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# A Flight Simulation Study of the Handling Characteristics of a Slender Wing Supersonic Transport Aircraft at Landing Approach Speeds

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*Summary.*

A ground based flight simulator has been used for piloting assessments of the handling characteristics of a slender wing supersonic transport aircraft during the landing approach. The simulation included two methods of representing the outside visual world, and, for some of the tests, cockpit motion in pitch and roll was also used.

Amongst the topics studied were the effects of turbulence, and the improvements in handling which could be brought about by autostabilization. Data is presented in the form of pilots' assessments on an opinion rating scale, measurements of the accuracy of performing landing approaches, and time histories of control usage and aircraft response.

A brief comparison of these handling assessments with the predictions of existing handling qualities criteria has also been made.

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## 1. *Introduction.*

The handling characteristics of a slender wing supersonic transport aircraft at landing approach speeds were briefly studied in tests made on the Aerodynamics Department piloted flight simulator[1] at R.A.E. Bedford during the summer of 1962. This preliminary study[2] showed that the main difficulties likely to be encountered with the basic handling of such aircraft lay in their increased rolling responsiveness to atmospheric turbulence, their sluggish behaviour in pitch, and the oscillatory nature of the motion resulting from the use of ailerons.

In 1963 further more detailed simulation studies were undertaken and these form the subject of the present Report. At that date the design of the joint Anglo-French supersonic airliner was still being evolved, so that the aircraft characteristics simulated represent an early stage in its development, many features having since been altered*. As a guide, the aircraft represented in these tests, shown in Fig. 1, had a landing weight of 160 000 lb, a reference wing area of 3337 sq ft, and the '4-bis' wing configuration. (Further technical details will be found in the tables and illustrations at the end of this Report.)

The study covered a number of aspects of the aircraft's handling at landing approach speeds and was aimed at providing some practical experience within R.A.E. of the aircraft's likely flying qualities. Particular features assessed were the handling during instrument landing approaches with various degrees

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*Because of the many design changes and improvements which naturally occur during the design of an aircraft, the handling characteristics represented during these simulation studies are not those of the Concorde aircraft in its final form. This Report has been included in the R. & M. series in order to provide a more complete record of research work done during the evolution of a supersonic transport aircraft.

of autostabilization; handling at centre of gravity positions beyond the normal aft limit; and the effect of limited rate of control-surface movement on lateral behaviour.

Other important aspects of the simulation were the use of two different methods of representing the pilot's view of the outside world, and the introduction of cockpit motion into the simulation. Comparative tests with these different visual and motion cues were aimed at providing a better understanding of the equipment needed for adequate simulation of this class of aircraft.

Most of the information obtained from this type of assessment is, of necessity, in the form of subjective pilot opinion, expressed either as general verbal and written comment, or by the use of a pilot opinion rating scale. In some cases however it has been possible to supplement these subjective results by a study of such features as pilot's control usage, measurements of the accuracy of performing certain flying tasks, and time histories of the aircraft's behaviour.

The Report is divided into several sections. Details of the setting up of the simulation are given in Section 2. The studies with different visual and motion cues are described in Section 3, followed by the assessments of the aircraft's handling qualities, under the various conditions mentioned above, in Section 4. These assessments are related to the existing criteria for satisfactory flying qualities in Section 5.

## 2. *Aircraft Simulation.*

### 2.1. *Equations of Motion and Aerodynamic Characteristics.*

The behaviour of the aircraft in response to control inputs and external disturbances was determined, in the usual manner, by continuous solution of the equations of motion on an analogue computer, which formed part of the flight simulator. An accurate simulation of the aircraft's characteristics over the speed range 115 to 175 knots was aimed at, the normal approach speed being 145 knots. Within this speed range the aerodynamic forces and moments varied correctly with dynamic pressure, and, where appropriate, the aerodynamic derivatives were varied as functions of incidence. The equations of motion used were those for a rigid aircraft, and these, together with the aerodynamic data, are given in detail in Appendix A, (also Figs. 29 to 41).

One aspect which should be specially mentioned is the representation of atmospheric turbulence. Fluctuations in incidence and sideslip due to turbulence were included in the computation by adding the outputs of two independent random noise generators to the incidence and sideslip obtained from the aircraft's kinematic equations. (The outputs of the random noise generators were properly shaped to correspond to known power spectra[1] for atmospheric turbulence.) This method implies that the whole length of the aircraft is simultaneously subjected to the same fluctuations in incidence (or sideslip), whereas in practice the changes occur progressively along the aircraft as it penetrates the disturbance. The simplification used here was felt to be acceptable for the present preliminary assessments, but its implications deserve more detailed study for future work.

The fore and aft component of turbulence was not represented.

### 2.2. *Flying Controls and Autostabilization.*

The use of elevons, rather than separate elevators and ailerons, on this aircraft necessitates the use of a control 'mixing envelope' to determine the available lateral control travel as a function of the longitudinal control position. Fig. 2 shows this envelope and lists the gearing between the control surfaces and the pilot's controls, together with their associated force gradients.

The cockpit of the simulator used for these tests had a single seat layout, originally intended for work on small fighter or research aircraft. Its layout was therefore not very representative of a large transport aircraft. For the present study a wheel control was fitted in place of the usual control stick, so that the wheel movements and force gradients could be made similar to those proposed for the actual aircraft. However the resulting layout was rather awkward, and the cockpit was somewhat cramped.

A single throttle, mounted on the left hand console, controlled the total engine thrust.

For most of the tests it was assumed that the control surfaces were actuated by idealised servo systems, which could follow the pilot's demands without any lag or other undesirable features. For one series of tests, however, a limitation was imposed on the maximum rate of control surface movement (*see* Section 4.3).

The autostabilization consisted of a pitch damper, a roll damper and an autothrottle. Neither yaw damper nor rudder-to-aileron interconnection was represented during these tests.

The pitch and roll dampers followed the simple law of applying pitching or rolling elevon deflections proportional to the rates of rotation about the appropriate body axis. The autostabiliser was assumed to be lag free, and the control deflections it could demand were not limited in any way. In practice, however, these did not exceed a few degrees. The gearings of the autostabiliser were 1·0 deg per deg/sec in pitch, and 0·4 deg per deg/sec in roll.

The autothrottle operated according to a control law which demanded thrust changes in proportion to the speed deviation from the datum of 145 knots. The gearing was 1000 lb/knot and its authority was not limited. The autothrottle law also contained a longer term integral error correction, which shifted the datum by about 5 knots per minute if the speed was held at a consistently high or low value.

2.3. *Flight Instruments.*

The flight instrument display represented a standard aircraft blind-flying panel, and part of it may be seen in Fig. 3. The instruments were of the dial and pointer type and included: two pointer airspeed indicator; three pointer altimeter; vertical speed indicator; turn and slip indicator; compass, and artificial horizon. The main criticisms of this instrument display concerned the standard artificial horizon, which was considered to be too insensitive for the precise control of pitch altitude needed on this aircraft. (The sensitivity was such that the horizon bar moved through about 1 in for a 30° change in aircraft attitude.)

2.4. *Visual Simulation of the Outside World.*

Two methods of simulating the pilot's view of the outside world were used during these trials. The first was a line pattern display[3], generated electronically on a large cathode ray tube which occupied the position of the aircraft's forward windscreen, (Fig. 3). The displayed pattern (Fig. 4) may be thought of as representing the perspective of the view seen by a pilot when flying diagonally across a landscape of uniform square fields. Inputs to the electronic equipment caused the pattern to vary in accordance with aircraft height and pitch attitude and to move with forward speed. It was also possible to depict changes in heading and sideslip on the display, but these features did not always function satisfactorily and they were therefore sometimes omitted. The impression of rolling motion was obtained by mechanical rotation of the scanning coils round the neck of the cathode ray tube, so that the whole display pattern rolled relative to the cockpit. Special care was taken to ensure that the servomechanism which rotated these coils was smooth in its operation and had adequate performance. Frequency response measurements made on this servo are shown in Fig. 7.

The field of view provided by this display was 34 deg in azimuth and 26 deg in elevation, when viewed from the normal pilot's eye distance of 22 inches.

Because of its similarity to the, so called, contact analogue displays, which are being developed for use in aircraft, the line pattern display will be called by that name for the remainder of this Report. It should be emphasised however that, in the present context, the display was intended to be simply a simulation of the pilot's outside view, and it is not suggested that it should form part of the real aircraft's equipment.

The alternative method of visual simulation was quite different. It depended on direct projection from a point source of light shining through a suitably marked transparency onto a 30 ft diameter screen which surrounded the cockpit. Two forms of this equipment were used. The 'Skyscape' projector, shown in Fig. 5, produced a view of the horizon, with a sky scene above, which indicated the aircraft's pitching, rolling and yawing motion in flight at altitude. These motions were achieved by mechanical rotation of the projector on its gimbal bearings. Special care was again taken to ensure that the performance of the servomechanisms used was adequate, and typical frequency response measurements, made on the roll servo, are shown in Fig. 7.

A development of the Skyscape projector, called the runway shadowgraph projector, was designed to give the pilot an indication of his position over the ground. The simulated view, illustrated in Fig. 6, consisted of a horizon, a wedge shaped outline representing the perspective shape of the runway, and a single transverse line representing the runway threshold. Small mechanical servos altered the range from the threshold and moved the transparency producing the runway image so as to depict changes in height and lateral offset.

The field of view provided by these directly projected visual displays was virtually unlimited, so that the pilot's view depended only on the cockpit cut off angles. These were made to resemble, as closely as possible, the aircraft cut off angles then proposed, but the subsequent introduction of a variable droop nose has radically altered the field of view on the current aircraft.

A comparative study of the contact analogue and Skyscape methods of visual simulation is described in Section 3.1.

2.5. *Cockpit Motion.*

The simulator cockpit was mounted on a motion system which allowed limited freedom of movement in pitch $\begin{pmatrix} +20° \\ -10° \end{pmatrix}$, and in roll ($\pm 15°$), (*see* Fig. 8). The pilot also experienced some heaving motion, as an accompaniment to the pitching motion, by virtue of his position some six feet ahead of the pitching axis. The mechanism was driven by hydraulic jacks giving a frequency response which was substantially flat up to about 1 cps for both axes, the phase lag at this frequency being 35 deg.

At the beginning of the present trials the quality of the motion provided by this system was unacceptable, so that the early tests had to be made with the cockpit fixed. However, improvements in the motion system were being made while the trials were in progress, and it was eventually brought into use towards the end of the programme. The main imperfection then remaining was that the rolling motion gave a perceptible jerk when starting from rest or reversing direction. Although this feature was not liked by pilots, it became less obtrusive with familiarity, and there was general agreement that the simulation with cockpit motion was much to be preferred to that without.

In this simulation the cockpit attitude in pitch and roll was made to correspond simply to the computed aircraft attitude. In one or two trials it was necessary to reduce the ratio of simulator cockpit motion, relative to real aircraft motion, in order to prevent the motion system being driven onto its stops. In such cases the cockpit instruments and external visual display continued to give a correct indication of the real aircraft attitude, and it is felt that this limitation was not serious.

A slight sideslipping sensation naturally occurred when the cockpit was banked, but this was considered to be acceptable in a flying task where the pilot's usual aim was to keep the wings substantially level. (For tests involving steady turning flight it is usual to include a 'leak' term in the attitude demanded from the motion system, so that the sideslipping sensation is lessened by the cockpit being slowly returned to the horizontal position. As indicated above this was not done in the present case, since it does introduce some undesirable features.)

A study of the values of the motion cue provided by this equipment is described in the following section.

3. *The Effect of Different Visual and Motion Cues.*

As mentioned previously, the performance of the cockpit motion system at the start of the simulation programme was so poor that its use was not considered worthwhile, and most of the handling assessments described in Section 4 were therefore made with the cockpit fixed. When the motion system was eventually brought to a satisfactory state, a series of tests was made to establish the value of the motion cue which it provided, and also to compare the two methods of simulating the outside view, which have been described in Section 2.4. Chronologically, the tests reported here were therefore amongst the last to be completed, but it is thought proper to describe them before the bulk of the handling trials, because of the light that they cast on those assessments.

3.1. *The Effect of Different Simulation Cues on Pilot's Control Following a Sudden Sidegust.*

One of the tasks which would require the quickest reaction from the pilot on this class of aircraft was considered to be the control of bank angle, following an encounter with a sudden sidegust. The roll response of the aircraft was particularly rapid because of the large rolling moment due to sideslip, combined with small moment inertia in roll, which are typical features of the slender wing layout. For instance, in the severest case tested in the present trials, the aircraft would attain a peak bank angle of 16°, in about 2 seconds, in the absence of any intervention by the pilot. Under these circumstances it might be expected that the type of visual or motion cue which informs the pilot of the disturbance would be of great importance, and this task was therefore chosen as a suitable, even, if exacting, test of the value of the various simulation cues. Since a thorough test of all the possible combinations of cues would have made the experiment excessively long, attention was concentrated on three cases:

(a) Fixed cockpit, contact analogue visual display.

(b) Fixed cockpit, Skyscape visual display.

(c) Moving cockpit, Skyscape visual display.

The tests were made during the simulation of ordinary landing approaches, using ILS to define the landing approach path. The pilot therefore had to refer to his flight instruments when controlling the flight path, but gained his information about the aircraft's attitude predominantly from the visual simulation of the outside world.

Sharp edged gusts (i.e. 'step' inputs in sideslip), at two levels of intensity, 15 ft/sec and 30 ft/sec, were represented, and the tests were made both with and without the roll autostabilization. The larger of the two gusts would cause the aircraft to roll through 16 deg when the autostabilizer was not working, and through 11 deg when it was working. Several sidegusts from either direction were represented during each approach, but the interval between them was large enough for one disturbance to be completely controlled before another occurred. In about half the tests continuous background turbulence, (rms level 3 ft/sec), was also represented, but the sharp edged gusts were always clearly recognizable by their character and severity.

The results of these tests are summarized in Table 2. This shows the mean increments in bank angle following the gust encounters, for the four test conditions (i.e. with and without roll autostabilization, at two gust levels), and for the three combinations of visual and motion cue; (a), (b) and (c) listed above. Preliminary analysis had shown that there was no significant difference in the results obtained with and without background turbulence, so these have been grouped together in Table 2.

A measure of the consistency in controlling the disturbance with the different cues is given by the standard deviation in peak bank angle during repeated trials, and this is also listed in Table 2.

The main conclusions to be drawn from these results are illustrated in Fig. 9. Here the bank angle which would have been reached in the absence of any intervention by the pilot has been taken as a rough measure of the severity of the disturbance. Against this the actual mean increments in bank angle have been plotted. Fig. 9 shows, for instance, that, in the case where the disturbance would have produced an uncorrected bank angle response of about 10 deg, the pilot's intervention had the following effect:

(a) With fixed cockpit and contact analogue display, peak bank angles were reduced to about 70 per cent of their full value.

(b) With fixed cockpit and Skyscape display, the angles were reduced to about 60 per cent of their full value.

(c) With moving cockpit and Skyscape display, the peak bank angles were only about 30 per cent of their full value.

Table 2 also shows that the variability in the peak bank angles during repeated trials in the moving cockpit tests was roughly half that in the fixed cockpit tests.

For smaller disturbances the percentage reductions in bank angle were not quite so large as those quoted above, there being some evidence of difficulty in reducing the bank angle excursions below about 2·5 deg, for the very sudden gust encounters represented in these tests. It will be remembered that no control system lags or other limitations were represented in these particular tests, and in practice such features might cause some deterioration in control. On the other hand the step gusts represented in the simulation were probably more sudden than those experienced in real flight.

Some of the reasons for the results obtained with the different simulation cues become apparent in studying the time histories of aileron angle and bank angle, made during these tests. Figs. 10 and 11 show such time histories, the records from a number of trials having been superimposed on each other. The instant at which the aircraft encountered the gust forms the common point on all these records, and the zero of the time scale.

The aileron time histories (Fig. 11) show that the initial reaction time, before the pilot took any corrective action, was appreciably longer in the tests with the cockpit fixed; (a mean of about 0·7 seconds, compared with 0·3 seconds for the test with motion and the stronger visual cue). As a result of this longer delay in the tests without motion the pilot's control action, when eventually applied, tended to reinforce the aircraft's natural oscillatory motion, rather than suppress the initial excursion in bank angle. Finding this, pilots were naturally unwilling to use the large and decisive control movements which they could adopt successfully when provided with the stronger simulation cues.

These results, showing the importance of the motion cue in simulating a task involving sudden disturbances, are to be expected, because the pilot is made directly aware of the accelerations which are taking place, in contrast to the information provided by visual displays which is largely positional.

The results given above also show some difference between the contact analogue and Skyscape visual displays. In practice it was found to be appreciably easier to damp out the aircraft's oscillatory motion with the Skyscape display, and this must, presumably, be attributed to the powerful impression of rolling conveyed through the peripheral vision.

The quantitative results obtained from these tests were supported by pilot's subjective impressions of the value of the various cues. Cockpit motion was felt to be specially valuable, because it enabled corrective control actions to be taken instinctively, whereas even the better visual display, on its own, needed some conscious interpretation.

### 3.2. *The Effect of Cockpit Motion on Pilot's Control in Continuous Turbulence.*

In the tests just described the pilot had to respond, as quickly as possible, to a sudden isolated disturbance, and the results showed the value of the motion cue in giving an immediate indication of its onset. Disturbances of the suddenness and severity represented in those tests are, fortunately, rather rare, but flight in continuous random turbulence is, of course, an everyday occurrence. Figs. 12 and 13 are time histories of instrument approaches made on the simulator, with and without cockpit motion, under random gusting with a level of 4·5 ft/sec rms. The aircraft had autothrottle and pitch damper, but no roll damper. Time histories of two approaches without motion are shown in Fig. 12, and of two approaches with motion in Fig. 13. In both cases the Skyscape visual display was used.

These records show that the bank angle excursions for the tests with motion were much lower than for those without, and that there was an accompanying trend towards brisker aileron movements—features which were both present in the previous tests with step side gusts. The accuracy of flying the approach is not shown on these records, but it was, in fact, also much improved in the tests with motion.

One way of describing the changes in the aileron and bank angle time histories more quantitatively is by comparing their power spectra, with and without cockpit motion. The power spectra for the four aileron time histories in Figs. 12 and 13 have been calculated and are shown in Fig. 14. Similarly, the power spectra for the bank angle time histories are shown in Fig. 15. In both cases there is a clear difference between the spectra with and without motion, the time histories taken from the tests with motion having noticeably higher frequency content. Rms values for the excursions in bank angle were found to be about 3 deg for the tests without motion and $1\frac{1}{2}$ deg for the tests with motion.

## 4. *Handling Assessments.*

In this Section the handling assessments of the aircraft's flying qualities at landing approach speeds are described. Section 4.1 deals with an overall assessment of the aircraft's behaviour, within the normal c.g. range, but with different degrees of autostabilization. Section 4.2 describes a study of the handling at extremely far aft c.g. positions. All of these tests were made with the simulator cockpit fixed. Section 4.3 describes some tests, in which cockpit motion was used, to study the effect of a rate limit on the roll control surface.

### 4.1. *Handling at Normal c.g. Positions, but with Different Degrees of Autostabilization.*

4.1.1. *Outline of the tests.* The task represented in these trials was that of flying an instrument approach from a height of 2000 ft down to a break-off height of 250 ft. The guidance used was similar to

ILS, but, for the sake of simplicity in computing, the sensitivity for displacements from the desired glide path was constant throughout the approach. (The sensitivity of the ILS used in actual airline operation normally increases with decreasing range from touch down.) Full scale deflection on the glide path indicator corresponded to an error of 100 ft, and FSD on the localiser indicator corresponded to an error of 700 ft. These values of sensitivity are roughly equal to those of the real ILS system at a height of 600 ft, (i.e. about 2 nm from touchdown).

Cockpit motion was not used for these tests. The pilot's view of the outside world was represented by the contact analogue display (described in Section 2.4) and this undoubtedly gave him better attitude information than that available from the flight instruments. However the work reported in the previous Section shows that the absence of the motion cue would make the pilot's task more difficult than in real flight, so that the assessments reported here may err on the pessimistic side.

Previous simulation studies have shown a marked effect of learning on the pilot's performance during trials of this type. All the pilots were therefore allowed from four to eight hours experience of the simulation, in which to make practice approaches, and to assess the handling characteristics with different amounts of autostabilization, before the precision of their approaches was measured. During this initial learning period various combinations of the three autostabilization modes (autothrottle, pitch damper and roll damper) were tried, but for the tests in which actual measurements were made it was necessary to limit the study (*see* Section 4.1.3), in order to obtain a statistically meaningful number of approaches in each condition. Tests were made both for calm conditions, and with a turbulence level of 4·5 ft/sec rms.

The pilots who took part in these tests were all experienced test pilots, but their background was generally of military, rather than civil, aviation.

4.1.2. *Qualitative handling assessments.* The handling assessments gathered during these tests were recorded in the form of numerical ratings on a pilot opinion-rating scale, together with notes of the comments made by the pilot while flying the simulator. The descriptive terms used to define the rating scale are listed in Table 1. In addition, each pilot was asked to give his overall views in a written report at the end of the programme. (An example of such a report is given in Appendix B.)

The opinion ratings given on the numerical scale are shown diagrammatically in Figs. 16 to 19. The ratings given by one individual pilot, for a particular test condition, are represented by a kite shape mark. The centre of this mark shows the mean of his ratings, (given in several repeated assessments), while the extremities show the spread in his ratings for the nominally identical test conditions. It should be noted that the number of assessments made at each condition varied from pilot to pilot, so that the comparative size of the marks is not, in this case, any measure of one pilot's consistency in rating compared with anothers. The ratings given by the six pilots always appear in the same sequence on the figures however.

The test conditions shown in the four figures are as follows:

| | |
|---|---|
| With turbulence, forward c.g. | —Fig. 16 |
| With turbulence, aft c.g. | —Fig. 17 |
| Still air, forward c.g. | —Fig. 18 |
| Still air, aft c.g. | —Fig. 19. |

The eight columns in each figure give the possible combinations of the autostabilizer modes (pitch damper, roll damper and autothrottle). They are actually listed in terms of autostabilizer 'failures' so that the benefit of, say, the pitch damper, should be found by comparing the assessment for 'no failures' with that for 'single failure—pitch damper'. It may be noted that, with the design philosophy currently adopted for the Concorde airliner, the chances of a complete 'failure' in any autostabilizer mode are extremely remote. The results presented here may, alternatively, be considered as the justification for including a particular autostabilizer mode in the design.

The variability in ratings is quite large, both for an individual pilot and between different pilots, but not more so than has been previously experienced in this type of handling qualities work[4,5]. An interesting feature is that the variability appears to be slightly larger for the tests made in calm air than for those made under turbulent conditions. This is possibly because the aircraft may appear to have quite good handling qualities in calm air, until it is accidently disturbed by mishandling of the controls, whereas in turbulence the aircraft is being continuously disturbed, so that its worst characteristics are immediately apparent. In the following discussion of the handling assessments, attention will be paid primarily to the results obtained from the tests made with turbulence.

Dealing first with the fully stabilized aircraft, (i.e. pitch damper, roll damper and autothrottle), the first columns of Figs. 16 and 17 show similar assessments at both c.g. positions, with numerical ratings centred on rating point 4, and lying mostly within one rating point to either side. Rating point 4 is defined, (*see* Table 1), as: 'Unsatisfactory. Acceptable, though with characteristics that would always be mildly WORRYING and MUST be improved if possible'.

The next three columns of Figs. 16 and 17 show the ratings given when only two out of the three autostabilizer modes were operating. Comparison of these ratings with those given to the fully stabilized aircraft show the effect on handling of failure of the mode listed. At forward c.g. (Fig. 16), the deterioration in rating when either pitch damper, roll damper or autothrottle was removed was very similar, amounting generally to about half a rating point. There were one or two isolated instances of the handling being rated as 'unacceptable', and one pilot consistently rated failure of the autothrottle worse than the others. From his comments it is evident that he found the extra work load involved in controlling the throttles manually was excessive.

At aft c.g. (Fig. 17) the effect of an autothrottle failure on handling was similar to that at forward c.g., just discussed. The effect when either pitch damper or roll damper was removed was however, much more marked at this c.g. than in the previous case. It should be mentioned that the actual lateral characteristics simulated did not vary with c.g. position, so that the more critical assessment of the effect of roll damper failure at aft c.g., compared with that at forward c.g., provides a good example of how changes in the longitudinal characteristics may affect the assessment of lateral characteristics. For both pitch damper and roll damper failures at this c.g. the variability in ratings was larger than in the previous cases, and there was no well defined mean. However four out of the six pilots gave ratings with a mean of greater than 5 (i.e. 'unacceptable').

The assessments for double failures (i.e. only one of the autostabilization modes operating) are too sparse to warrant much comment, but of the three possible combinations of failures there is some evidence to suggest that failure of pitch damper and autothrottle together would cause the greatest difficulties.

The last columns of Figs. 16 and 17 show the ratings given to the basic (i.e. unstabilized) aircraft. The mean ratings of all six pilots were greater than 5 (i.e. 'unacceptable'), and half the pilots gave ratings with a mean greater than $6\frac{1}{2}$, the level at which the handling is doubtful even when considered as an emergency condition.

These numerical ratings provide a convenient summary of the pilot's overall assessment of the aircraft, but they do not, of course, indicate the causes of his criticism. There were two main features of the aircraft's handling which gave rise to consistently adverse comment. The first might be broadly termed the lateral sensitivity, both to excitation by turbulence and in response to deliberate control inputs. Generally speaking the aircraft was considered too lively, with the result that there was an almost continuous oscillatory rolling motion, partly, no doubt, induced by the pilot himself. The frequency of this motion was too high to produce appreciable translational movements of the aircraft, so that its direct effect on flight path holding was small. However it did make the precise selection of a given bank angle more difficult, and thus affected the ease of manoeuvring.*

The second major problem was that of longitudinal control, and this was felt by the pilots to be as serious as the lateral difficulty described above. In contrast, however, the problem in this case was one of too sluggish a control response. Most pilots found that they were unable to control the rate of descent, with sufficient precision, by the technique they usually adopted; that is by using the elevator directly to adjust the rate of descent, as indicated by the vertical speed indicator. Such a procedure almost invariably led to gross overcontrolling and to the setting up of 'phugoid like' oscillations. A more satisfactory method of producing changes in rate of descent was by adjusting the aircraft's attitude by an amount which experience had shown to give the desired change in vertical speed. However the artificial horizon fitted in the simulator was considered too insensitive for this technique to be used properly.

**See* footnote, page 2.

It should be stressed again that the assessments reported above were made during a simulation without cockpit motion, and the subsequent tests, already described in Section 3 showed that this cue made the simulator appreciably easier to fly. A further indication of the effect of better simulation cues on pilot opinion ratings may be gained from the results reported subsequently in Section 4.3.

4.1.3. *Quantitative measures of approach performance.* The measurements of approach performance were not started until each pilot had several hours experience of the simulation, and was thoroughly accustomed to the aircraft's handling with various autostabilization failures. To allow the results to be analysed by statistical methods, the trials were organized on a formal pattern, and only five conditions were tested at each c.g. position. These were: the fully stabilized aircraft, the basic (unstabilized) aircraft, and single failures of either the pitch damper, the roll damper or the autothrottle.

The first approach in each trial was always made in the easiest condition, (i.e. full autostabilization, forward c.g. position and calm air). This run was made largely to refamiliarize the pilot with the experiment. Ten approaches were then made with the various combinations of c.g. position and autostabilizer operation listed in Table 3, all these approaches being in turbulence of 4·5 ft/sec rms. These runs were made in a random order, but warning lights in the cockpit showed the pilot which of the autostabilization modes was not operating.

Measurements were made of the integral modulus errors in glide path and localiser holding throughout each approach, together with the errors in these parameters at the break-off height. Pilot's commented that they placed primary emphasis on achieving a satisfactory position at the break-off height, rather than aiming to minimize the errors throughout the approach. Most of the analysis has therefore been concentrated on the errors measured at 250 ft. Average values of these errors at each test condition, together with their standard deviations, are given in Table 3. Because the guidance system was not identical to that used in airline operations, (having constant displacement sensitivity—*see* Section 4.1.1), the actual numerical values of these errors are of less practical significance than their relative magnitudes. Five pilots took part in these trials, two of them making four trials each, two of them making three trials each, and the remaining one making only one trial.

Statistical tests of the results listed in Table 3 showed relatively few significant differences in the errors for the different conditions (using variance ratio tests with a significant level of 1 per cent). As might have been expected, there was a significant increase in both vertical and lateral errors with the introduction of turbulence. Apart from this there were no significant increases in the errors at forward c.g. for any of the test conditions. At aft c.g. there was a significant increase in the vertical errors with failure of either pitch damper or roll damper, but the errors were then similar to those for the basic aircraft.

These findings show some agreement with the pilot opinion ratings reported in the previous Section, where, it may be remembered, the handling with pitch or roll damper failure at aft c.g. was found to be considerably more difficult than at forward c.g.

Figs. 20 and 21 show plots of the vertical and lateral errors for those cases where the statistical tests indicated significant changes in the accuracy of flying. The effect of turbulence on the fully stabilized aircraft is shown in Fig. 20. The standard deviation of the lateral errors was increased by some 75 per cent, and that of the glide path errors by about 300 per cent. Fig. 21 shows similar plots for those cases at aft c.g. where autostabilization failures led to a deterioration in accuracy. The errors in glide path holding were roughly doubled, but the lateral errors were unchanged. An examination of continuous trace recordings made during these trials showed however that the bank angle excursions during approaches without the roll autostabilizer were appreciably larger than for the fully stabilized aircraft.

4.2. *Handling at c.g. Positions beyond the Normal aft Limit.*

The large movement of the aerodynamic centre between the subsonic and supersonic operating régimes on this aircraft poses a difficult problem in trimming, if excessive trim drag under cruise conditions is to be avoided. To overcome this, a fuel transfer system for adjusting the c.g. position in flight is an essential feature of the design. An important factor in determining the characteristics of this system is the most rearward c.g. position which can be accepted at landing approach speeds. A brief assessment was therefore made of the handling at c.g. positions beyond the proposed normal aft limit (0·52 $c_0$). The same simulation equipment as for the study previously described was used, (i.e. fixed cockpit and contact analogue display), and only the fully autostabilized aircraft in turbulence of 4·5 ft/sec rms was considered.

Early on in these tests it was evident that there was insufficient down-elevator travel available, even to trim the aircraft at c.g. positions aft of about 0·55 $c_0$, and the presence of this elevator limit became progressively more intrusive during manoeuvring as the c.g. was moved aft of about 0·535 $c_0$. This condition was rated as completely unacceptable. On the assumption that such a limitation could be removed by design changes, the tests were continued with the pitching moments adjusted so that the aircraft trimmed with the elevator closer to its neutral position. These changes did not affect the stability of the aircraft but merely altered the trim position.

The results of these tests are shown in Fig. 22. Pilot opinion ratings deteriorated progressively as the c.g. was moved back from the normal aft limit of 0·52 $c_0$, and ratings of 'unacceptable' were recorded when the c.g. was aft of about 0·54 $c_0$. The static margin at this point was −0·035. Results from tests on the B.A.C. simulator at Filton[6], also with fixed cockpit and contact analogue display, are shown in the same figure. They show the same general trend, but the ratings were about half a point worse throughout. The turbulence level for the Filton tests was slightly higher however, being 6 ft/sec rms instead of $4\frac{1}{2}$ ft/sec rms.

Pilots commented that much more anticipation was needed at the rearward c.g. positions to prevent the pitch attitude from overshooting the required value during any manoeuvre. One pilot described the handling at 0·55 $c_0$ as like 'sitting on a knife edge'.

### 4.3. *The Effect of Limited Rate of Control-Surface Movement on Handling.*

For the tests described in the previous Sections, the power controls were represented as ideal, having no lags or other imperfections between the movement of the pilot's control wheel and the corresponding deflection of the aerodyanamic control surface. At the time of this simulation programme there was some doubt about the flow capacity of the aircraft's hydraulic pumps, under certain highly loaded conditions, and there was consequently the possibility that the maximum rate of control-surface movement might be severely restricted (values as low as 10 deg/sec were suggested at one time). Such a limitation might have important effects on the aircraft's handling qualities[7].

During the present tests the power controls in roll were represented by a second order system, having a rate limit which could be varied between 5 deg/sec and 100 deg/sec. (The second order system had an undamped natural frequency of 3 cps, and a damping ratio of 0·7.)

The task was generally similar to that described in the previous Sections, except that cockpit motion, and the runway shadowgraph display (2.4) provided the simulation cues. The latter enabled the landing approach to be continued down to touchdown, although the representation in the final stages of the landing flare was not considered sufficiently realistic for an assessment of that manoeuvre to be made. The turbulence level was slightly higher than that used previously; 6 ft/sec instead of $4\frac{1}{2}$ ft/sec. Tests were made both with and without the roll damper, but the pitch damper and autothrottle were working in both cases. The c.g. position was 0·52 $c_0$ (aft).

The variation in pilot opinion rating as the maximum rate of control-surface movement was altered is shown in Fig. 23. Fig. 23(a) shows the test results with roll damper, and Fig. 23(b) shows those without.

It was difficult to find a definite value of control-rate limiting at which handling difficulties always occurred. For the same value of limiting, a pilot could sometimes achieve a perfectly satisfactory approach, while at other times he was scarcely in control at all. This seemed to be because the effect of the limit was to cause pilot-induced oscillations, which might be triggered off in one case by a random sequence of adverse disturbances, but which did not occur in another.

If they were not told which condition they were testing, pilots found that they could not differentiate consistently between conditions with limits of 20 deg/sec, and 30 deg/sec, although they were aware that some limitation was taking place. Trace recordings show that for these conditions the demanded rate of control was only large enough to cause saturation at isolated instances. With rate limits of 15 deg/sec and below, however, the severity of the limit was always correctly assessed. The trace recordings showed then that saturation was taking place almost continuously.

Fig. 24 shows the last few seconds of an approach, with a rate limit of 15 deg/sec, in which an undamped oscillation built up, due to the pilot's control actions getting out of phase with the aircraft's motion. It was found that this was particularly likely to happen at this stage in the landing, probably because of the tighter control which the pilot tried to use just before touch down.

At the highest values of control-surface rate, the characteristics were virtually indistinguishable from those represented in the previous trials. Pilots assessments for these conditions may therefore be compared with those given earlier to provide an indication of the effect of the better simulation cues which were available for this exercise.

Fig. 23(a) shows that the fully stabilized aircraft, without control-rate limiting effects, (i.e. $\mathring{\xi}_{max} > 30$ deg/sec), was assigned a rating of between 3 and 4. The value is not well defined because there were only two assessments, but it is only slightly, if any, better than that given in the previous, fixed cockpit, studies (Fig. 22). With the roll damper failed, the ratings given for rate limits greater than 30 deg/sec lay between 3 and $4\frac{1}{2}$. Bearing in mind the increased turbulence level of the present tests, the results do show an improvement in the ratings, which previously lay between 4 and 7·5, Fig. 17. The results are too sparse to allow of a firm conclusion, but there is some indication that the numerical ratings reported in Section 4.1.2 for the fully stabilized aircraft would not have been greatly changed, if cockpit motion had been used in the assessment, but that the ratings given for the various failure cases might have been somewhat improved.

## 5. *Comparison with Existing Handling Criteria.*

In this Section the characteristics of the simulated aircraft will be related to existing handling qualities criteria. It is not to be expected that a complete assessment of the aircraft's behaviour could be made on the basis of these criteria alone, because of the multiplicity of factors which go to make up an aircraft's flying qualities. However they should provide a basis on which to judge whether particular features, for instance Dutch roll damping or speed stability, are likely to be satisfactory.

What should be looked for particularly in this comparison are cases in which the criteria predict unsatisfactory characteristics, but which are assessed in practice as being satisfactory. Such cases must cast doubt on the validity of the criterion, at least for this type of aircraft. In the opposite situation, where the practical assessment is less favourable than that predicted, the conclusion to be drawn is not so certain, since the poor handling may result from features not covered by the criterion.

### 5.1. *Longitudinal Handling Qualities.*

The values of various parameters which are used in the existing criteria for longitudinal handling qualities have been calculated for the simulated aircraft at its normal approach speed of 145 knots, and at the two c.g. positions used for most of the tests, i.e. 0·50 $c_0$ (forward) and 0·52 $c_0$ (aft). Trim conditions for these two c.g. positions are given in Table 4, and the longitudinal stability derivatives, based on the data shown in Figs. 29 to 41, are listed in Table 5.

Table 6 gives the calculated values of static margin, manoeuvre margin and stick force/$g$ at the two c.g. positions, and also shows the effect of pitch damper and autothrottle on these parameters.

The proposed flying qualities requirements[8] for the supersonic transport aircraft call for correct longitudinal static stability, (i.e. 'correct slopes for stick force in relation to speed'). The static stability of the simulated aircraft without autothrottle was just about neutral at the aft c.g. position, but with the autothrottle operating the aircraft was barely stable at forward c.g. This appreciable de-stabilizing effect of the autothrottle on static margin was a result of the engine thrust line being offset below the c.g.[9]. The simulated aircraft therefore only met the proposed requirement for static stability at the forward c.g. positions, and then only marginally so when the autothrottle was operating.

The manoeuvre margin was always positive, the manoeuvre point being at about 0·58 $c_0$ with the pitch damper, and at about 0·55 $c_0$ without the damper.

Criteria are proposed in Refs. 10 and 11 for the dynamic longitudinal stability characteristics of large aircraft which should result in satisfactory handling. In the present case the dynamic longitudinal characteristics were somewhat unusual. At aft c.g. the conventional 'short period' oscillation became aperiodic, the characteristic equation having two real negative roots.

The longer period motion took the form of a conventional phugoid oscillation at forward c.g., without the autothrottle, but the latter caused the motion to become aperiodic. At aft c.g. the motion was aperiodic both with and without the autothrottle, and the negative static margin resulted in one of the real roots being positive.

The short period characteristics of the simulated aircraft are compared with the criterion of Ref. 10 in Fig. 25. For those cases where the motion was aperiodic, and 'equivalent' frequency and damping was calculated from the relationships:

$$\omega_n^2 = \lambda_1 \lambda_2$$

$$2\zeta_{\text{S.P.}} \, \omega_n = \lambda_1 + \lambda_2 \,.$$

On this criterion the aircraft characteristics at forward c.g. and with the pitch damper operating were correctly predicted as lying in the 'acceptable but unsatisfactory' region. However the actual deterioration in the handling qualities with rearward c.g. movement, (Figs. 16 and 17) was not quite as large as the criterion predicted.

At forward c.g. and without the pitch damper the criterion is again a little severe, compared with the actual assessments, but the deterioration to 'unacceptable' at aft c.g. was accurately predicted.

The characteristics of the simulated aircraft are compared with the alternative criterion of Ref. 11 in Fig. 26. This criterion takes into account the parameter $L_\alpha \left( = \dfrac{qS}{mV} \dfrac{dC_L}{d\alpha} \right)$, being a measure of the rate of change of flight-path angle with change in incidence, as well as the short period frequency and damping. The value of $L_\alpha$ for the simulated aircraft was 0·65 $\text{sec}^{-1}$.

On this criterion the best condition tested, i.e. forward c.g. and pitch damper operating, was predicted as just satisfactory. This is rather more optimistic than the overall rating actually given to the simulated aircraft, but, as it was an overall rating, there may have been other features which detracted from the handling.

The boundary between the regions of 'acceptable but unsatisfactory' and 'unacceptable' handling behaviour is not defined for the larger values of $\dfrac{L_\alpha}{\omega_n}$ and $\zeta$ in Ref. 11. However, if it is assumed to follow the general shape of the boundary to the 'satisfactory' region, the characteristics predicted for the aircraft at forward c.g. without the damper, and at aft c.g. with the damper are roughly similar, both falling in the 'acceptable but unsatisfactory' region. This accords quite well with the simulator assessments. This criterion also predicts the more marked deterioration in handling at aft c.g. without the pitch damper.

From this rather limited comparison it would appear that the handling criterion of Ref. 11 gives slightly better predictions for this class of aircraft than does that of Ref. 10.

Out of interest, the short period characteristics of a number of transport aircraft in current airline service have also been plotted in Figs. 25 and 26, the data being taken from Ref. 12. The difference between the predicted supersonic transport aircraft characteristics and those of present day subsonic airliners is noteworthy.

Recommendations for the speed stability of an aircraft, when constrained to follow a rectilinear flight path, are also given in Ref. 10. In order for the motion to be considered 'satisfactory', a subsidence with a time constant not greater than 50 sec is required. Divergent motion may be 'acceptable but unsatisfactory' provided that the time constant is greater than 25 seconds. The simulated aircraft was speed unstable without the autothrottle, having a divergent time constant of 26 seconds—only just above the minimum acceptable value quoted above. With autothrottle operating however the motion was well within the requirement for 'satisfactory' characteristics, having a subsidence time constant of 12 seconds. The handling assessments made on the simulator with and without autothrottle, (*see* Figs. 16 and 17) seem to be broadly consistent with the criterion given in Ref. 10.

### 5.2. *Lateral-Directional Handling Qualities.*

Recommendations for the lateral-directional handling qualities of large aircraft have been put forward in Ref. 13. The features covered include; roll response, characteristics of lateral oscillation and spiral modes, and values of the roll to yaw coupling parameter $\omega_\phi/\omega_d$.

The roll-response characteristics of the simulated aircraft, with and without the roll damper, are plotted in Fig. 27 together with the boundaries proposed in Ref. 13 for the regions of 'satisfactory', 'acceptable but unsatisfactory' and 'unacceptable' behaviour. For both aircraft conditions the characteristics fall into the 'satisfactory' region, but without the damper the rolling power is close to the upper limit, (corresponding to a steady roll rate of 60 deg/sec), which was tentatively suggested in Ref. 13. With the roll damping, however, the characteristics fall nearly in the centre of the 'satisfactory' region.

The characteristics of the lateral oscillation are shown in Fig. 28, together with the criterion of Ref. 13. With the roll damper the characteristics fall in the 'satisfactory' region, but without it they are predicted as being 'acceptable but unsatisfactory'. The handling assessments made on the simulator, with and without the roll damper, (*see* Fig. 16 and Fig. 17) were broadly consistent with the criterion.

The spiral mode was stable, both with and without the roll damper, having subsidence time constants of 70 seconds and 23 seconds respectively. These characteristics for the spiral mode should be satisfactory according to the criterion of Ref. 13, which calls for a spiral mode time constant of greater than 20 seconds irrespective of whether the stability is positive or negative. The spiral characteristics gave rise to no adverse comment during the simulator assessment.

The roll to yaw coupling parameter $\omega_\phi/\omega_d$, had the value 0·65 without the roll damper, and 0·74 with the damper. It has been suggested that manoeuvring difficulties are likely to be encountered when the value of $\omega_\phi/\omega_d$ is less than about 0·7, because of the very oscillatory response to a step aileron input which is associated with low values of this parameter. Certainly the nature of the aileron response was one of the main points of criticism of the lateral handling during the present tests. For this reason it is planned to incorporate an interconnection between aileron and rudder in the design, this feature allowing the value of $\omega_\phi/\omega_d$ to be adjusted independently of the aircraft's other aerodynamic characteristics.

## 6. *Conclusions.*

The main handling features of the slender wing supersonic transport aircraft, as represented in these simulation tests, were such as might perhaps have been expected from its shape. Precise lateral control was difficult, particularly in turbulence, because of the large rolling moments due to sideslip, combined with small rolling moment of inertia, which are features typical of the slender-wing layout. Longitudinal control was made more than usually sluggish by the large pitching inertia.

Handling difficulties arising from these features made it extremely doubtful whether the basic aircraft, simulated in these trials* (i.e. without autostabilization) would be acceptable for airline service, even allowing for the generally pessimistic nature of simulation assessments. There must even be doubt at present as to whether the basic aircraft characteristics would be acceptable for an emergency condition.

However, the use of simple pitch and roll damping brought about a considerable improvement in the aircraft's handling, and with this autostabilization the aircraft was assessed as acceptable, but with certain characteristics which must be improved if possible.

The design of autostabilization being considered at the time of writing should bring about additional improvements in lateral behaviour over that found in the simulator, because of the use of higher gain in the roll damper, (1·0 deg of aileron per deg/sec instead of 0·4 deg per deg/sec used in the simulator tests), the introduction of a yaw damper, and the inclusion of an interconnection between the aileron and rudder controls. The latter should allow the value of the roll to yaw coupling parameter, $\omega_\phi/\omega_d$, to be increased to its optimum value of about 1·0, with a consequent reduction in the oscillatory nature of the aircraft's response to roll control.

Improvements in longitudinal control may prove more difficult to effect than those in lateral control, since the main problem here is to speed up a basically sluggish response, rather than to damp down an oversensitive one. Various modifications to the simple autostabilizer law used in the present tests have been proposed, with the aim of improving the aircraft's pitching response, but further simulator studies

**See* footnote, page 2.

will be needed to assess their effectiveness. Attention to the aircraft's static stability is also needed, since the proposed flying qualities requirements are not met at aft c.g. and with autothrottle operating.

Studies of the importance of visual and motion cues in the simulation showed that cockpit motion, in particular, played a very important part in increasing the realism of the simulation, and provided vital cues in controlling the effects of external disturbances. There was also some evidence that a projected visual display, giving a wide viewing angle and allowing information to be gathered through the peripheral vision, was more satisfactory than a narrower angle display produced on the face of a cathode ray tube.

Specific tests to study the effect of rate limiting on the aircraft's roll control surfaces showed that severe handling difficulties could be expected with a rate limit of 15 deg/sec or below. The presence of rate limiting was apparent to the pilot at values up to 30 deg/sec.

## LIST OF SYMBOLS

| | | |
|---|---|---|
| $c_0$ | Reference chord length | ft |
| $C_L, C_D, C_Y$ | Aerodynamic coefficients of lift, drag and sideforce | — |
| $C_M, C_l, C_n$ | Aerodynamic coefficients of pitching, rolling and yawing moment | — |
| $g$ | Acceleration due to gravity | ft/sec$^2$ |
| $h$ | Height above ground | ft |
| $I_{XX}, I_{YY}, I_{ZZ}$ | Moments of inertia about the rolling pitching and yawing body-datum axes | slug ft$^2$ |
| $I_{XZ}$ | Product of inertia | slug ft$^2$ |
| $L_\alpha$ | Parameter in longitudinal response equation (*see* Section 5.1) | sec$^{-1}$ |
| $m$ | Aircraft mass | slugs |
| $M_X, M_Y, M_Z$ | Pitching moments due to engine thrust about the rolling, pitching and yawing axes | lb ft |
| $P, Q, R$ | Rates of roll, pitch and yaw about aircraft body axes | rad/sec or deg/sec |
| $P_W, Q_W, R_W$ | Angular-velocity components of the flight-path axis system | rad/sec or deg/sec |
| $q$ | Dynamic pressure ( $= \frac{1}{2}\rho V^2$) | lb/ft$^2$ |
| $S$ | Reference wing area | ft$^2$ |
| $T_X, T_Z$ | Engine thrust components along the $X$ and $Z$ body axes | lb |
| $V$ | Velocity along the flight path | ft/sec |
| $\alpha$ | Incidence | deg |
| $\beta$ | Sideslip | deg or rad |
| $\zeta$ | Rudder angle | deg or rad |
| $\zeta_{S.P.}$ | Damping of longitudinal short period oscillation | — |
| $\eta$ | Elevator angle | deg or rad |
| $\theta_B, \phi_B, \psi_B$ | Euler attitude angles in pitch, roll and yaw for aircraft body axes | rad |
| $\theta_W, \phi_W, \psi_W$ | Euler attitude angles in pitch, roll and yaw for flight path axis system | rad |
| $\lambda_1, \lambda_2$ | Roots of longitudinal stability quartic | |
| $\mu_1, \mu_2$ | Relative density parameters | |
| $\xi$ | Aileron angle | deg or rad |
| $\rho$ | Air density | slugs/ft |
| $\tau_R$ | Roll-mode time constant | sec |
| $\omega_d$ | Undamped natural frequency of the lateral oscillation | rad/sec |

| | | |
|---|---|---|
| $\omega_n$ | Undamped natural frequency of the longitudinal s.p. oscillation | rad/sec |
| $\omega_\phi$ | Parameter in the numerator of the lateral response equation | — |

*Suffices*:

| | |
|---|---|
| $B$ | Denotes aircraft body axes |
| $W$ | Denotes the flight-path axis system |
| $T$ | Denotes trimmed conditions |

Stability derivatives: the stability derivatives listed in Tables 5 and 7 are based on the normal British definitions (as listed in Ref. 21 for instance), except that the reference chord length $c_0$ is always used in place of tail arm, $l_T$, or span, $b$, in the standard definitions.

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## APPENDIX A

### *Equations Used to Represent the Aircraft's Motion.*

A.1. *Translational Motion.*

The equations governing the translational motion of the aircraft's centre of gravity were related to an axis system based on the flight path. In this system the $X$ (forward) axis was aligned along the instantaneous flight path direction: the $Z$ (normal) axis was perpendicular to it and in the aircraft's plane of symmetry, while the $Y$ (lateral) axis was mutually perpendicular to the other two.

The translational motion was defined by three variables: the acceleration along the flight path ($\dot{V}$), and the components of the flight path angular velocity about the $Y$ and $Z$ axes. These components were denoted by $Q_W$ and $R_W$ respectively.

The complete equations of motion for a rigid aircraft in these terms have been derived by Howe[14]. In the following paragraphs the complete equation is given first, followed by the simplified equation which was used in this simulation. Simplifications were necessary because of the limited capacity of the analogue computer, but the terms involved were generally small and their overall effect on the accuracy of the simulation is believed to be unimportant.

(a) *Equation for acceleration along the flight path*

Complete equation:

$$\dot{V} = \frac{T_X}{m}\cos\alpha\cos\beta + \frac{T_Z}{m}\sin\alpha\cos\beta - g\sin\theta_W + \frac{qSC_D}{m}\cos\beta + \frac{qSC_Y}{m}\sin\beta\,.$$

Simplified equation used:

$$\dot{V} = \frac{T_X}{m}\cos\alpha - g\,.\,\theta_W + \frac{qSC_D}{m} + \frac{qSC_Y}{m}\,.\,\beta\,. \qquad \text{(A.1)}$$

(b) *Equation for angular velocity of the flight path about the Y axis*

Complete equation:

$$Q_W = \frac{T_X}{mV}\sin\alpha - \frac{T_Z}{mV}\cos\alpha - \frac{g}{V}\cos\theta_W\cos\phi_W + \frac{\rho VSC_L}{2m}\,.$$

Simplified equation used:

$$Q_W = \frac{T_X}{mV}\sin\alpha - \frac{g}{V}\cos\phi_W + \frac{\rho VSC_L}{2m}\,. \qquad \text{(A.2)}$$

(c) *Equation for angular velocity of the flight path about the Z axis*

Complete equation:

$$R_W = -\frac{T_X}{mV}\cos\alpha\sin\beta + \frac{g}{V}\cos\theta_W\sin\phi_W + \frac{\rho VSC_D}{2m}\sin\beta + \frac{\rho VSC_Y}{2m}\cos\beta\,.$$

Simplified equation used:

$$R_W = -\frac{T_X}{mV}\,.\,\beta\,.\cos\alpha + \frac{g}{V}\sin\phi_W + \frac{\rho VSC_D}{2m}\,.\,\beta + \frac{\rho VSC_Y}{2m}\,. \qquad \text{(A.3)}$$

A.2. *Rotational Motion.*

The equations governing the aircraft's rotational motion were related to an axis system fixed in the aircraft. The origin of this axis system was the aircraft's centre of gravity. The $X_B$ (rolling) axis was parallel to the fuselage datum line, the $Z_B$ (yawing) axis was perpendicular to the fuselage datum line and in the aircraft's plane of symmetry, while the $Y_B$ (pitching) axis was mutually perpendicular to the other two.

The aircraft angular velocities about the $X_B$, $T_B$ and $Z_B$ axes were denoted by $P$, $Q$ and $R$ respectively.

As in the previous section the complete equations[14] are given first in the following paragraphs, followed by the simplified equations used for this simulation. Again, the overall effect of these simplifications on the accuracy of the simulation is believed to be unimportant.

(a) *Equation for pitching rotation about the $Y_B$ axis*

Complete equation:

$$\dot{Q} = \left[\frac{I_{ZZ}-I_{XX}}{I_{YY}}\right]P\,.\,R+\frac{I_{XZ}}{I_{YY}}[R^2-P^2]+\frac{M_Y}{I_{YY}}+\frac{qS\,c_0\,C_M}{I_{YY}}.$$

Simplified equation:

$$\dot{Q} = \left[\frac{I_{ZZ}-I_{XX}}{I_{YY}}\right]P\,.\,R+\frac{M_Y}{I_{YY}}+\frac{qS\,c_0\,C_M}{I_{YY}}. \tag{A.4}$$

(b) *Equation for rolling rotation about the $X_B$ axis*

Complete equation:

$$\dot{P} = \left[\frac{I_{YY}-I_{ZZ}}{I_{XX}}\right]Q\,.\,R+\frac{I_{XZ}}{I_{XX}}[\dot{R}+PQ]+\frac{M_X}{I_{XX}}+\frac{qS\,c_0\,C_l}{I_{XX}}.$$

Simplified equation:

$$\dot{P} = \left[\frac{I_{YY}-I_{ZZ}}{I_{XX}}\right]Q\,.\,R+\frac{I_{XZ}}{I_{XX}}\dot{R}+\frac{qS\,c_0\,C_l}{I_{XX}}. \tag{A.5}$$

(c) *Equation for yawing rotation about the $Z_B$ axis*

Complete equation:

$$\dot{R} = \left[\frac{I_{XX}-I_{YY}}{I_{ZZ}}\right]P\,.\,Q+\frac{I_{XZ}}{I_{ZZ}}[\dot{P}-QR]+\frac{M_Z}{I_{ZZ}}+\frac{qS\,c_0\,C_n}{I_{ZZ}}.$$

Simplified equation:

$$\dot{R} = \left[\frac{I_{XX}-I_{YY}}{I_{ZZ}}\right]P\,.\,Q+\frac{I_{XZ}}{I_{ZZ}}\dot{P}+\frac{qS\,c_0\,C_n}{I_{ZZ}} \tag{A.6}$$

A.3. *Kinematic Equations*

The kinematic equations, which relate such variables as incidence, sideslip and aircraft attitude to the components of motion discussed in Sections A.1 and A.2, have also been derived by Howe[14].

(a) *Equation for rate of change of incidence*
Complete equation:

$$\dot{\alpha} = \frac{Q \cos\beta - Q_W - [P \cos\alpha + R \sin\alpha] \sin\beta}{\cos\beta}.$$

Simplified equation used:

$$\dot{\alpha} = Q - Q_W - [P \cos\alpha + R \sin\alpha] . \beta . \tag{A.7}$$

(b) *Equation for rate of change of sideslip*
Complete equation used:

$$\dot{\beta} = R_W - R \cos\alpha + P \sin\alpha . \tag{A.8}$$

(c) *Equation for rate of change of flight path Euler angle-pitch attitude*
Complete equation used:

$$\dot{\theta}_W = Q_W \cos\phi_W - R_W \sin\phi_W . \tag{A.9}$$

(d) *Equation for rate of change of flight path Euler angle-azimuth angle*
Complete equation:

$$\dot{\psi}_W = \frac{R_W \cos\phi_W + Q_W \sin\phi_W}{\cos\theta_W}.$$

Simplified equation used:

$$\dot{\psi}_W = R_W \cos\phi_W + Q_W \sin\phi_W . \tag{A.10}$$

(e) *Equation for rate of change of flight path Euler angle-roll angle*
Complete equation:

$$\dot{\phi}_W = \frac{P \cos\alpha + R \sin\alpha + Q_W \sin\beta}{\cos\beta} + \frac{R_W \cos\phi_W + Q_W \sin\phi_W}{\cot\theta_W}$$

Simplified equation used:

$$\dot{\phi}_W = P \cos\alpha + R \sin\alpha + Q_W . \beta + R_W \cos\phi_W + Q_W \sin\phi_W . \tag{A.11}$$

(f) *Equation for rate of climb*
Complete equation used:

$$\dot{h} = V \sin\theta_W . \tag{A.12}$$

(g) *Equation for lateral tracking velocity*
Complete equation:

$$\dot{\varepsilon}_y = V \sin\psi_W .$$

Simplified equation used

$$\dot{\varepsilon}_y = V \,.\, \psi_W \,. \tag{A.13}$$

A.4. *Aircraft Attitude.*

The following simplified equations were used to derive the Euler attitude angles in body axes from the flight path attitude angles given by (A.9), (A.10), (A.11). The complete equations may be found in Ref. 14.

(a) *Pitch attitude*

$$\theta_B = \theta_W + \alpha \,. \tag{A.14}$$

(b) *Bank angle*

$$\phi_B = \phi_W \,. \tag{A.15}$$

(c) *Heading*

$$\psi_B = \psi_W - \beta + \phi_W \sin \alpha \,. \tag{A.16}$$

---

## APPENDIX B

### *A Pilot's Overall Report of the Simulation.*

B.1. *General Characteristics*

The basic aircraft felt very much as its shape suggested it should, i.e. an aircraft possessing lots of inertia in pitch and very little in roll. The more immediately obvious characteristic, that of low rolling inertia, was never more than a nuisance, although the strong rocking oscillations developed at times would be looked upon as more than a nuisance by passengers, but pitch control at times verged upon the disastrous.*

The main difficulty in pitch control showed itself in a tendency to over-control longitudinally, and the normal artificial horizon did not provide precise enough pitch information to prevent this.

Autostabilization did indeed make a more reasonable aircraft out of it and the aircraft as simulated with full autostabilization should certainly be acceptable in airline service.

B.2. *Effect of Autostabilization Failure.*

Removing any one channel of pitch, roll or throttle automatics caused only a small deterioration in the ability to fly the aircraft with a reasonable degree of accuracy, but a second failure increased the work load markedly.

Failure of the roll autostabilizer alone caused a noticeable increase in rocking but very little change in accuracy or ability to maintain a steady glide path. However, as already mentioned, the passengers would soon start complaining if there were many roll channel failures under turbulent conditions.

Autothrottle failure meant an increase in workload and concentration required to fly the aircraft, but generally the airspeed could be maintained reasonably accurately. (Say $\pm 5$ knots, which is however much worse than could be expected for a present day airliner.) It should be pointed out that any further distraction or lack of concentration could cause much greater divergences in airspeed in a short time.

Pitch autostabilization failure caused a tendency to overcontrol, as described earlier, and accurate pitch attitude holding was necessary with a noticeable increase in pilot tension.

B.3. *Effect of Changing c.g. Position*

As the c.g. was moved aft, longitudinal control at first became easier. The reasons for this were thought to be, firstly because in the forward c.g. condition the stick was uncomfortably close to the pilot's chest, and, secondly, because aircraft response became livelier, and this improved response cut down the overcontrolling tendency.

As the c.g. moved further aft the decrease in longitudinal stability began to have a more adverse effect on longitudinal control but the aircraft was still fully controllable. Further aft movement still was characterised by more and more tendency to hit the forward elevator step until a point was reached where full forward stick was insufficient to stop a nose-up pitch even of small amplitude.

B.4. *Simulator Equipment.*

B.4.1. *Contact Analogue Visual Display.*

The contact analogue visual display was not very much liked, the main reasons for this being that it was too close to the pilot's eyes and the small amount of the display visible on the approach meant that the individual lines appearing on the screen gave an illusion of the aircraft diving, and also caused the horizon to be markedly saucer shaped.

Despite these drawbacks the display was used extensively to provide a more precise pitch control than that available from the artificial horizon.

Lack of yaw information was another drawback of this display.

B.4.2. *Skyscape Visual Display*

The Skyscape display which was briefly investigated during these trials was a great improvement on previous trials, mainly because the horizon was lower and the 'sitting in a bowl' effect had disappeared.

*See footnote, page 2.

Pitch information derived from the Skyscape horizon was, to my surprise, as good as from the contact analogue display and roll information, mainly from peripheral vision, was much better.

B.4.3. *Runway Shadowgraph Display.*

The runway display was surprisingly good, but it still suffered from serious drawbacks, mainly, it is thought, because of the lack of visual detail. The first trial on the runway display was made without a threshold line, and soon showed the need for an aiming point, as most of the landings were in the undershoot. Enough information was available to start the landing flare, but not enough to complete it, and when close to the runway there was not enough detail visible to be able to detect drift across it soon enough.

B.4.4. *Cockpit Motion*

Although the previous jerkiness in pitch had been eliminated, an initial hesitation in roll of the moving cockpit was disliked at first, so much so that no cockpit movement was preferred. However on subsequent trials opinion was changed greatly in favour of having the cockpit motion.

B.5. *Sidegust Studies*

Step sidegusts, whilst never feeling like anything that might be encountered in the air, still provided some very useful lessons. The successive reduction in reaction time to roll disturbances, and consequent reduction of maximum roll divergence, with change to Skyscape display and cockpit motion was immediately obvious. A disconcerting, and slightly annoying secondary effect of the step sidegust was the hesitation in roll which occurred during the recovery manoeuvre, usually at about the wings level position. This fooled the pilot into centralising the controls just as the roll continued. This hesitation was probably due to yaw, (lack of yaw information has already been mentioned), and could be catered for either by leaving the corrective aileron on, even though the instruments were telling you to take it off, or by using a large rudder input with the necessary coarse aileron deflection.

The cross-wind effect which was built in with the step sidegust was another disconcerting effect and made the use of the runway presentation much more difficult.

B.6. *Studies of Aileron Rate Limiting.*

The maximum rate of application of aileron was limited on some approaches to cater for a similar possible limitation on the actual aircraft. The main manifestation of this showed itself in an inability, or reduced ability, to control roll disturbances, and felt in the simulator very much the same as an increase in atmospheric turbulence.

B.7. *General Remarks*

Obviously, a simulator is never going to give an exact representation of an aircraft and it is possible to learn certain 'tricks' to help in flying the simulator which are not typical of normal flying techniques. The obvious example of this happens when the simulator is perfectly in trim and you can leave it *ad infinitum*, hands off, whilst it flys a perfect approach for you. On this subject the turbulence which is applied to the simulator to provide disturbances and prevent the aircraft being flown hands-off is reasonably representative of actual atmospheric turbulence.

To combat the tendency to overcontrol in pitch, mentioned previously, the technique used was to treat the contact analogue display as an extra flight instrument providing fine pitch attitude information. The artificial horizon itself did not show changes in attitude until it was too late to prevent a coarse control movement to recover, so it was usually left out of the instrument scan pattern and the contact analogue display used as an enormous artificial horizon. It should be pointed out that the overcontrolling in pitch was at its worst in the first few trials and slowly disappeared with more and more practice. By the time that cockpit motion was available, the tendency was virtually gone, so it was not possible to assess with accuracy what the effect of having cockpit motion from the start would have been, but one might suppose that it would have been most beneficial.

It was found out fairly rapidly that one-handed flight was difficult and tiring, so autothrottle failures meant that accuracy deteriorated rapidly throughout the glide path if one hand was kept on the throttle. The technique developed in the case of autothrottle failure was to fly the aircraft two-handed down as accurate a glide path as possible, which prevented the airspeed from wandering overmuch, and only taking the left hand off the stick now and again to make small throttle adjustments. This meant that extra concentration was needed to keep glide path errors to a minimum, but the further challenge involved seemed to produce this concentration and overall accuracy did not suffer much.

*Table of Data used in Simulating the Aircraft.*

*Dimensions, etc.*

| | |
|---|---|
| Reference wing area | 3337 sq ft |
| Reference wing chord | 84·4 ft |

(n.b. the reference wing chord is the linear dimension used in forming all the non-dimensional aerodynamic coefficients both longitudinal and lateral.)

| | |
|---|---|
| Moment arm of engine thrust below c.g. | 2·5 ft |
| Inclination of the thrust line to body datum | 0° |

*Weight and inertias**

| | |
|---|---|
| Landing weight | 160 000 lb |
| Pitch inertia $I_{YY}$ | 5 794 450 slug-ft$^2$ |
| Roll inertia $I_{XX}$ | 864 790 slug-ft$^2$ |
| Yaw inertia $I_{ZZ}$ | 6 407 080 slug-ft$^2$ |
| Product of inertia $I_{XZ}$ | −58640 slug-ft$^2$ |

*Inertias are quoted about the body axis system defined in Appendix A.2.

*Aerodynamic data*

The aerodynamic characteristics represented in this simulation were based almost entirely on data from reports issued by the design firm. For computational purposes empirical expressions were fitted to describe the data over the incidence range of interest. These expressions are listed below and are also plotted for comparison with the original data in Figs. 29 to 41. Angles are in radians except for the angle of incidence which is in degrees.

(a) *Lift coefficient. Fig.* 29. *Data from Refs.* 15, 17

$$C_L = -0{\cdot}16+0{\cdot}058\alpha^\circ+0{\cdot}64\eta\,.$$

(b) *Drag coefficient. Fig.* 30. *Data from Ref.* 16

$$C_D = -0{\cdot}01+0{\cdot}00084\,(\alpha^\circ)^2-[0{\cdot}023-0{\cdot}0104\alpha^\circ]\,\eta\,.$$

(c) *Sideforce coefficient. Figs.* 36 *and* 39. *Data from Refs.* 17, 18, 20

$$C_Y = -[0{\cdot}446+0{\cdot}0088\,\alpha^\circ]\,\beta+0{\cdot}0975\,\xi+0{\cdot}148\,\zeta\,.$$

(d) *Pitching-moment coefficient**. *Figs.* 32, 33 *and* 34. *Data from Refs.* 17, 19

$$C_M = 0{\cdot}0155-0{\cdot}00145\,\alpha^\circ-0{\cdot}204\,\eta-0{\cdot}32\frac{Qc_0}{V}-0{\cdot}17\frac{\dot{\alpha}c_0}{V}+\Delta h\,(C_L\cos\alpha+C_D\sin\alpha)\,.$$

*About a datum c.g. position of 0·50 $c_0$

(e) *Rolling-moment coefficients. Figs.* 35, 37, 38, 40 *and* 41. *Data from Refs.* 17, 18, 20

$$C_l = -0{\cdot}11\,\xi+[0{\cdot}0146+0{\cdot}00054\,\alpha^\circ]\,\zeta-[0{\cdot}03+0{\cdot}0118\,\alpha^\circ]^\circ\,\beta-0{\cdot}20\,\frac{Pc_0}{2V}+[0{\cdot}0485+0{\cdot}00303\,\alpha^\circ]\,\frac{Rc_0}{2V}.$$

(f) *Yawing-moment coefficient. Figs.* 35, 37, 38, 40 *and* 41. *Data from Refs.* 17, 18, 20

$$C_n = -0{\cdot}045\,\xi-0{\cdot}091\,\zeta+[0{\cdot}11-0{\cdot}0001(\alpha^\circ)^2]\,\beta-0{\cdot}195\,\frac{Rc_0}{2V}-[0{\cdot}0057\,\alpha^\circ]\,\frac{Pc_0}{2V}.$$

TABLE 1

*Pilot Opinion Rating Scale for Civil Transport Aircraft.*

| Adjective rating | Numerical rating | Description | Can be landed? |
|---|---|---|---|
| Satisfactory | 1 | Excellent—no comment | Yes |
| | 2 | Very good—pleasant to fly. No tricks or special techniques required | Yes |
| | 3 | Good—pleasant to fly generally but with certain *irritations* which can be lived with but *should* be improved if possible. | Yes |
| Unsatisfactory | 4 | Acceptable though with characteristics that would always be mildly *worrying* and *must* be improved if possible. | Yes |
| Unacceptable | 5 | Flyable but with *unpleasant* characteristics requiring constant concentration and/or tiring techniques. | Probable |
| | 6 | Unacceptable for continuous operation. Satisfactory in emergency. | Probable |
| | 7 | Unacceptable—doubtful even in emergency. | Improbable |
| Catastrophic | 8 | Completely unacceptable. Dangerous or completely unflyable. | No |

Ratings should be based on routine operations rather than special experimental conditions.

TABLE 2

*Peak Bank Angles Following a Sharpedged Sidegust*
*Data from Tests with Different Simulation Cues.*

| Test condition | Peak bank angle response | Cockpit | Visual | No. of runs | Bank angle with pilot control | |
|---|---|---|---|---|---|---|
| | | | | | Mean | Std. dev. |
| Roll damper operating 15 ft/sec sidegust | 5·5° | Fixed | Analogue | 10 | 3·8° | 0·8° |
| | | Fixed | Skyscape | 14 | 3·1° | 1·4° |
| | | Moving | Skyscape | 9 | 2·5° | 0·9° |
| Roll damper inoperative 15 ft/sec sidegust | 8·0° | Fixed | Analogue | 7 | 5·6° | 1·5° |
| | | Fixed | Skyscape | 19 | 4·7° | 1·3° |
| | | Moving | Skyscape | 10 | 2·7° | 0·7° |
| Roll damper operating 30 ft/sec sidegust | 11·0° | Fixed | Analogue | 24 | 8·1° | 1·8° |
| | | Fixed | Skyscape | 13 | 6·3° | 2·5° |
| | | Moving | Skyscape | 15 | 3·6° | 0·9° |
| Roll damper inoperative 30 ft/sec sidegust | 16·0° | Fixed | Analogue | 28 | 10·7° | 3·3° |
| | | Fixed | Skyscape | 27 | 7·9° | 2·3° |
| | | Moving | Skyscape | 17 | 5·1° | 1·3° |

TABLE 3

*Glide Path and Localiser Errors at Break-off Height* (250 *ft*) *for Various Autostabilization Cases.*

| c.g. position | Autothrottle | Pitch damper | Roll damper | Turbulence | Standard deviation of glide path errors ft | Standard deviation of localiser errors ft | |
|---|---|---|---|---|---|---|---|
| Fwd | Yes | Yes | Yes | No | 8 | 43 | Fig. 20(a) |
| Fwd | Yes | Yes | Yes | Yes | 36 | 73 | Fig. 20(b) |
| Aft | Yes | Yes | Yes | Yes | 23 | 114 | Fig. 21(a) |
| Fwd | No | Yes | Yes | Yes | 38 | 88 | |
| Aft | No | Yes | Yes | Yes | 29 | 72 | |
| Fwd | Yes | No | Yes | Yes | 32 | 41 | |
| Aft | Yes | No | Yes | Yes | 46 | 94 | Fig. 21(b) |
| Fwd | Yes | Yes | No | Yes | 23 | 55 | |
| Aft | Yes | Yes | No | Yes | 51 | 62 | Fig. 21(b) |
| Fwd | No | No | No | Yes | 45 | 133 | |
| Aft | No | No | No | Yes | 46 | 125 | Fig. 21(c) |

## TABLE 4

*Trim Conditions for a 3° Approach at 145 kt*
*(A.U.W. 160 000 lb)*

| | c.g. at 0·50 $c_0$ | c.g. at 0·52 $c_0$ |
|---|---|---|
| $\overset{\circ}{\alpha}_T$ | 13·9 | 13·2 |
| $C_{L_T}$ | 0·641 | 0·644 |
| $C_{DT}$ | 0·151 | 0·143 |
| $\overset{\circ}{\eta}_T$ | −0·30 | +3·62 |
| $T$ lb | 28 480 | 26 360 |

## TABLE 5

*Longitudinal Stability Derivatives for Approach Conditions*

Approach speed 145 kt ≡ 245·1 ft/sec
Weight 160 000 lb (Mass 4969 slugs)
Ref. wing area 3337 sq ft
Ref. wing chord 84·4 ft
Thrust line 2·5′ below c.g.
Glide path 3°.

$\mu_1 = 7{\cdot}45 \qquad \hat{t} = 2{\cdot}56 \qquad I_B = 0{\cdot}164$

| Derivative | With autothrottle ($A_u$ = 1000 lb/kt) | | Without autothrottle | |
|---|---|---|---|---|
| | c.g. 0·50 $c_0$ | c.g. 0·52 $c_0$ | c.g. 0·50 $c_0$ | c.g. 0·52 $c_0$ |
| $X_U$ | −0·445 | −0·438 | −0·151 | −0·143 |
| $X_W$ | −0·347 | −0·311 | −0·347 | −0·311 |
| $Z_U$ | −0·572 | −0·571 | −0·641 | −0·644 |
| $Z_W$ | −1·74 | −1·73 | −1·74 | −1·73 |
| $m_U$ | −0·0125 | −0·0123 | −0·0035 | −0·0033 |
| $m_W$ | −0·0415 | −0·0063 | −0·0415 | −0·0063 |
| $\overline{m}_{\dot{W}}$ | −0·085 | −0·085 | −0·085 | −0·085 |
| $m_q$ | −0·160 | −0·160 | −0·160 | −0·160 |
| $m_q^*$ | −0·458 | −0·458 | −0·458 | −0·458 |

*with pitch damper.

## TABLE 6

*Longitudinal Stability and Control Characteristics under Landing Approach Conditions*

*A.U.W.* 160 000 lb

$V_A$ 145 kt

(i) *Static margin* $K_n$

| c.g. position | Autothrottle | $K_n$ |
|---|---|---|
| 0·50 $c_0$ | 0 | +0·020 |
| 0·50 $c_0$ | 1000 lb/kt | +0·003 |
| 0·52 $c_0$ | 0 | −0·002 |
| 0·52 $c_0$ | 1000 lb/kt | −0·017 |

(ii) *Manoeuvre margin* ($H_m$) *and stick force per 'g'*

| c.g. position | Pitch damper | $H_m$ | S.F./g |
|---|---|---|---|
| 0·50 $c_0$ | $G_q = 0$ | +0·048 | 29 lb/g |
| 0·50 $c_0$ | $G_q = 1{\cdot}0$ | +0·090 | 54 lb/g |
| 0·52 $c_0$ | $G_q = 0$ | +0·026 | 15 lb/g |
| 0·52 $c_0$ | $G_q = 1{\cdot}0$ | +0·068 | 39 lb/g |

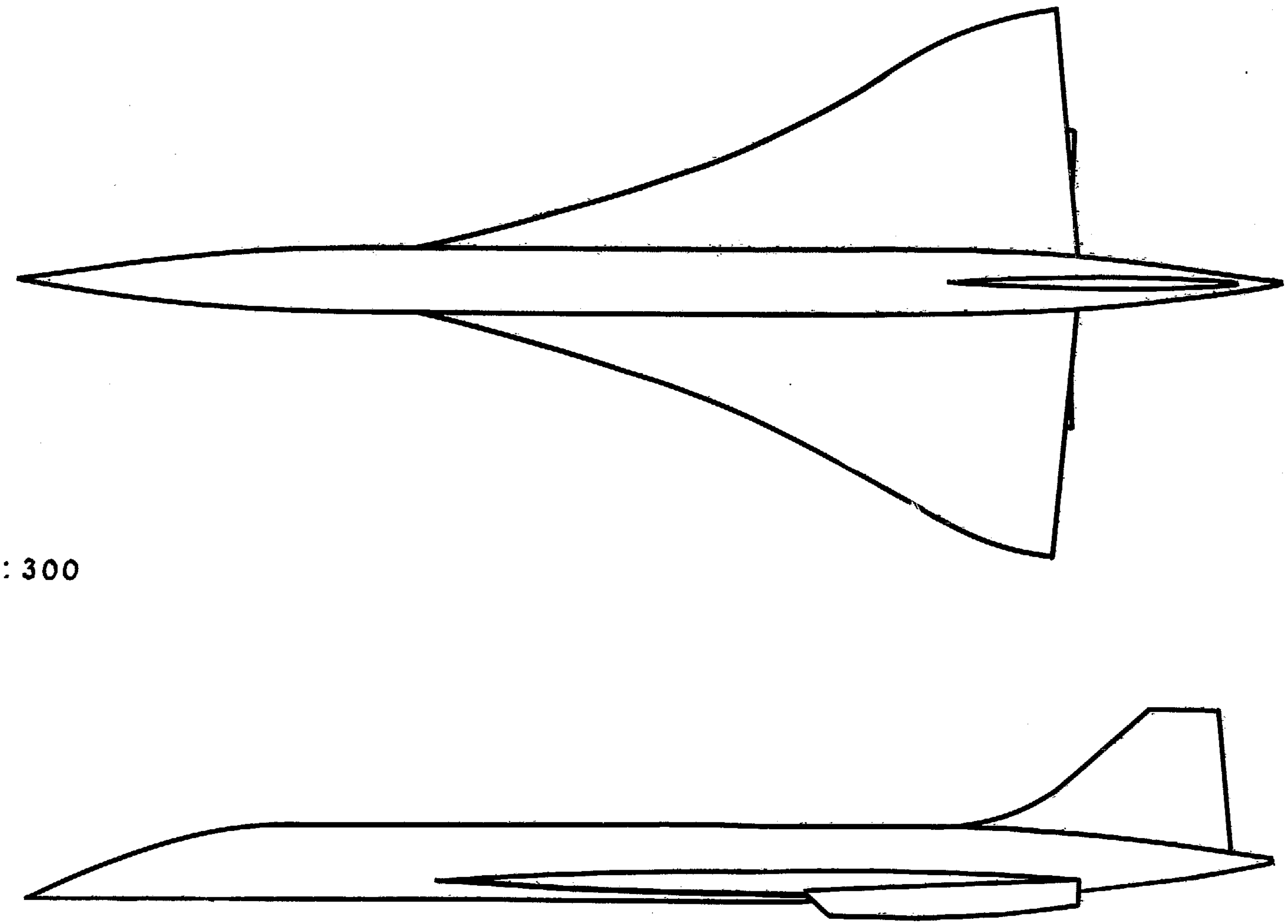
## TABLE 7

*Lateral Stability and Control Derivatives for Approach Conditions*

Approach speed 145 kt ≡ 245·1 ft/sec
Weight 160 000 lb
Ref. wing area 3337 sq ft
Ref. wing chord 84·4 ft

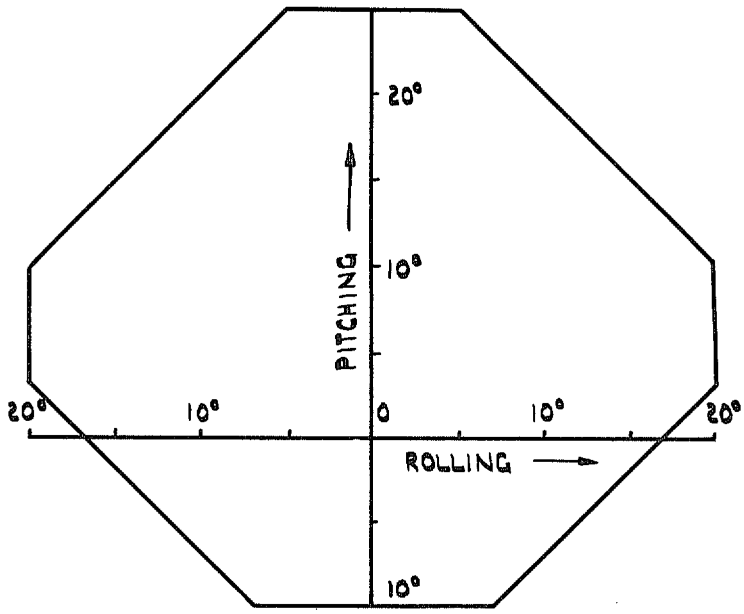
$\mu_2 = 14{\cdot}9$  $\hat{t} = 2{\cdot}56$  $\alpha_B = 13{\cdot}5°$

| Derivatives | Value referred to body datum axes | Value referred to stability axes |
|---|---|---|
| $y_V$ | −0·282 | −0·282 |
| $y_\xi$ | +0·049 | +0·049 |
| $y_\zeta$ | +0·074 | +0·074 |
| $l_V$ | −0·189 | −0·162 |
| $l_\xi$ | −0·110 | −0·118 |
| $l_\zeta$ | +0·022 | 0 |
| $n_V$ | +0·092 | +0·134 |
| $n_\xi$ | −0·045 | −0·018 |
| $n_\zeta$ | −0·091 | −0·094 |
| Damping derivatives with roll damper operating | | |
| $l_p$ | −0·456 | −0·463 |
| $l_r$ | +0·089 | +0·154 |
| $n_p$ | −0·182 | −0·119 |
| $n_r$ | −0·195 | −0·188 |
| Damping derivatives with roll damper not operating | | |
| $l_p$ | −0·200 | −0·197 |
| $l_r$ | +0·089 | +0·090 |
| $n_p$ | −0·077 | −0·077 |
| $n_r$ | −0·195 | −0·234 |
| Inertia coefficients | | |
| $I_A$ | +0·097 | +0·135 |
| $I_C$ | +0·725 | +0·688 |
| $I_E$ | −0·007 | −0·137 |



SCALE 1 : 300

FIG. 1. General arrangement of the aircraft simulated.




CONTROL MIXING ENVELOPE

CONTROL GEARINGS, ETC

| | | |
|---|---|---|
| PITCH | 1" STICK MOVEMENT FOR 3·7° ELEVON DEFLECTION | |
| | 11 lb STICK FORCE PER INCH OF STICK TRAVEL | |
| | BREAKOUT FORCE ABOUT 0·5 lb | |
| ROLL | 35° OF WHEEL TRAVEL FOR 20° ELEVON DEFLECTION | |
| | 15 lb WHEEL FORCE FOR FULL TRAVEL | |
| | BREAKOUT FORCE ABOUT 1 lb | |
| YAW | 3·5" PEDAL MOVEMENT FOR 30° RUDDER DEFLECTION. | |
| | 50 lb PEDAL FORCE FOR FULL TRAVEL | |

NB LINEAR GEARINGS BETWEEN ALL PILOTS CONTROLS AND CONTROL SURFACES

FIG. 2. Control characteristics.

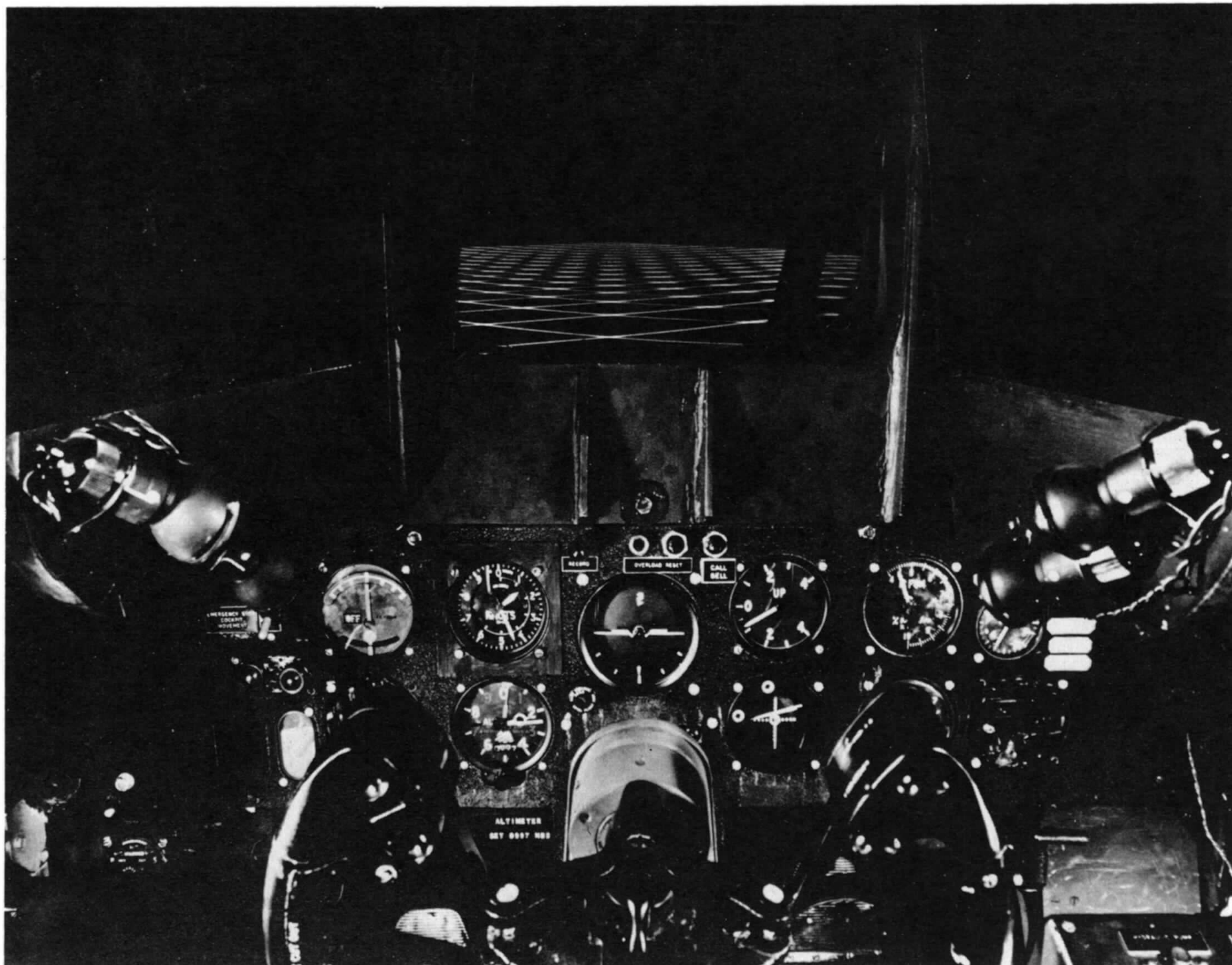



FIG. 3. Simulator flight instrument panel and display.

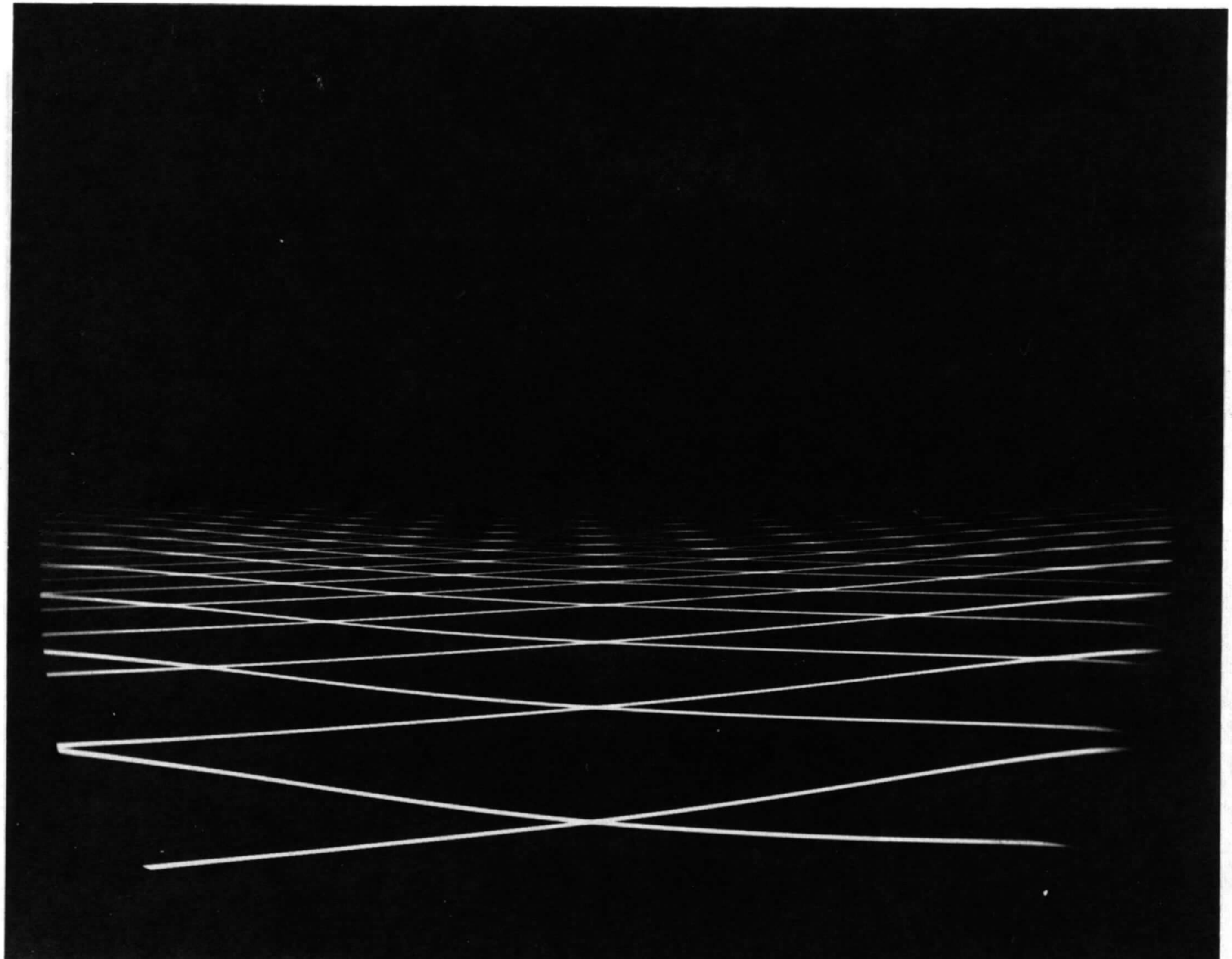


FIG. 4. Contact analogue visual display.

FIG. 5. The skyscape visual simulation.

FIG. 6. Runway shadowgraph projected visual display.

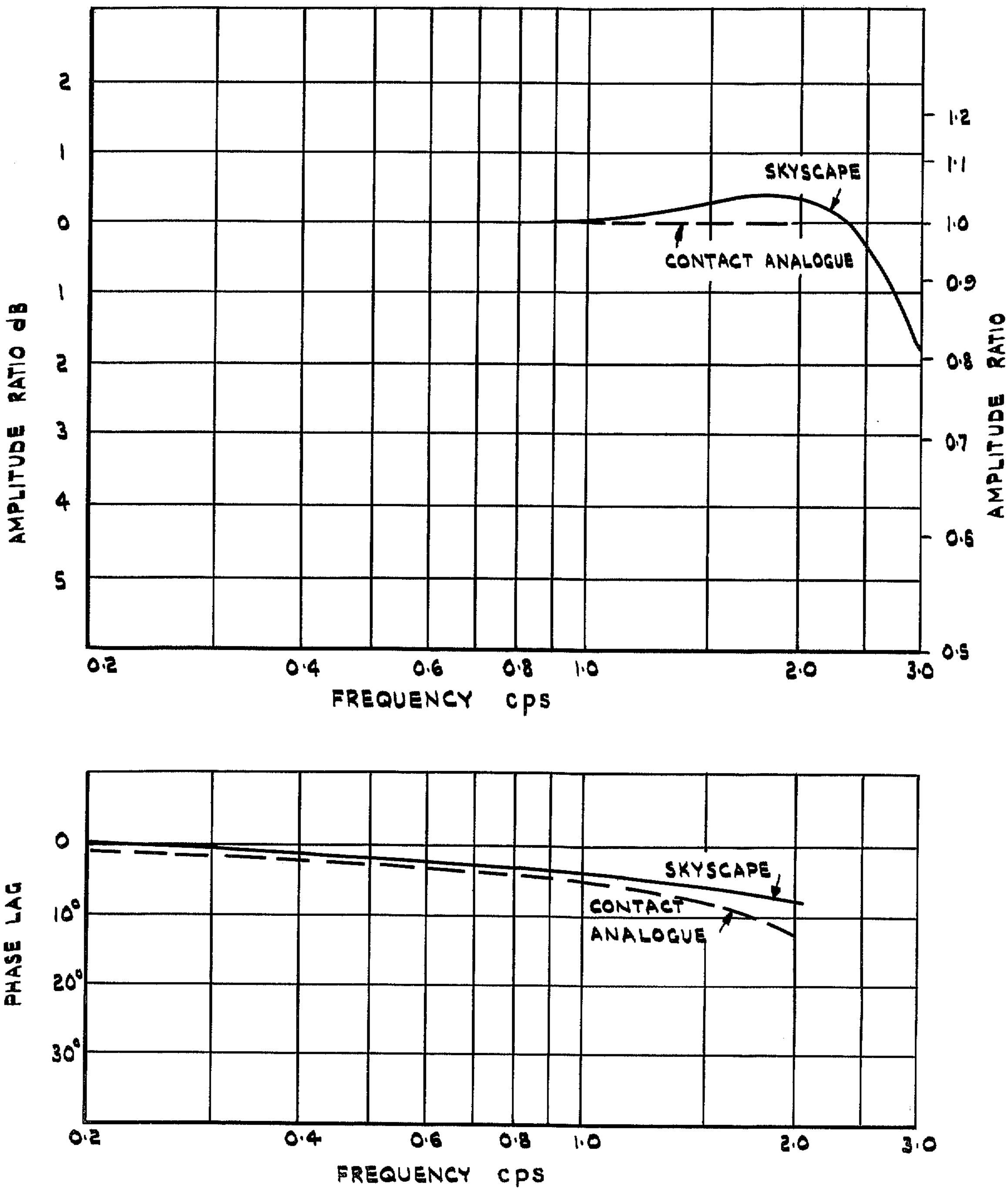



FIG. 7. Frequency response of mechanisms producing the rolling motion in the two visual displays.

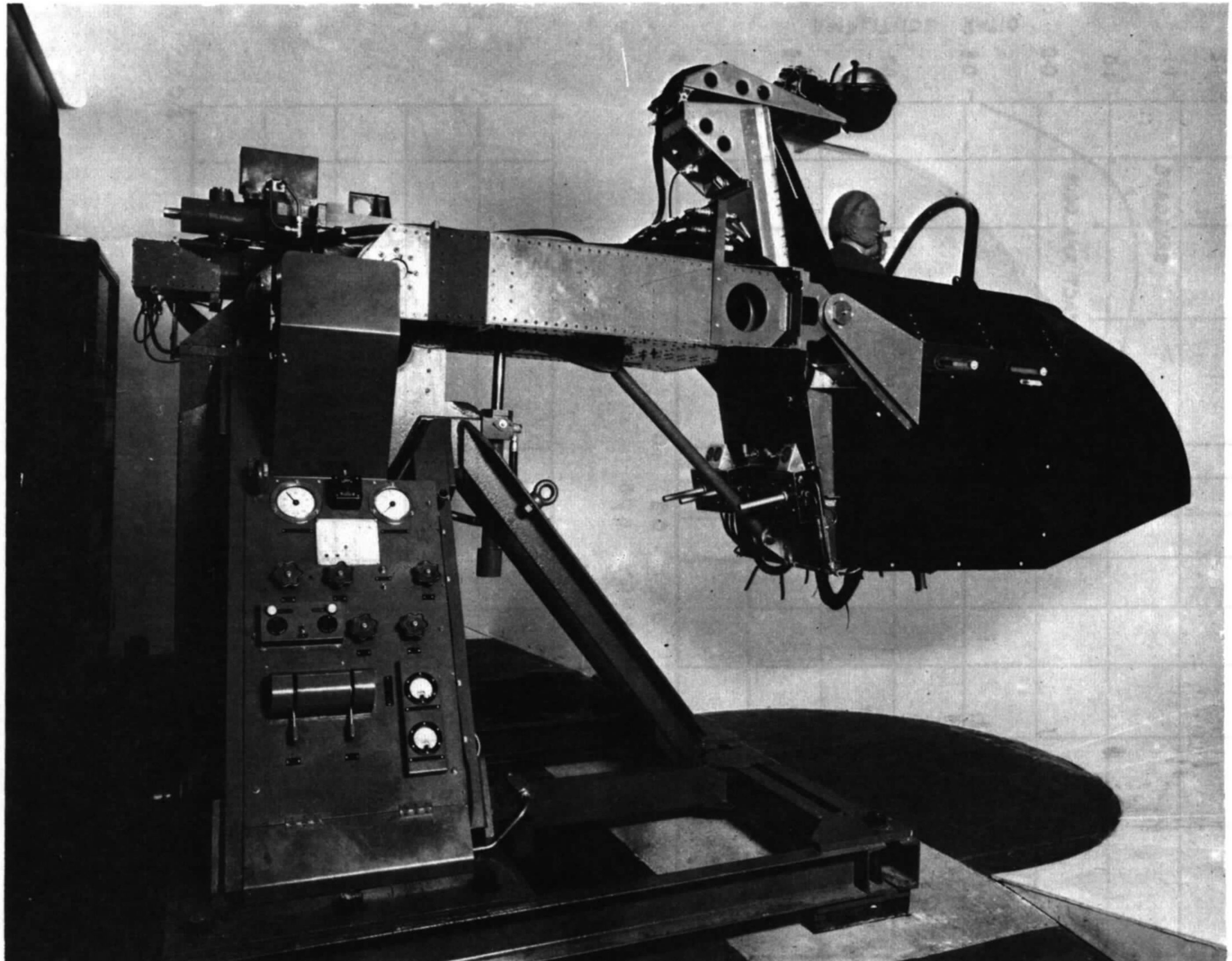


FIG. 8. The simulator cockpit and moving mechanism.

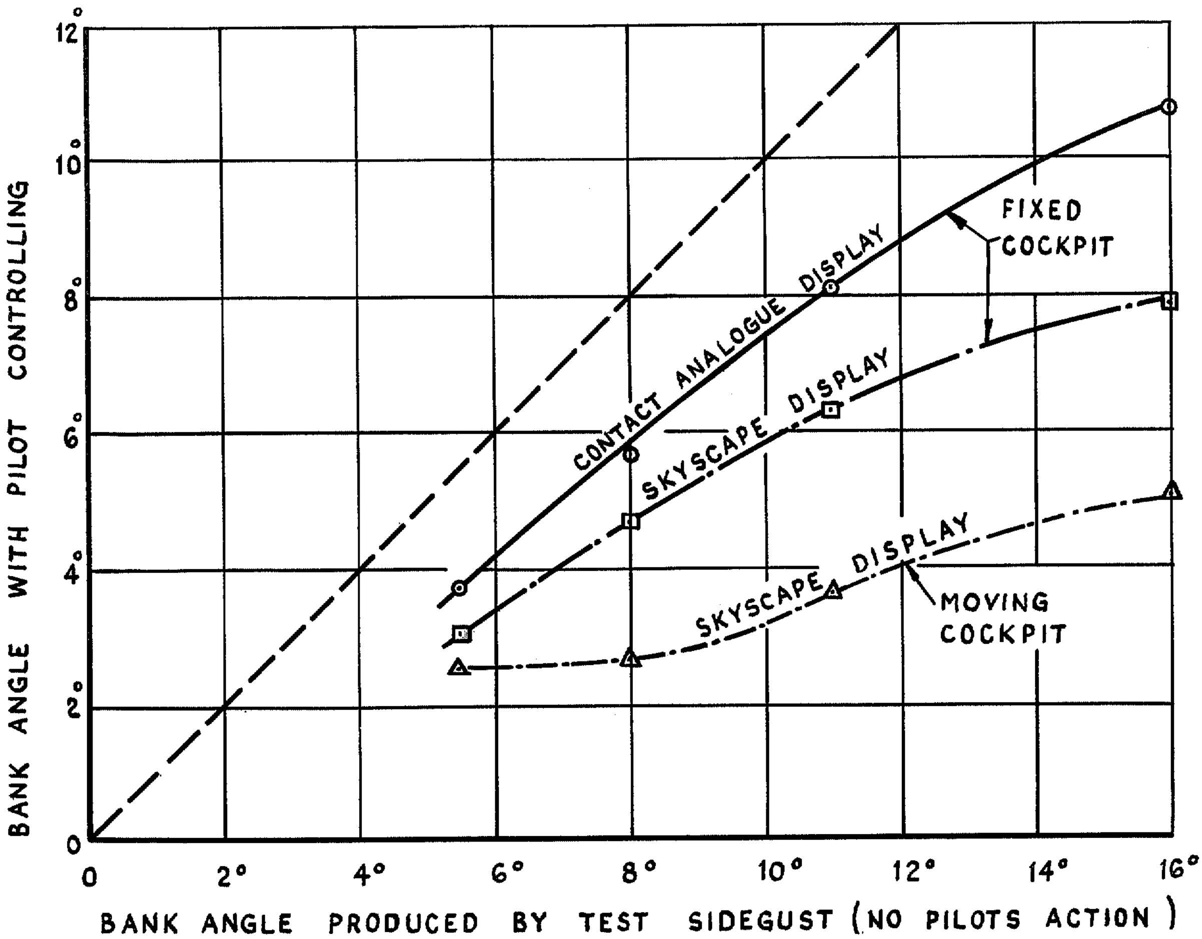



FIG. 9. The effect of different simulation cues on pilots control of bank angle after a sharpedged sidegust.

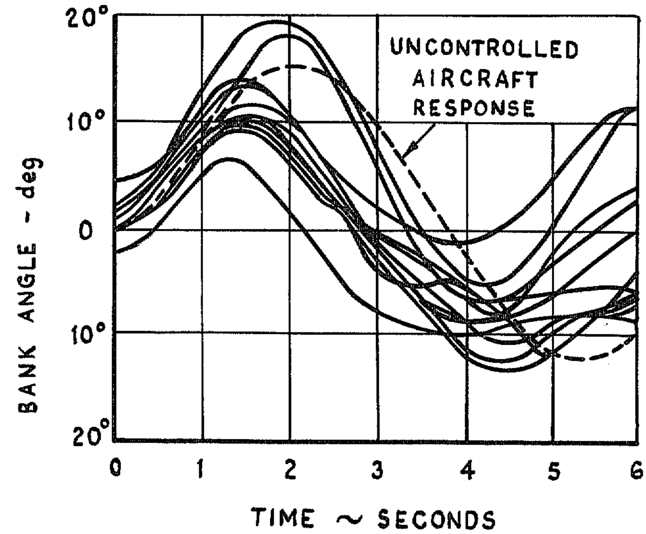



FIG.10(a) CONTACT ANALOGUE DISPLAY NO MOTION

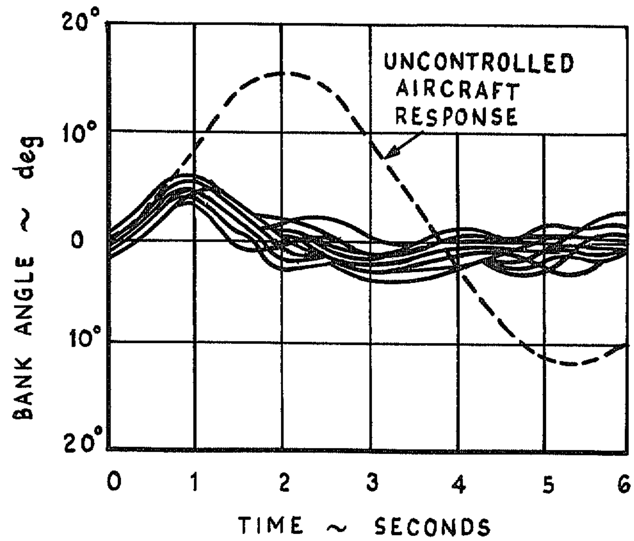



FIG.10(b) SKYSCAPE DISPLAY AND COCKPIT MOTION

FIG. 10. Time histories of bank angle following an encounter with a 30 ft/sec sidegust showing the influence of simulation cues on controllability. No roll damper.

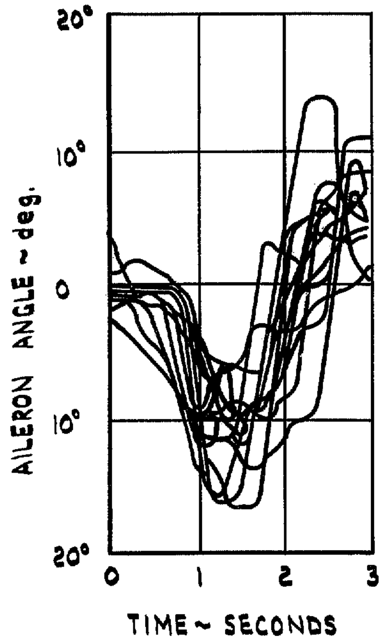



FIG. 11a. Contact analogue display. No motion.

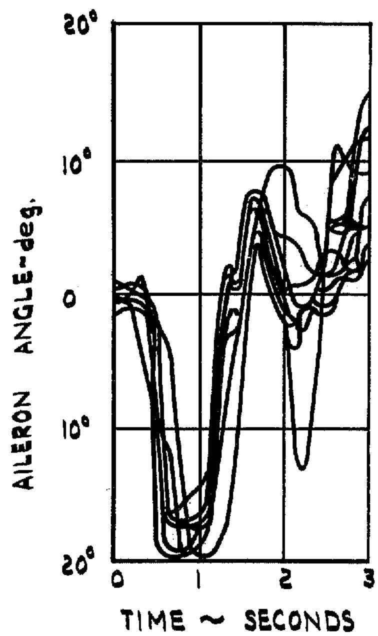



FIG. 11b. Skyscape display and cockpit motion.

FIG. 11. Time histories of aileron angle during tests illustrated in Fig. 10.

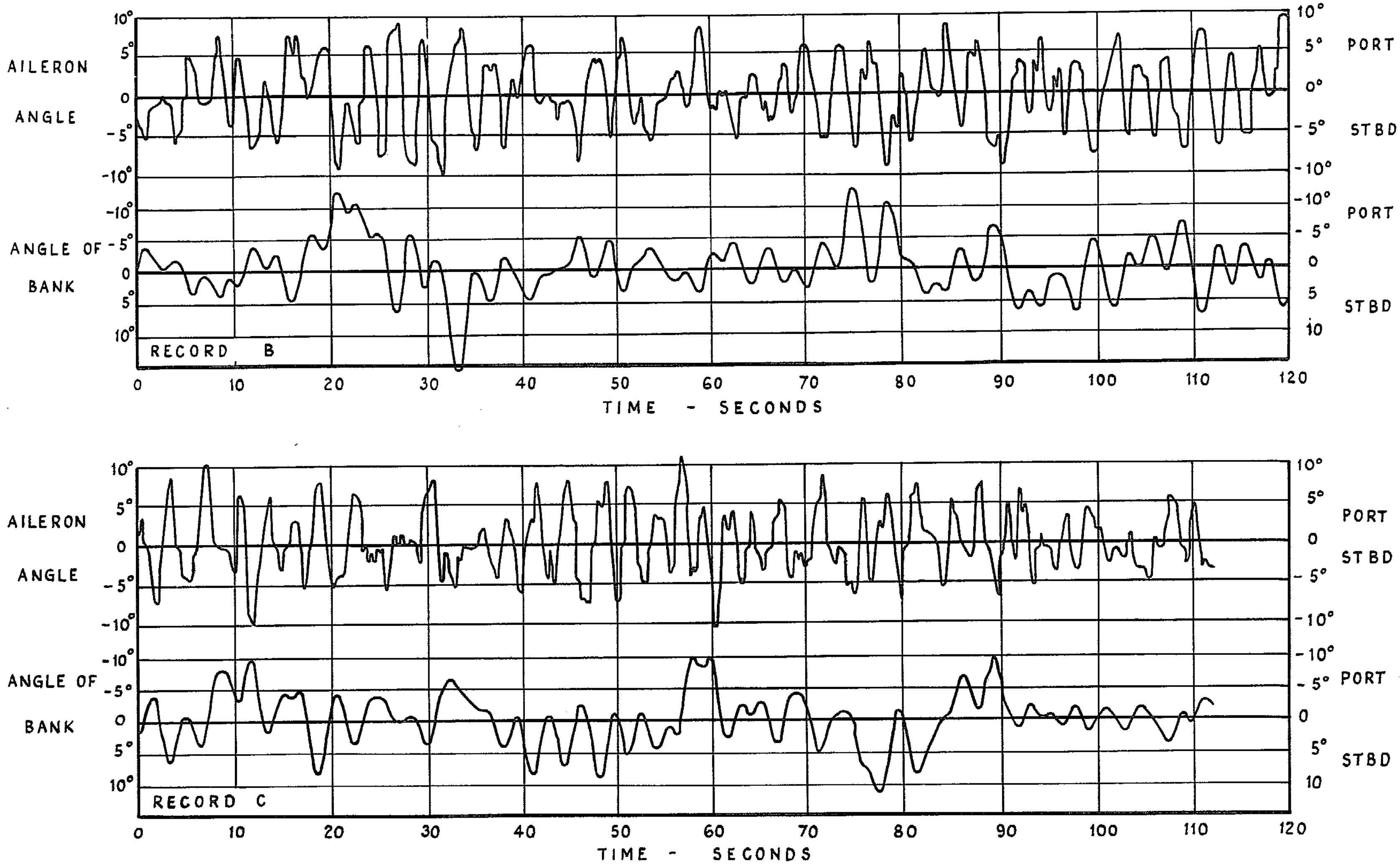



FIG. 12. Time histories of aileron angle and angle of bank during simulated instrument approaches without cockpit motion.

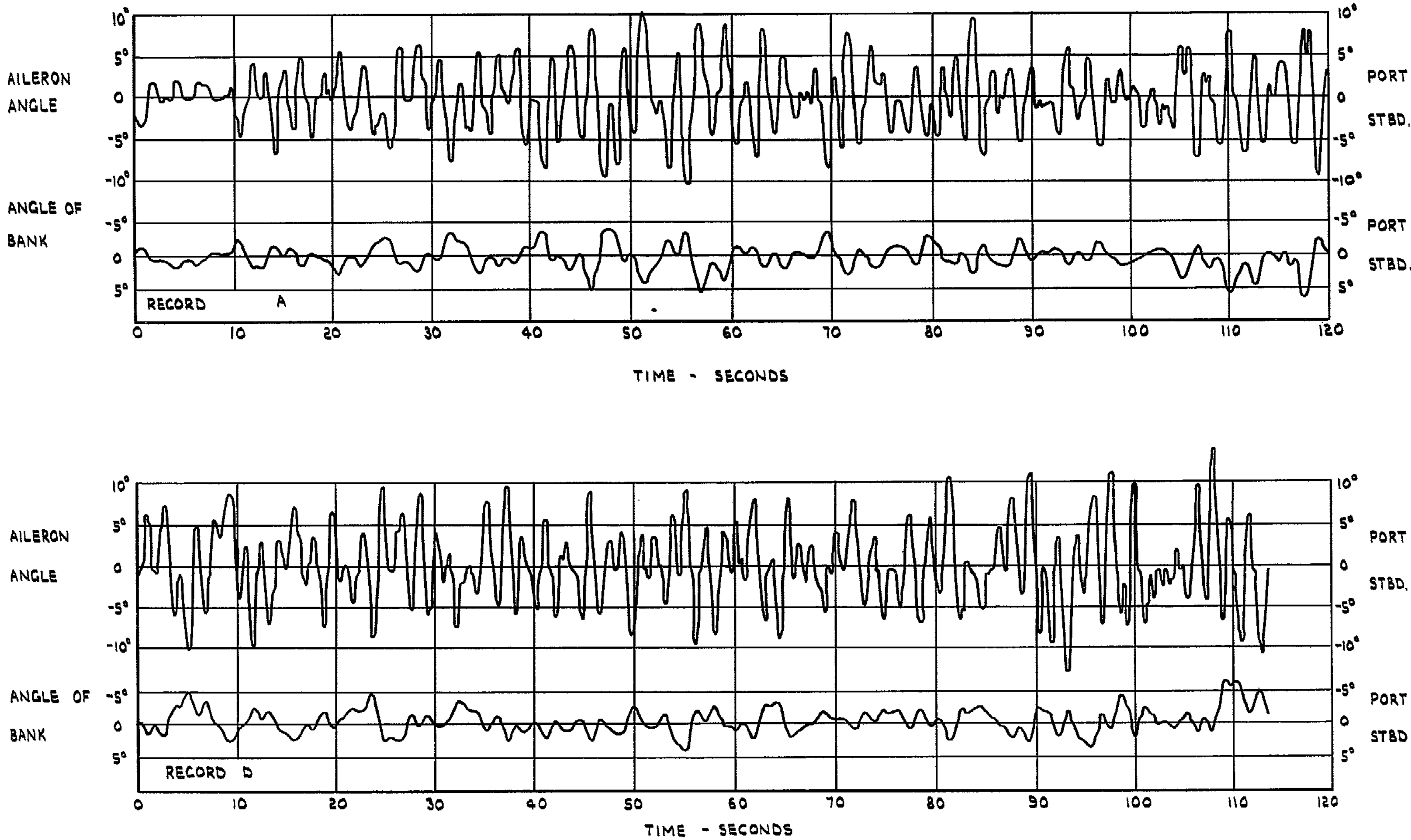



FIG. 13. Time histories of aileron angle and angle of bank during simulated instrument approaches with cockpit motion.

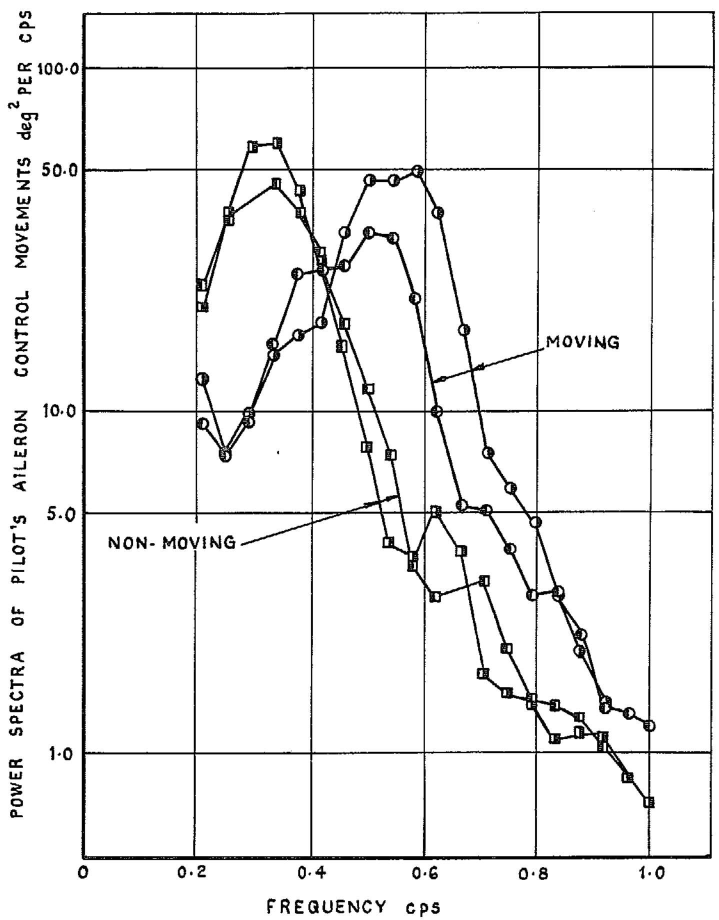



FIG. 14. Power spectra of pilot's aileron control movements with and without cockpit motion.

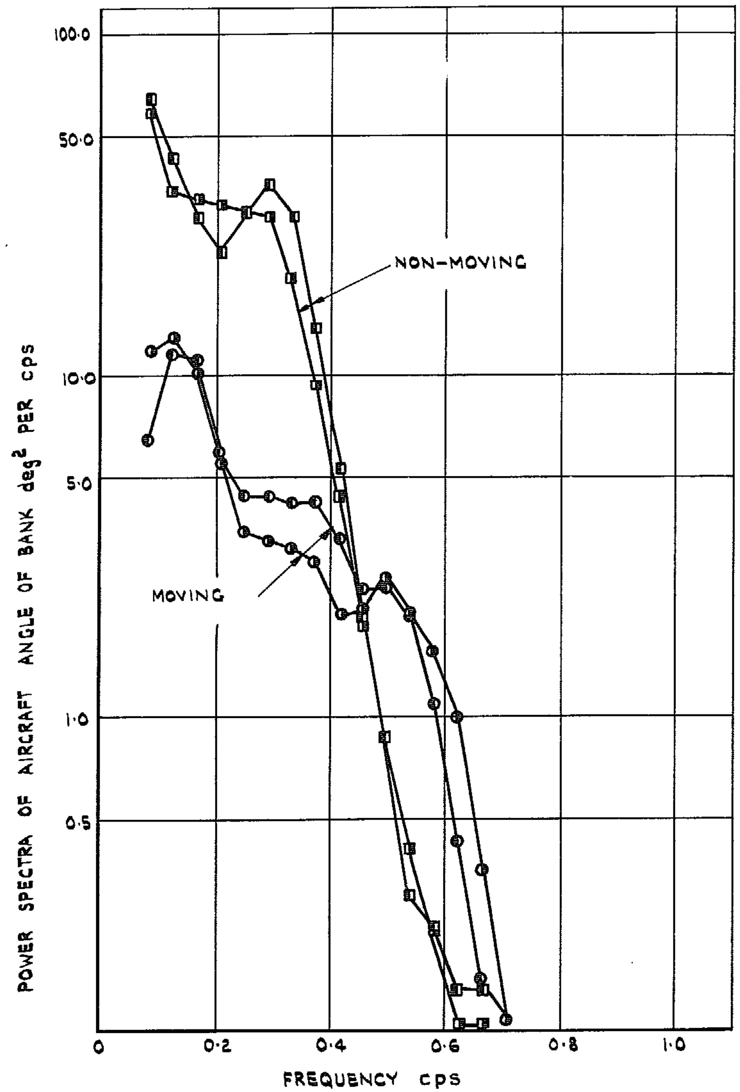



FIG. 15. Power spectra of bank angle during simulated flight through turbulence with and without cockpit motion.

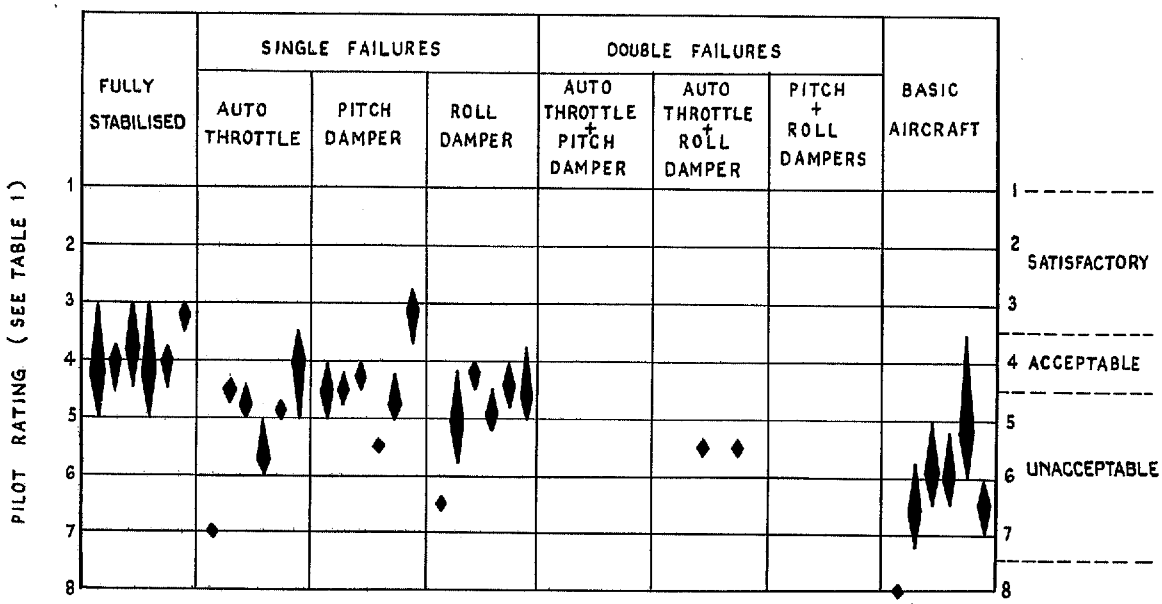



FIG. 16. Effect of auto stabilisation failures on handling in turbulence (4·5 ft/sec RMS). Forward CG (0·50 $c_0$).

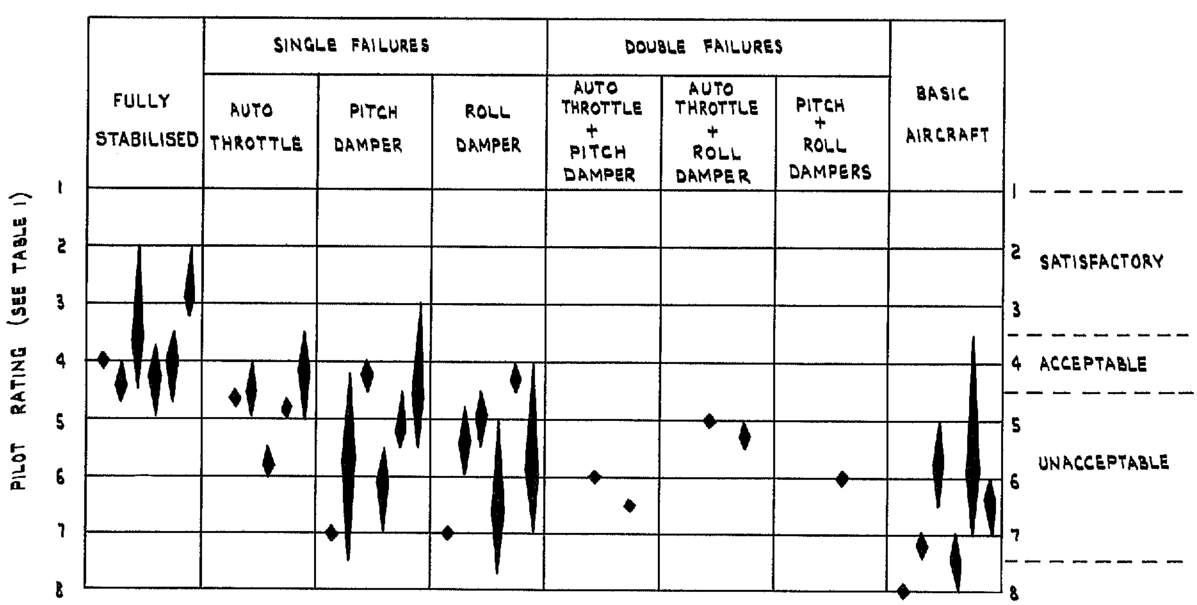



FIG. 17. Effect of autostabilization failures on handlings in turbulence (4·5 ft/sec rms). Aft cg (0·52 $c_0$).

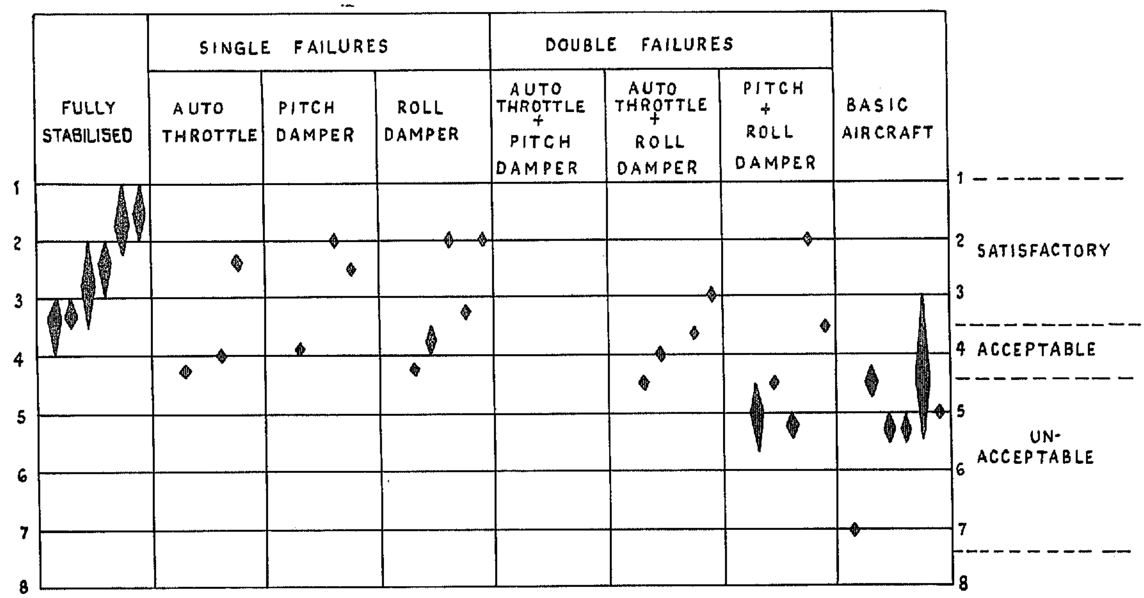



FIG. 18. Effect of autostabilization failures on handling in calm air. Forward cg ($0{\cdot}05\ c_0$).

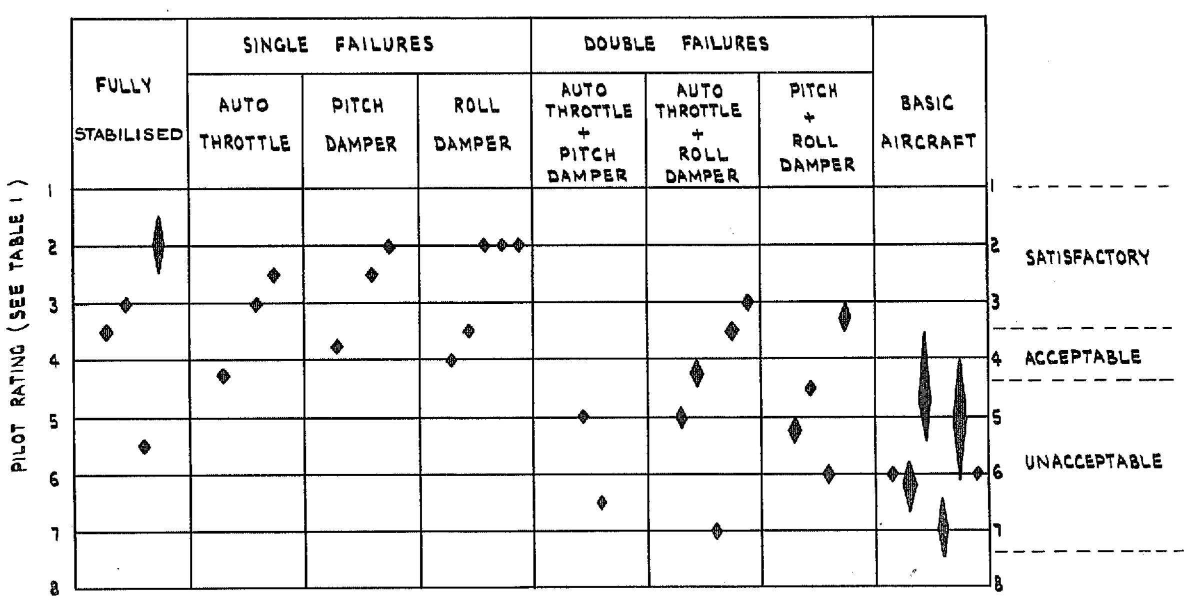



FIG. 19. Effect of autostabilization failures on handling in calm air. Aft cg ($0{\cdot}52\ c_0$).

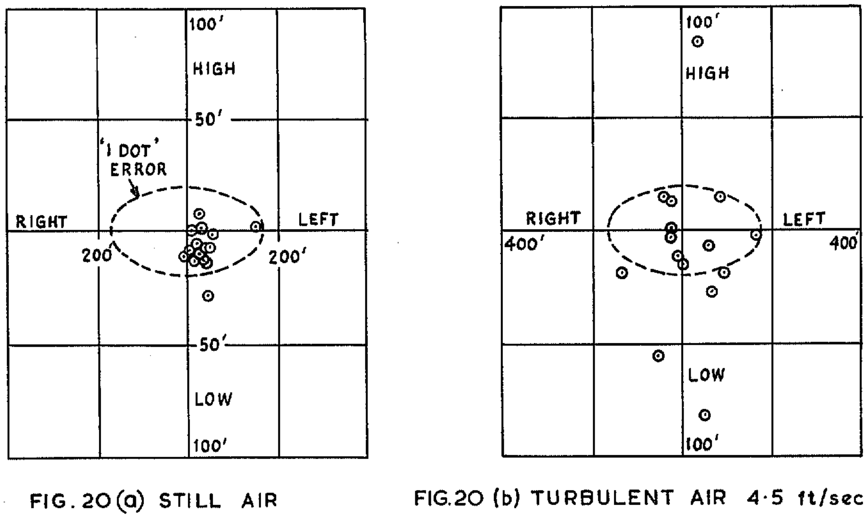



FIG. 20(a) STILL AIR    FIG. 20 (b) TURBULENT AIR 4·5 ft/sec

FIG. 20. Height errors and lateral positioning errors at the end of instrument approaches with and without turbulence. Fully stabilised aircraft. Forward cg.

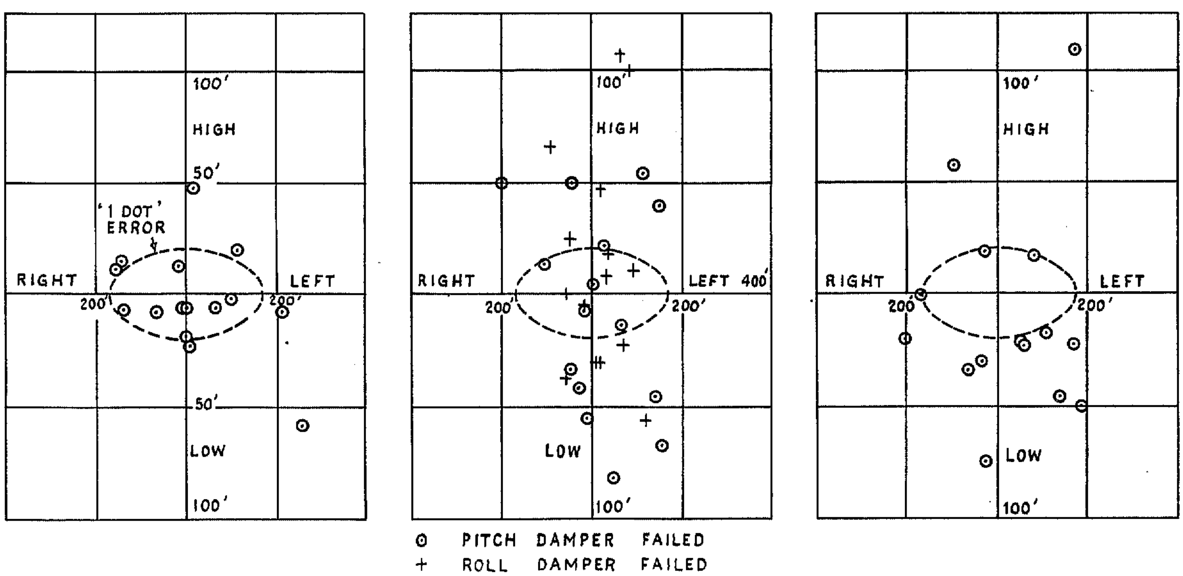



FIG. 21a. Fully stabilized.

FIG. 21b. Single Failures. (Pitch or roll damper failed).

FIG. 21c. No stabilization. (Pitch damper, roll damper and autothrottle failed).

FIG. 21. Height errors and lateral positioning errors at the end of instrument approaches for various failure cases. Aft cg, 4·5 ft/sec turbulence.

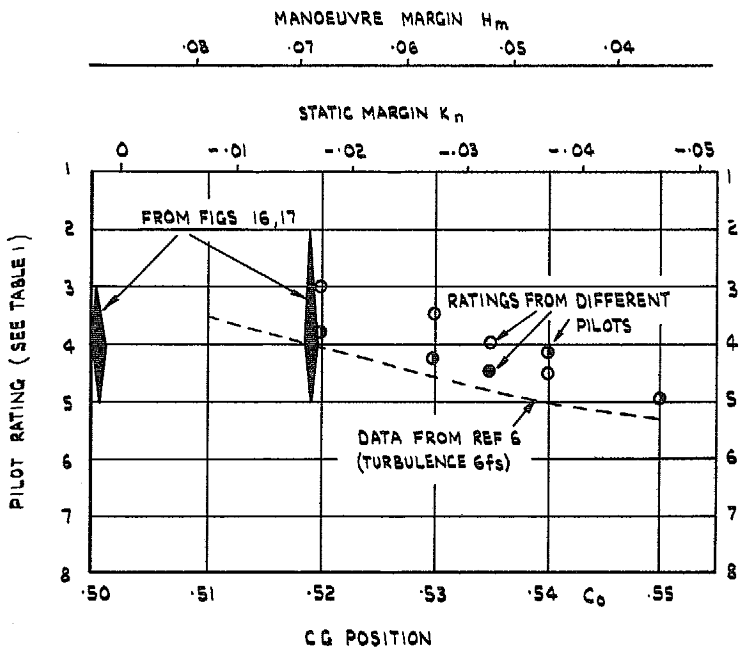



FIG. 22. Effect of rearward cg movement on handling. Fully stabilised aircraft. Turbulence 4·5 ft/sec rms. (Forward elevator limit removed).

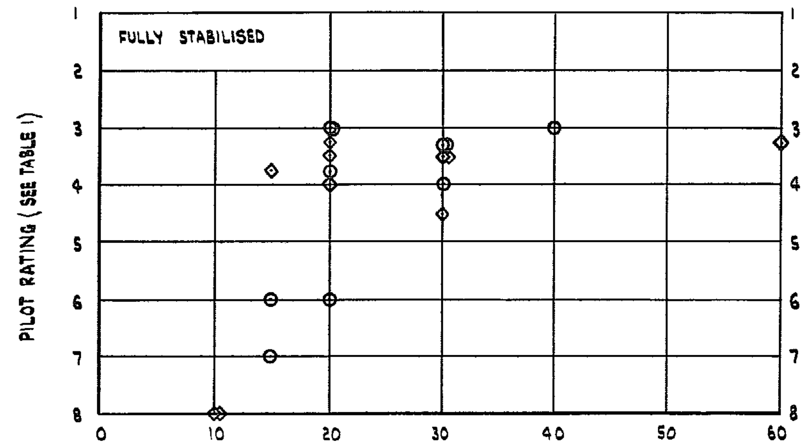



FIG. 23a. Rate limit on elevons $\xi_{max}$°/sec.

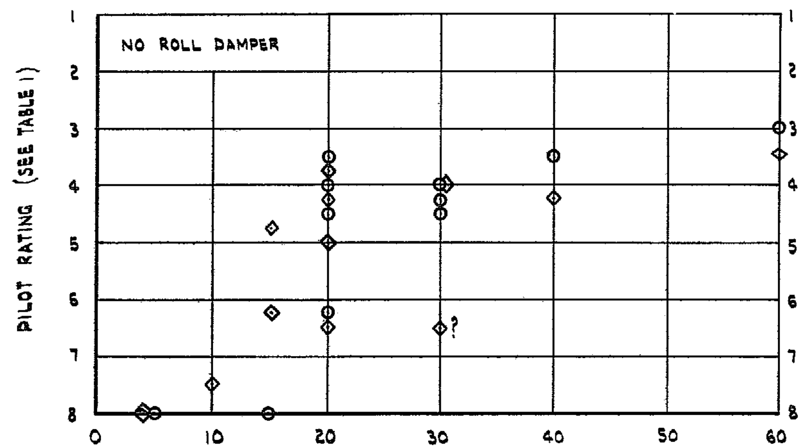



FIG. 23b. Rate limit on elevons $\xi_{max}$°/sec.

FIG. 23. Effect of rate limit of control surface on handling. Roll control with and without roll stabiliser.

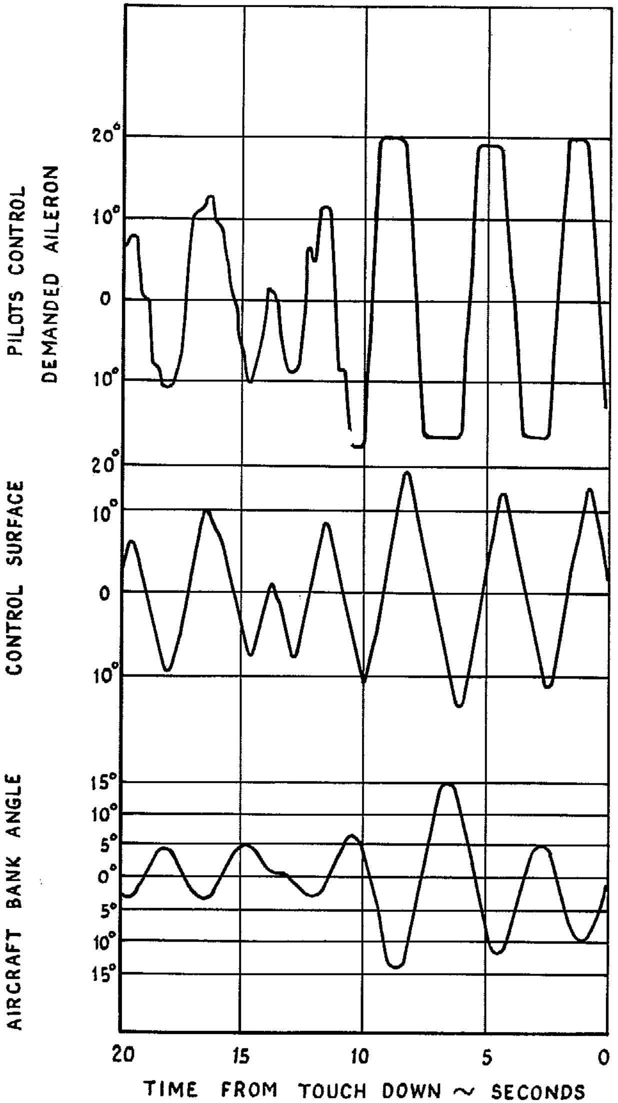



FIG. 24. Time history showing roll control difficulty due to rate limit (15°/sec) on elevons.

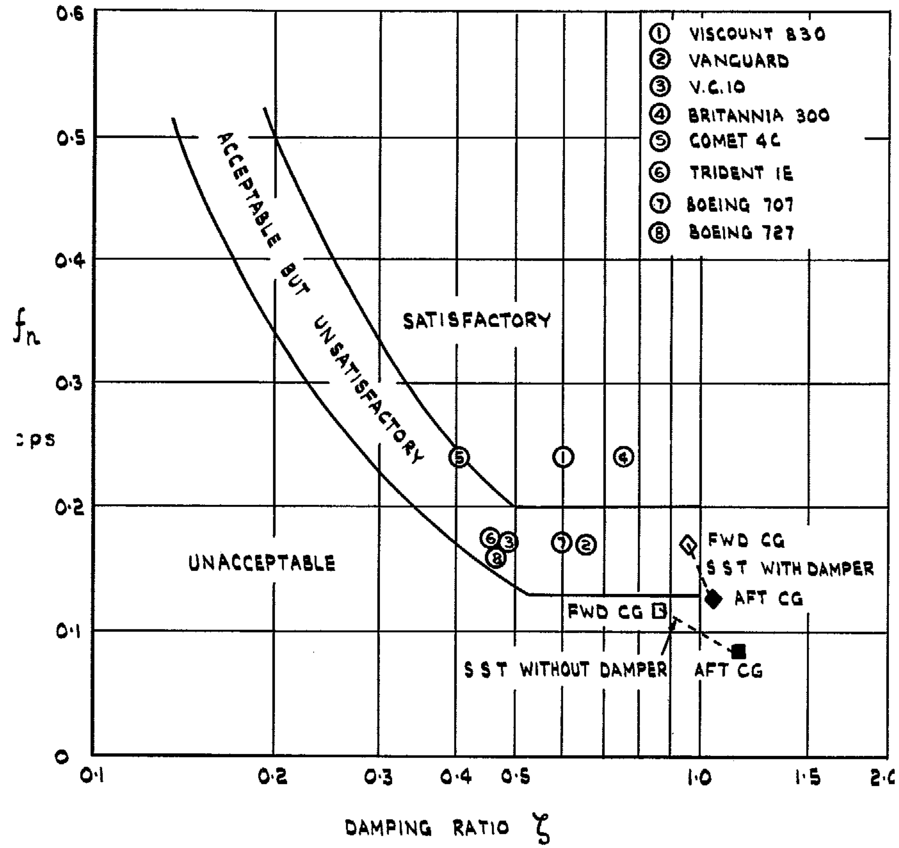



FIG. 25. Simulated SST longitudinal short-period characteristics in relationship to handling qualities criteria of Ref. 10 and current transport aircraft.

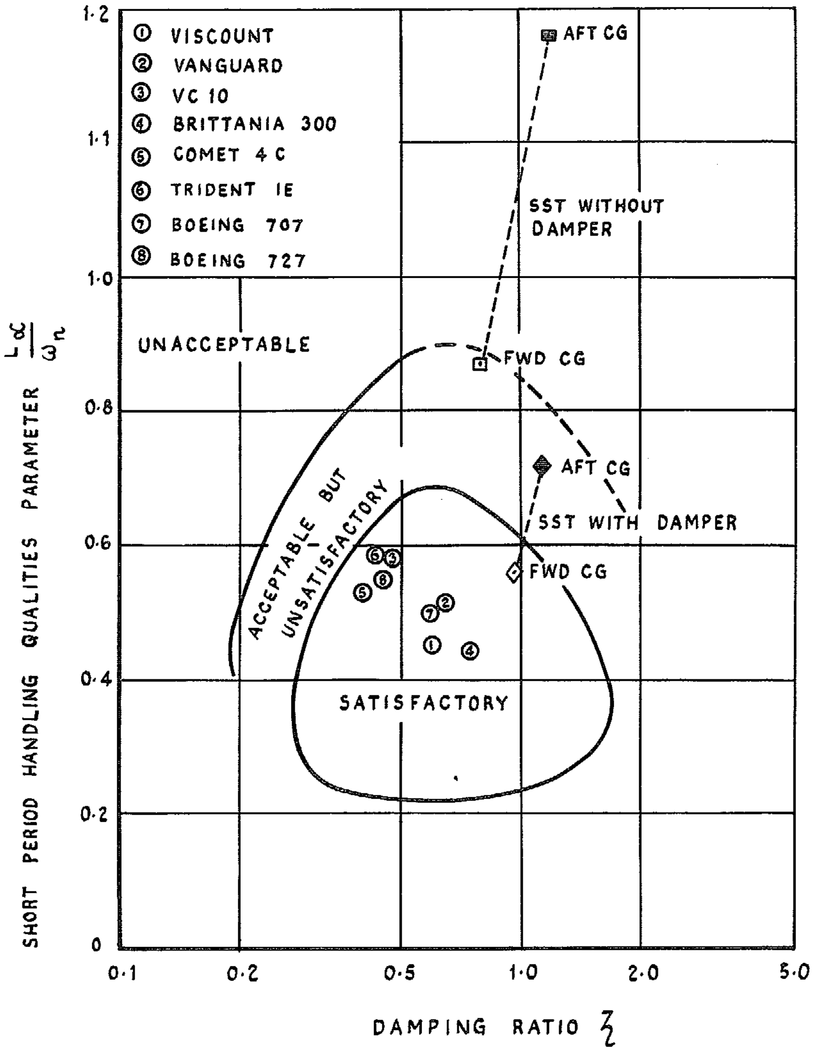



FIG. 26. Simulated SST longitudinal short-period characteristics in relationship to handling qualities criteria of Ref. 11 and current transport aircraft.

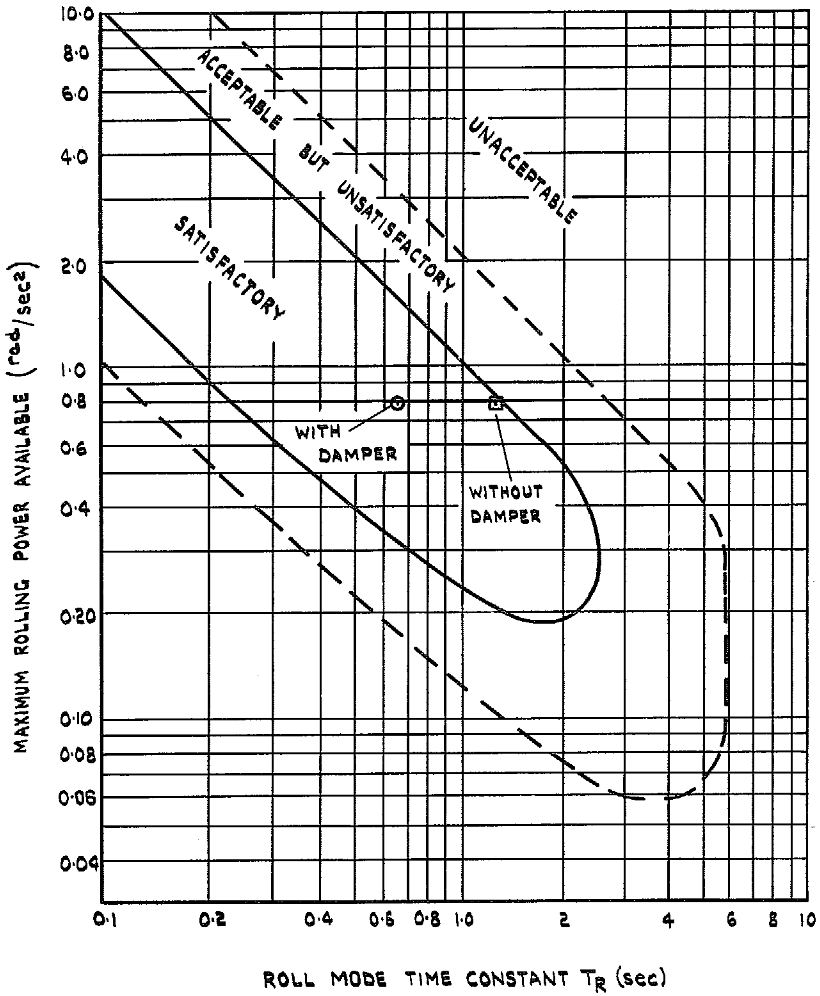



FIG. 27. Present aircraft roll response characteristics in relationship to handling qualities criteria of Ref. 13.

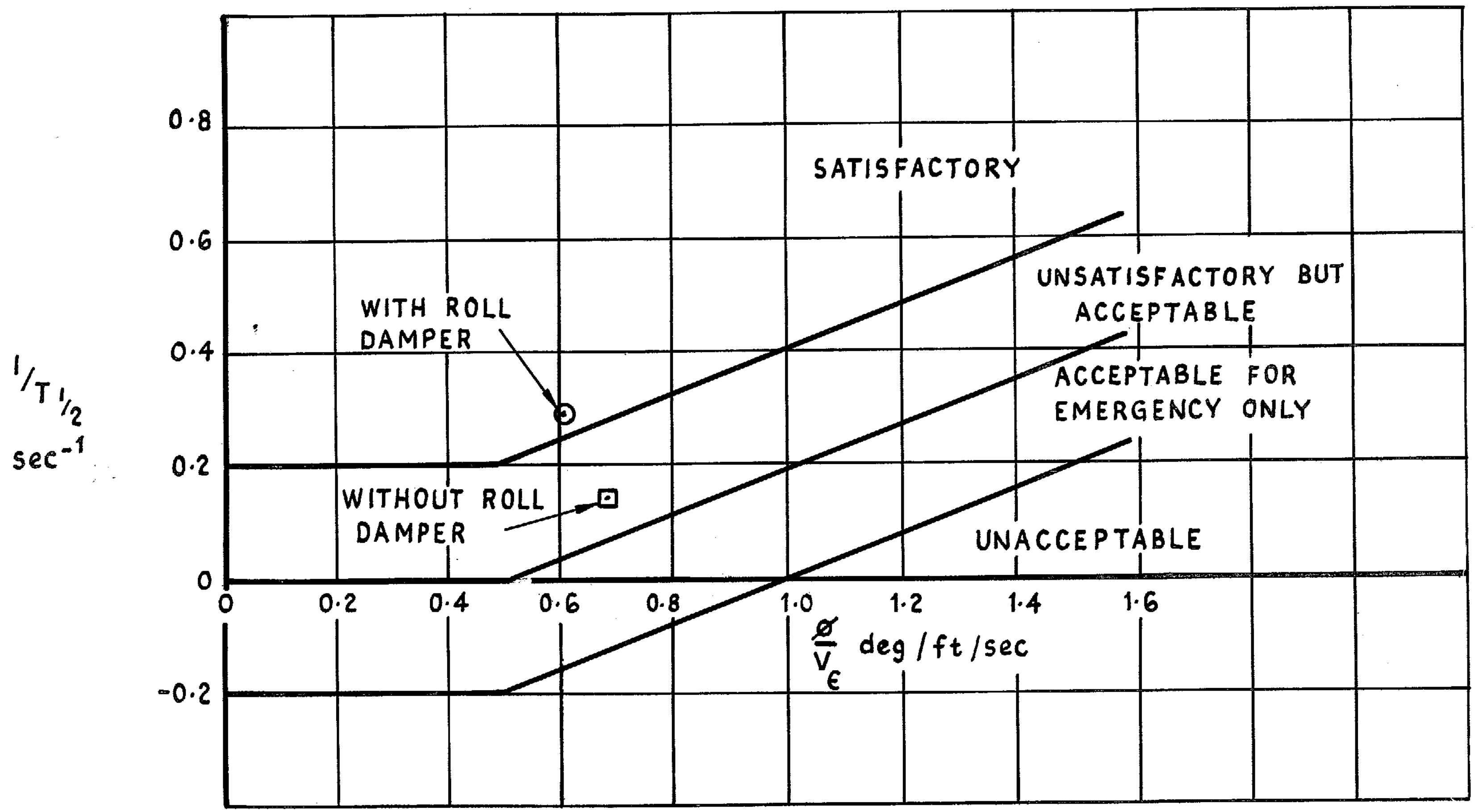



FIG. 28. Present aircraft lateral short-period mode in relationship to handling qualities criteria of Ref. 13.

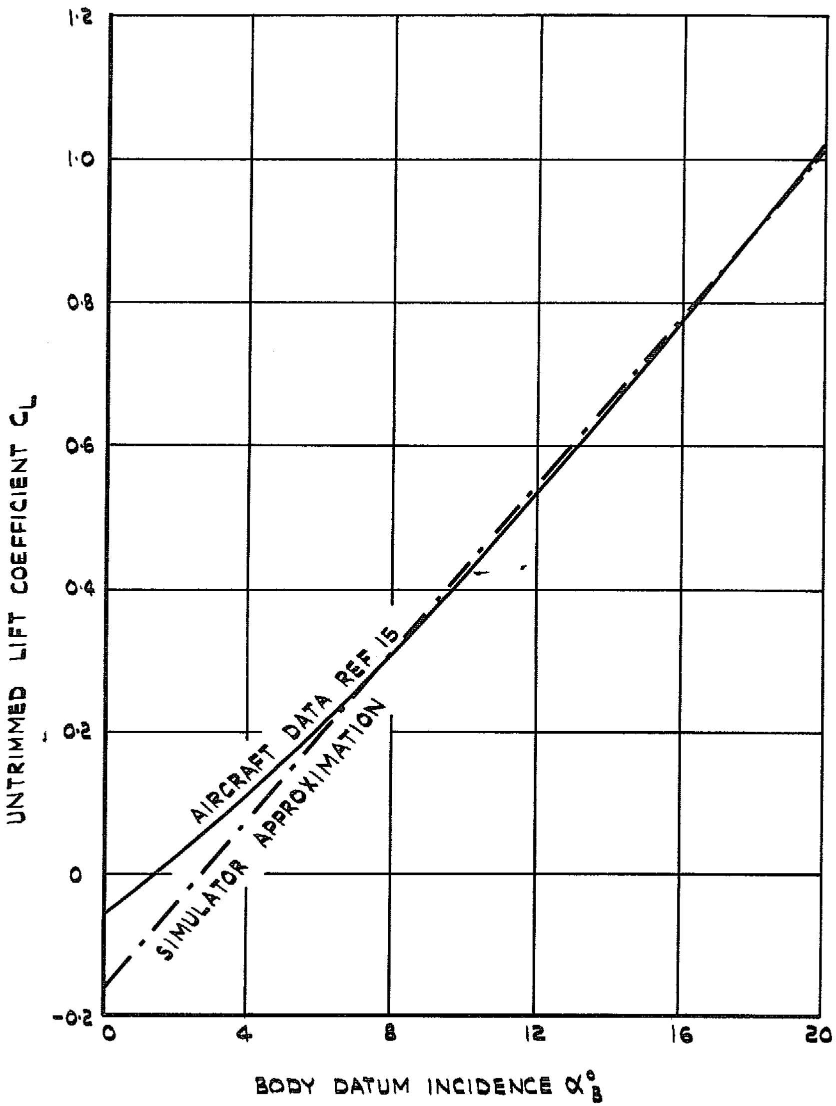



FIG. 29. Aerodynamic data used for the simulation. Lift *vs* incidence.

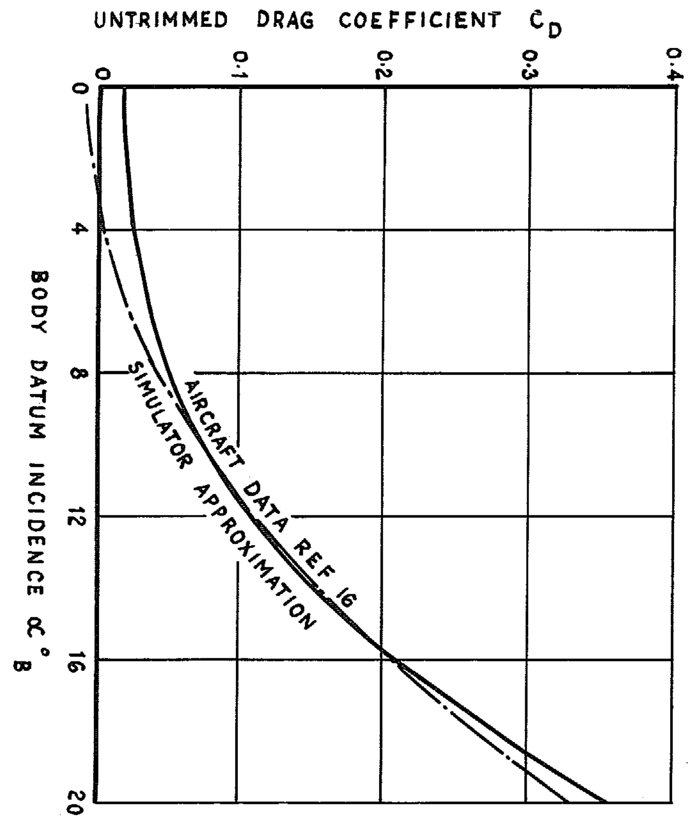



FIG. 30. Aerodynamic data used for the simulation. Drag *vs* incidence. Undercarriage down.

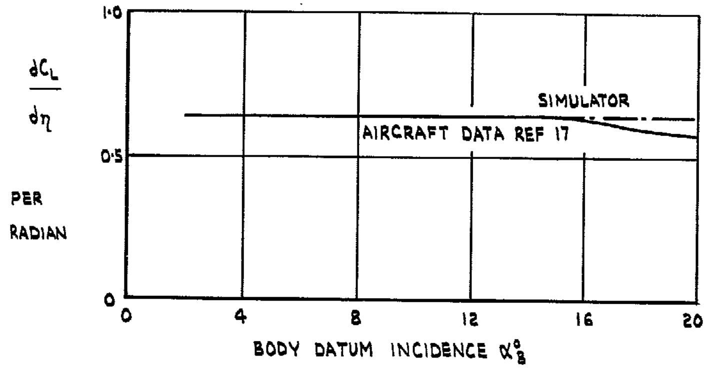



FIG. 31a. Lift due to elevator.

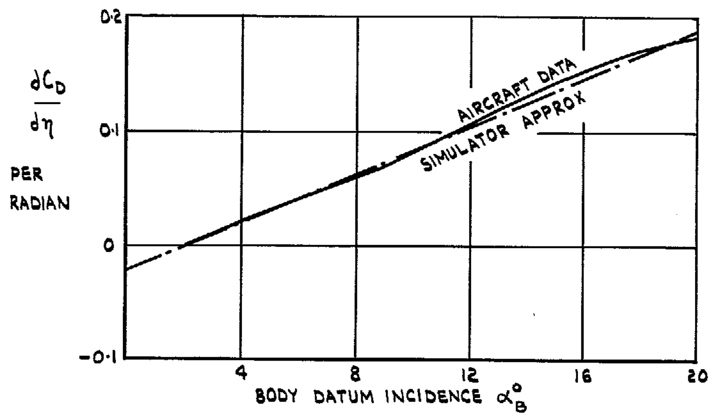



FIG. 31b. Drag due to elevator.

FIG. 31. Aerodynamic data used for the simulation. Lift and drag due to elevator.

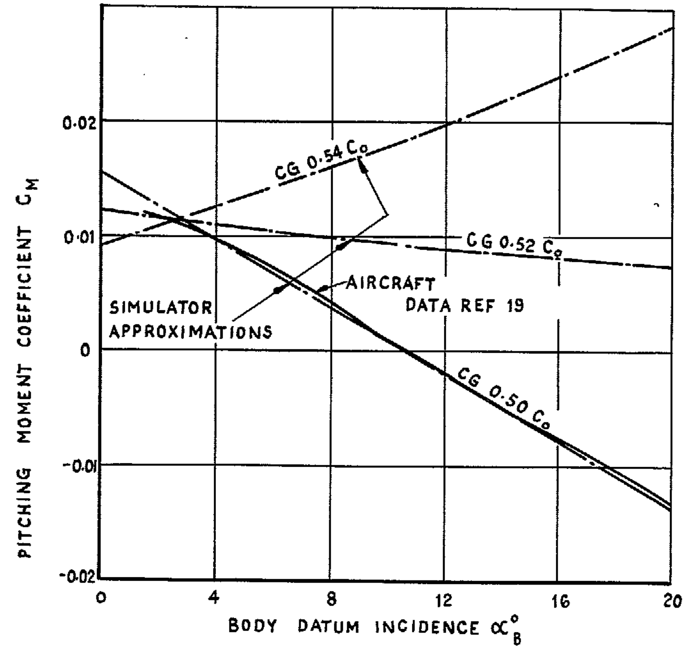



FIG. 32. Aerodynamic data used for the simulation. Pitching moment *vs* incidence for cg at 0·50 *c*.

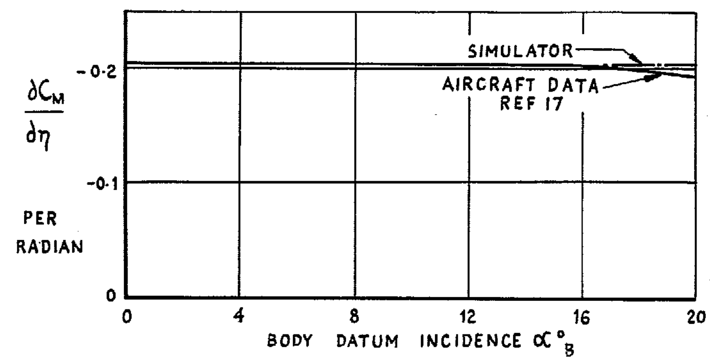



FIG. 33. Aerodynamic data used for the simulation. Pitching moment due to elevator for cg at 0·50 $c_0$.

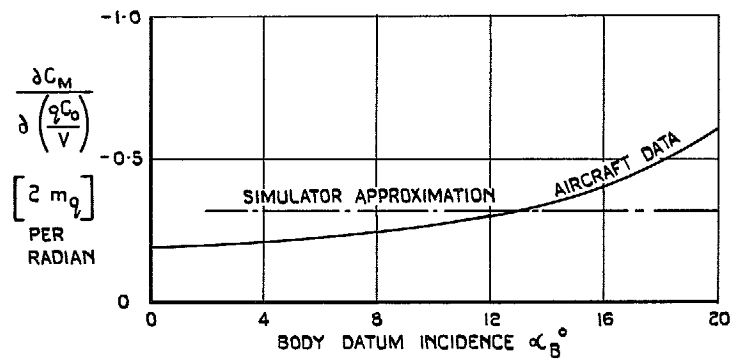



FIG. 34a. Damping due to rate of pitch.

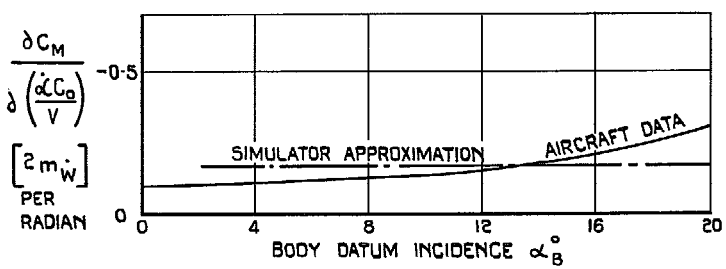



FIG. 34b. Damping due to rate of pitch.

FIG. 34. Aerodynamic data used for the simulation. Damping derivatives in pitch for cg at 0·50 $c_0$.

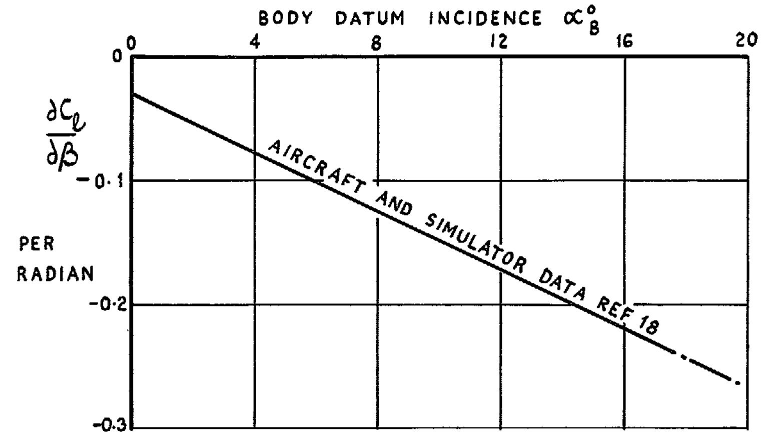



FIG. 35a. Rolling moment due to sideslip $l_v$.

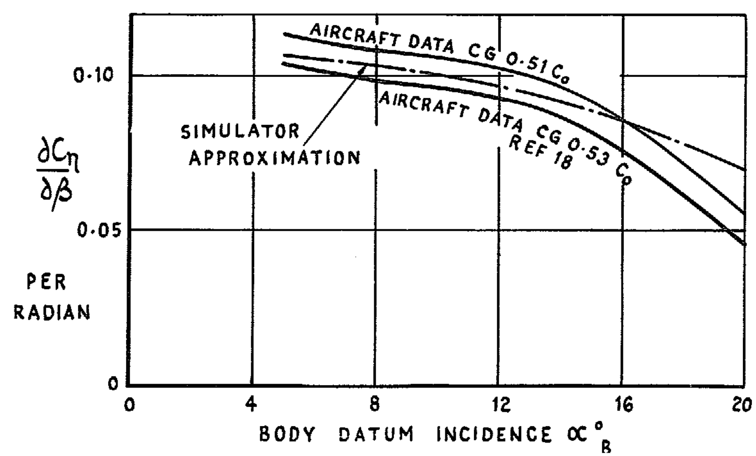



FIG. 35b. Yawing moment due to sideslip $n_v$.

FIG. 35. Aerodynamic data used in the simulation. Moment derivatives due to sideslip.

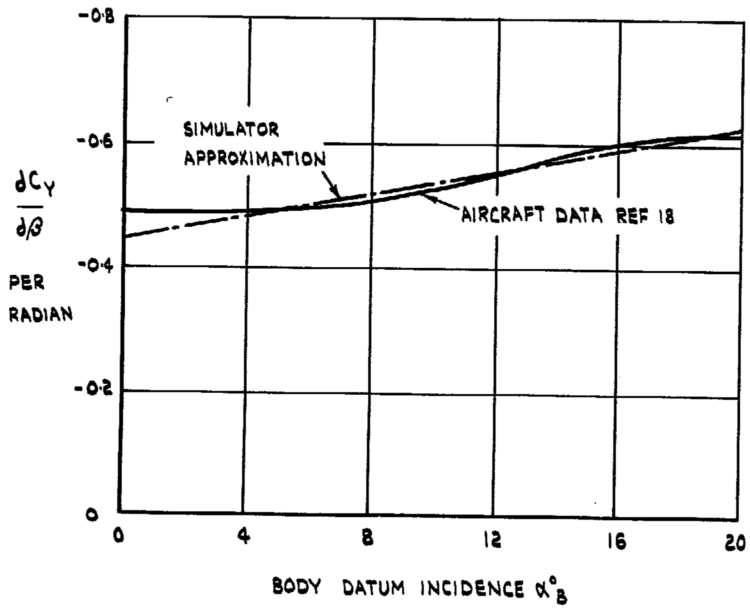



FIG. 36. Aerodynamic data used in the simulation. Sideforce derivative due to sideslip.

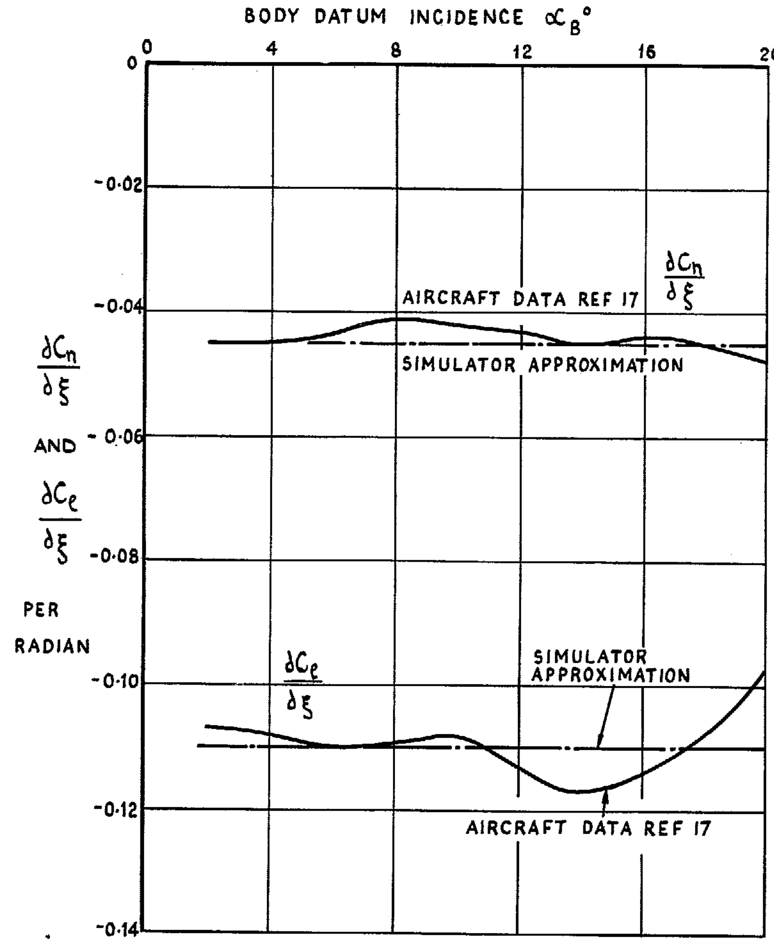



FIG. 37. Aerodynamic data used in the simulation. Rolling and yawing moment derivatives due to aileron.

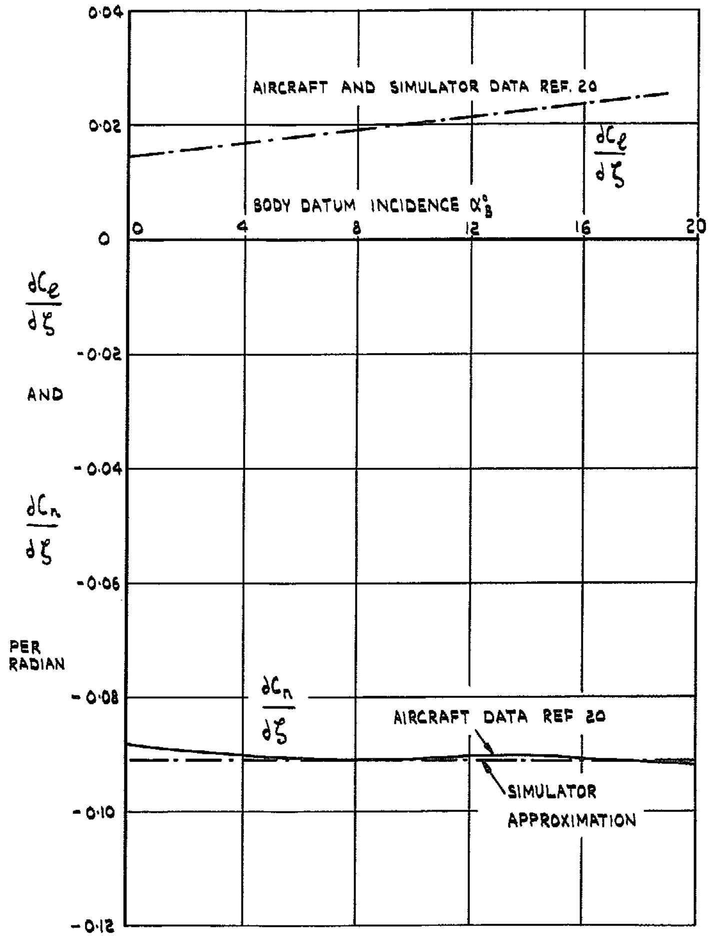



FIG. 38. Aerodynamic data used in the simulation. Rolling and yawing moment derivatives due to rudder.

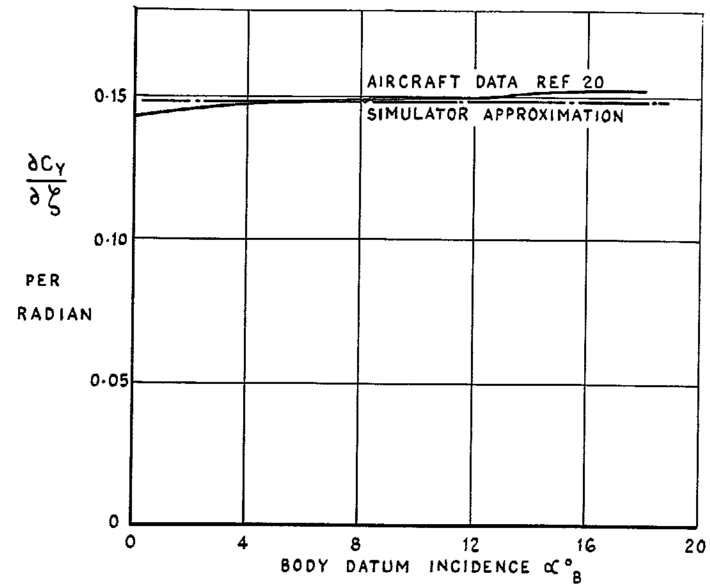



FIG. 39a. Sideforce due to rudder.

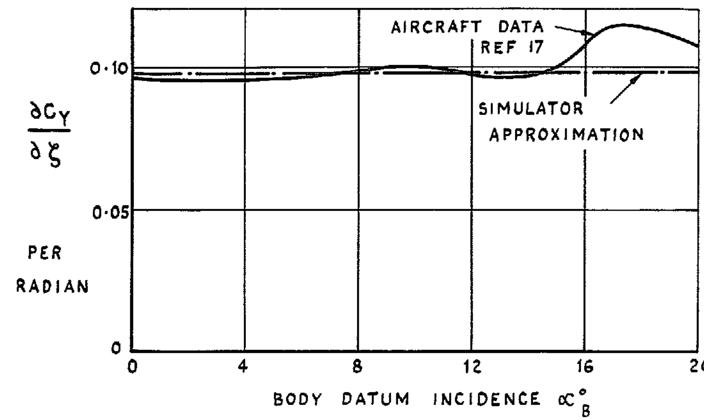



FIG. 39b. Sideforce due to aileron.

FIG. 39. Aerodynamic data used in the simulation. Sideforce derivatives due to the rudder and ailerons.

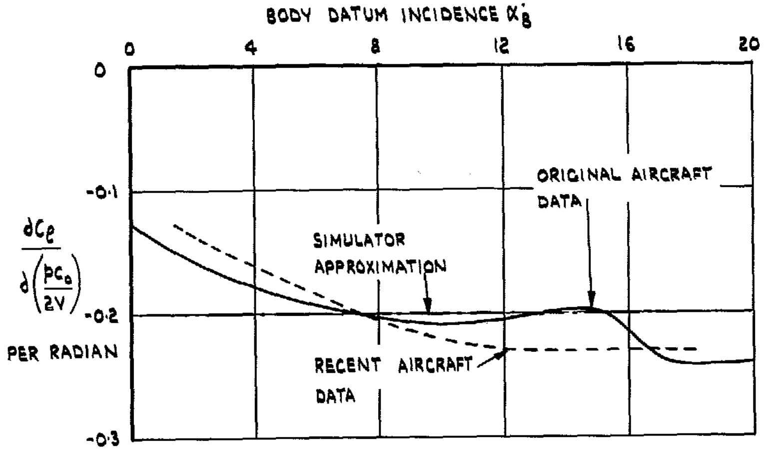



FIG. 40a. Rolling moment due to rate of roll.

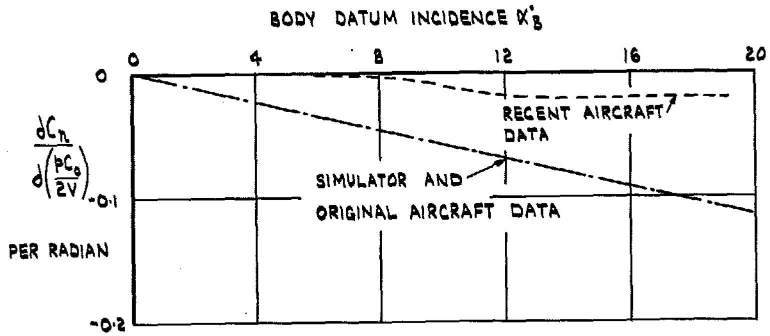



FIG. 40b. Yawing moment due to rate of roll.

FIG. 40. Aerodynamic data used for the simulation. Rolling and yawing moment derivatives due to rate of roll.

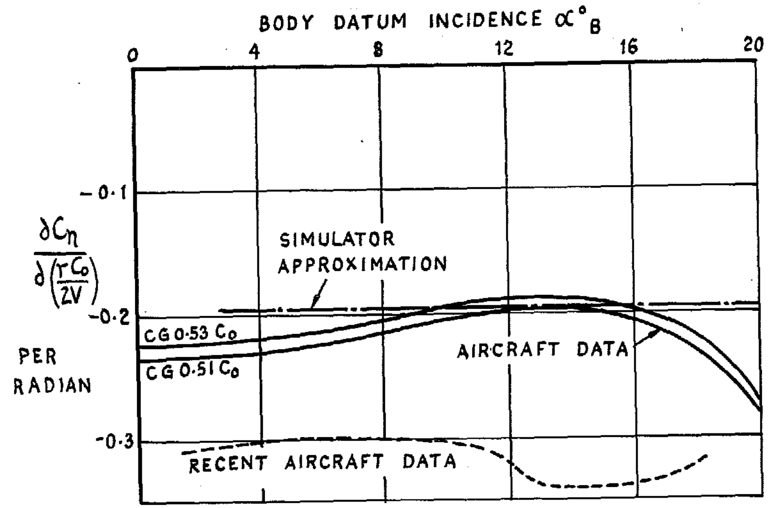



FIG. 41a. Yawing moment due to rate of yaw $\eta_r$.

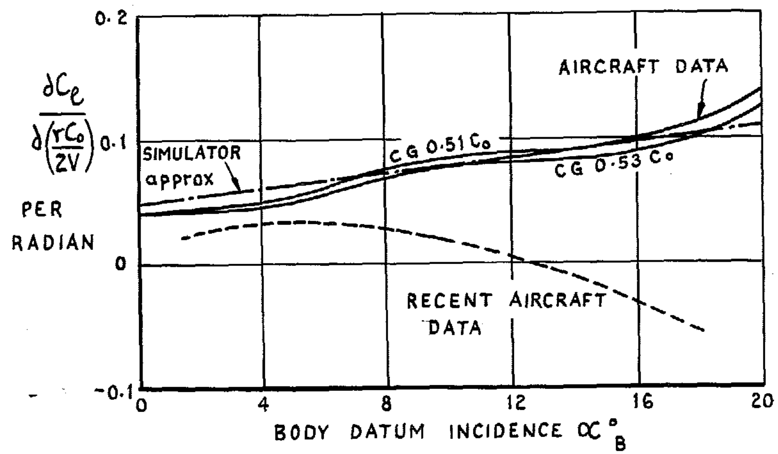



FIG. 41b. Rolling moment due to rate of yaw $l_r$.

FIG. 41. Aerodynamic data used for the simulation. Rolling and yawing moment derivatives due to rate of roll.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