. Effect of pilot technique on touchdown attitude.

Various criteria have been proposed for judging the aileron power required, and a typical one is shown in Fig. 19, where the maximum rolling power required is given as a function of the rolling moment due to the steady crosswind. This particular set of curves was derived from fllght simulator studies carried out in the early stages of the SST exercise in Britain, but other studies have given generally similar results.

In deriving these results both the side slipping and "kickoff drift" techniques were used, and both seemed to lead to about the same amount of aileron (the sideslipping being slightly more severe, and also requiring more rudder power). More recent studies have suggested that in the full kickoff drift case it is very difficult to get accurate correspondence between rudder and aileron application and quite large bank errors may result. It appears probable that the final technique will be a relatively slow application of rudder during the flare to partially align the aircraft with the runway and then a final manoeuvre to correct the residual heading and bank errors. This is the type of technique now being used in many cases on the big jets.

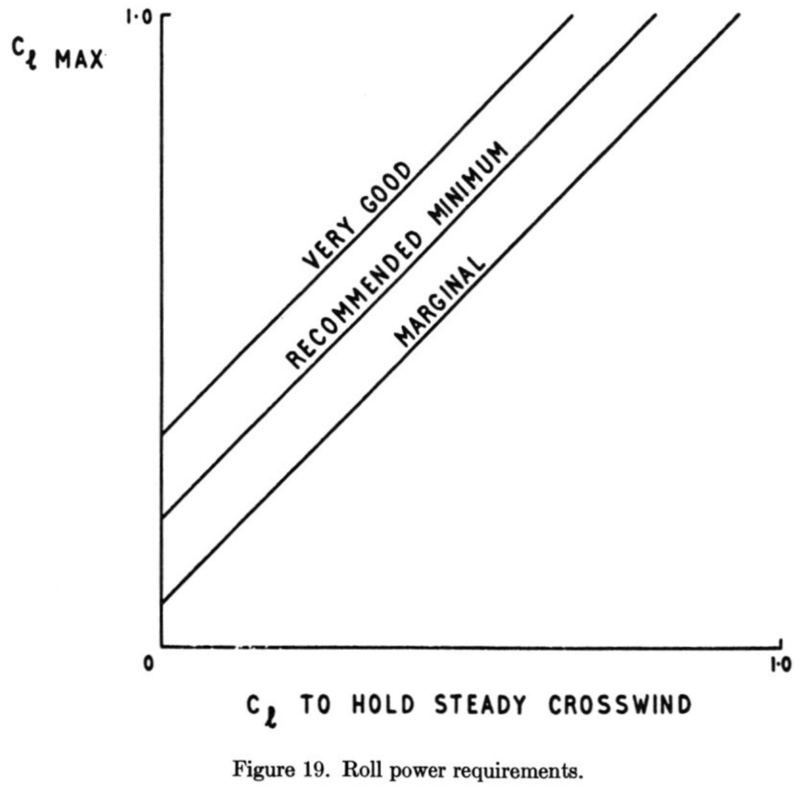

Figure 19. Roll power requirements.

Whatever technique is finally adopted, it can easily be shown that in order to be able to deal with 25- or 30-knot crosswind the greater part of the trailing edge must be used as ailerons, including the inboard part of the span. A direct result of this is the strong "favourable" aileron induced yawing moment mentioned above. Unfortunately, although this yawing moment is favourable in normal flight manoeuvres it is unfavourable for the crosswind landing case, as can be seen from Fig. 20. Thus the crosswind landing may also be a design case for the rudder, becoming more critical than engine failure at takeoff.

TAKEOFF

Ground Roll. There are no novel factors affecting the SST during the major part of the ground roll. The problem of lateral displacement during engine failure may be more severe than usual, partly because of the rather high thrust/weight ratios and partly because the rather short fin arm gives rise to an unusually large rudder-side-force/rudder-yawing-moment ratio.

However, this problem is critically dependent on engine position and rudder power, and although it may give rise to the design case for the rudder there is no reason to believe it poses any inherent difficulty.

Rotation and Initial Flare. As on many other aircraft, the problem of raising the nose wheel with the centre of gravity in its most forward position gives rise to the elevator design case.

The slender aircraft is probably more sensitive than most conventional aircraft to rotation technique. Since the unstick attitude is greater than usual, harsh use of the elevator can build up high rates of pitch which are difficult to check and could lead to excessive flight attitudes. On the other hand, because of the high induced drag it is most desirable that the time spent at the higher incidences should be as short as possible. As a corollary of this, if the rotation is checked at too low an incidence and the error not corrected very significant increases in take off distance can result.

Thus it appears that a fairly steady pull-off at a moderate rate of pitch is the ideal technique for this type of aircraft, and it may well be that some form of takeoff director will be needed to give good and consistent performance. It is my personal opinion that this will not necessarily have to be a very sophisticated device, and that an improved pitch rate display might even be sufficient by itself.

There is a further reason for wishing to have a moderate rotation rate. Nearly all of the rolling moments due to sideslip come from the wing incidence term, and so increase rapidly during rotation. Thus during a crosswind takeoff the pilot will tend to feel that he is experiencing a lateral gust

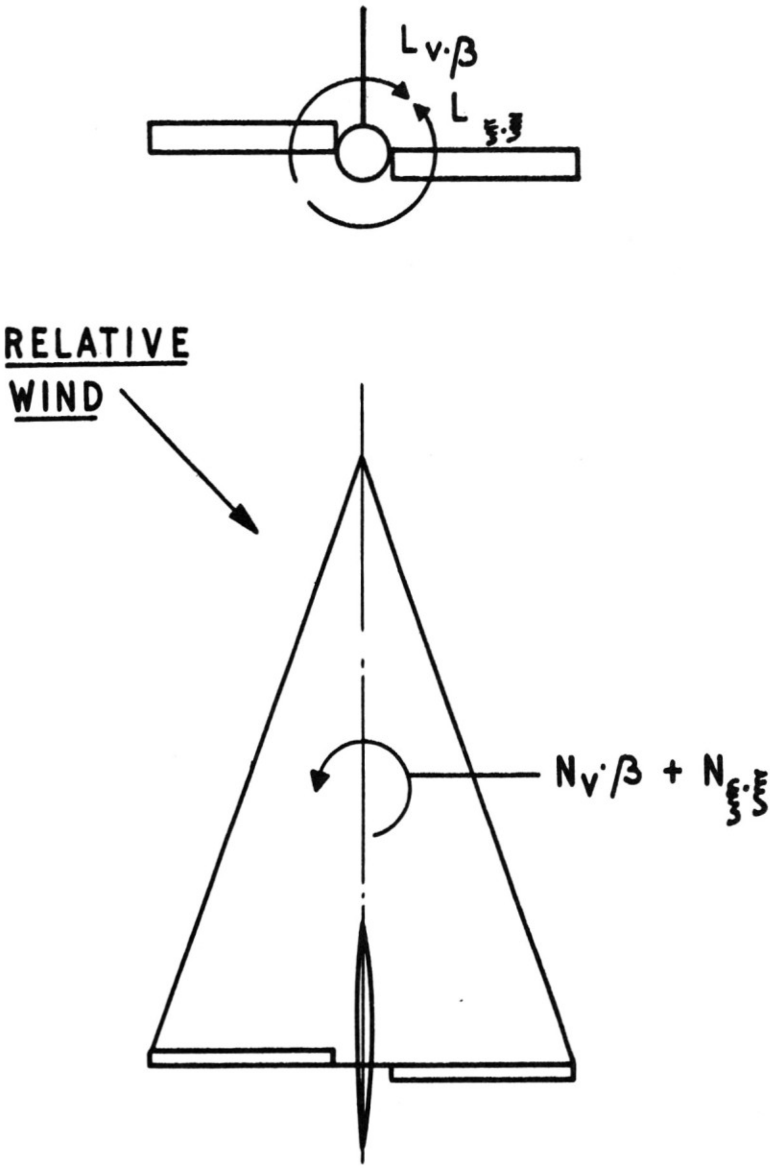

Figure 20. Crosswind landing.

with a rise time proportional to the rotation time. Thus very rapid rotation could lead to wing-dropping problems at unstick.

Initial Climb. Because of the high induced drag, the climb gradient is more sensitive than usual to small departures from the nominal speed. Because of the shape of the drag polars, this increase in sensitivity only occurs for speeds near the climb speed; for large speed errors, particularly low speeds, the slender aircraft may be less sensitive than current aircraft as is shown in Fig. 21.

This again means that for optimum performance the pilot will probably need better guidance than current instruments give him.

Because the need to hold a very accurate flight path is not so great as it is on the approach, speed stability will not normally present a problem. However, some proposed types of guidance rely on the pilot's holding a constant attitude during this phase. This type of restraint on the aircraft motion can also give rise to a type of speed instability, but one which occurs at much lower speeds than the normal one associated with a restrained flight path. It appears unlikely that this will cause any difficulties with currently proposed designs.

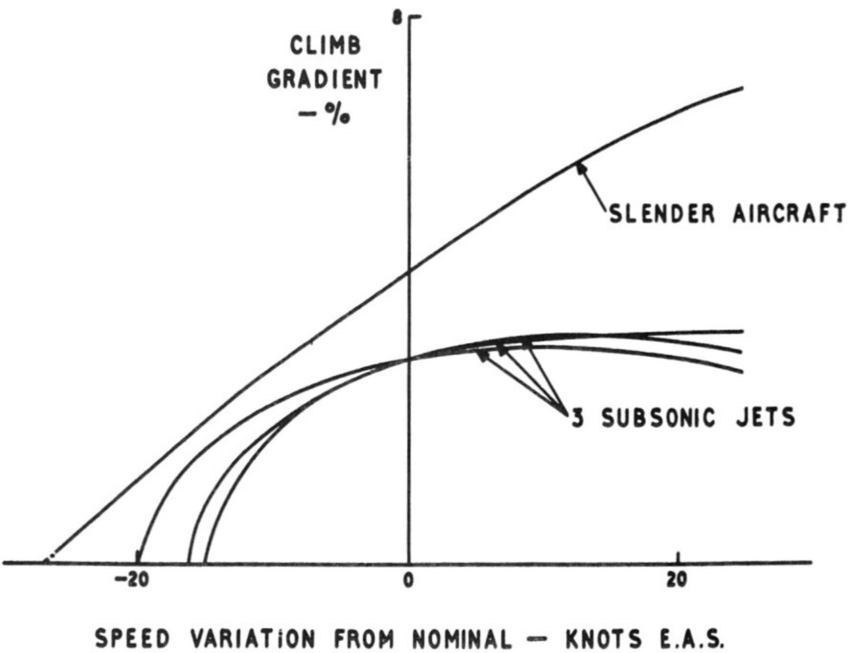

Figure 21. Effect of speed variation on climb gradient.

CONCLUSIONS

As I said in the introduction, the emphasis in this paper has been on those aspects of the handling characteristics of large slender aircraft which are likely to prove novel and, possibly, troublesome. This necessary concentration on the novel should not, however, lead us to forget that in most respects a slender aircraft behaves in a perfectly normal manner.

It is this large area of normalcy which enables us to deal with its novel problems in a relatively simple manner, and to be able to say that the artificial aids should be provided as aids to the pilot rather than as features essential to the safety of the aircraft.

REFERENCE

1. Pinsker, W. J. G., "The Lateral Motion of Aircraft, and in Particular of Inertially Slender Configurations," *R.A.E. Tech. Report, Aero.* 2656.

COMMENTARY

D. K. M. MENDELA (*Hawker Siddeley Aviation, DeHavilland Division, Hatfield, Herts., England*): Would Mr. Goldsmith agree that to check finally new supersonic aircraft handling characteristics, provision of full-scale control rig, connected to a suitable simulator fitted with good display is very desirable? In the long run it may save development flying, contribute to aircraft safety and provide the pilot with the familiarization of the complete flying control system. It is felt that a check of the complete loop of human pilot–aircraft-control system–aircraft aerodynamics is very necessary.

REPLY

I think that if one wishes merely to check the handling characteristics it is quite possible to get adequate simulation of the control-system characteristics without going to a full-scale control rig; in fact, purely computational simulation will be sufficient. That does not mean that it is not a good thing to have a control system rig in its own right—I believe that there are very strong reasons for doing this. I do not think, however, that even if one has a control rig and flight simulator it is necessarily a good thing to combine them; certainly one should keep the facility for simulating the control system. This is for purely practical reasons, since a rig doing systems development is most unlikely to have its programme of shut downs and modifications fitting in with the requirements of a flight-simulation programme. The two facilities are in fact trying to do very different jobs.

COMMENTARY

G. H. LEE (*Handley Page, Ltd., Cricklewood, London*): A point of some possible significance regarding the handling of slender aircraft at low speeds arises from the marked difference between the expected and "actual" Cooper ratings for the lateral behaviour of the Handley Page HP-115, a point brought out by Mr. O'Hara's paper earlier this week. It seems that one explanation may be that the acceleration cues given to the pilot by the motion of the aeroplane were of great help. Another point is that the controls of the HP-115, being manual, were without significant phase lag or lost motion. It may well be that had we had power operated flying controls on that aircraft the inevitable lost motion might have made the aeroplane harder to fly. On a big aeroplane, of course, with its lower frequencies, losses through the PFC loop would probably be less important than for a small aeroplane.

There arises, therefore, the general point that perhaps criteria for the handling properties of aircraft should contain parameters representing the control characteristics (aerodynamic as well as mechanical) in addition to the basic aircraft lateral behaviour, as at present.

REPLY

I quite agree with Mr. Lee on the inadequacy of current handling criteria when applied to slender aircraft. I do not think that we yet know why this is; it may well have something to do with the acceleration cases being more pronounced on this type of aircraft.

I also agree that the control-system characteristics are of very great importance and must be included in any detailed study of laterial behavior. However, the BAC Type 221 has power operated controls and has also proved more docile than was expected, so the good qualities of the HP-115 are probably not entirely due to its manual system.