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A Pre-Flight Simulation of the B.A.C. 221 Slender-Wing Research Aircraft

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Summary.

A piloted simulation study of the handling characteristics of the B.A.C. 221 aircraft in the approach configuration was made in preparation for the first flight of the aircraft. The simulation included a simplified representation of the outside visual world, and cockpit motion in pitch and roll.

Values of the aircraft's lateral derivatives and moments of inertia were varied to allow for uncertainties in the predicted aircraft characteristics. Optimum control gearings and centre of gravity position for first flight were also investigated.

The Fairey Delta 2 aircraft, from which the B.A.C. 221 derives, was also simulated to allow comparison with existing flight experience. Since the completion of the simulation the first flight of the B.A.C. 221 has made possible a retrospective assessment of the value of the simulation.

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Section.

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*Replaces R.A.E. Technical Report TR 66 165—A.R.C. 28 859.

CONTENTS—*continued*

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1. *Introduction.*

The B.A.C. 221 is a research aircraft built to study the behaviour of a slender wing shape at both high and low speed. It has been developed from the Fairey Delta 2, a 60° tailless delta wing aircraft[1,2,3,4], by modifications which include a new wing fitted to a lengthened fuselage, and a new undercarriage, but it retains the Rolls Royce Avon RA28 engine and the fin of the Fairey Delta 2. Fig. 1 shows the plan views of the two aircraft and Table 1 compares the geometric and inertia data pertinent to this simulation.

The Fairey Delta 2 is generally judged to be a very demanding aircraft to fly and the modifications into an Ogee wing design give it, in some respects, even more extreme characteristics. It was felt, therefore, that it would be wise to obtain, in advance of first flight, an assessment of the controllability of the B.A.C. 221 on a simulator. The tests were restricted to the approach configuration, as this was expected to be the most critical flight condition. Consequently the simulation covered the speed range up to 175 kt and represented the aircraft with undercarriage locked down and nose fully drooped. One of the aims of the experiment was to find optimum values for the centre of gravity position, the elevator and aileron gearings, and for the approach speed for first flight, since there is a degree of control over these parameters on the aircraft. Certain lateral derivatives and the inertias, were varied to establish the possible effects of errors in wind-tunnel measurements and in estimates of inertias.

Since the Fairey Delta 2, although of a less advanced shape, is clearly sufficiently related to the B.A.C. 221 to make it a useful standard of comparison, it was also simulated to be used as a datum reference. As an unmodified Fairey Delta 2 was still flying at Bedford at the time of the exercise, pilots participating in the simulation were able to obtain a certain amount of direct comparison with flight.

2. *Description of the Aircraft.*

The B.A.C. 221 is a single-seat research aircraft built to study the behaviour of a slender wing at high and low speeds. Fig. 1 shows a plan view of the aircraft and Table 1 lists the dimensional data pertinent to this simulation. The aircraft has several features which might be expected to affect the handling, some affecting the physical environment of the pilot and others affecting the aerodynamic characteristics. Those features which are relevant to the approach configuration are discussed below.

(i) *Sensitivity to lateral turbulence.* As a result of the high value of $(-l_v)$ and the low roll damping and roll inertia, the B.A.C. 221 was expected to be subject to considerable excitation of rolling motion in flight through atmospheric turbulence.

(ii) *Rolling response to ailerons.* Although the rolling power of the ailerons should be very adequate, the dynamic response of the aircraft to lateral control may, nevertheless, be unsatisfactory. As a result of the aileron yawing moment, combined with high $(-l_v)$ and low n_v, there will be a marked hesitation in roll in response to a step aileron input. This is illustrated in Fig. 2 which shows that, after a high initial build up in rate of roll, the rate of roll changes sign, reducing the angle of bank and, for very low values of n_v, the bank angle may even be reversed. This effect might be expected to cause piloting difficulties, but it could be alleviated by using rudder to reduce the sideslip. Fig. 2 also shows that the hesitation becomes more marked as $(-l_v)$ is increased or as n_v is decreased.

(iii) *Speed instability.* Due to the extremely low aspect ratio of the wing, the B.A.C. 221 will be exposed to the well known difficulties of flight below minimum drag speed over a substantial part of the low speed range. In Fig. 3 the speed stability time constant is plotted against speed for this aircraft and for the Fairey Delta 2 in the approach configuration. The minimum boundaries proposed in Ref. 5 for long, visual approaches ('airfield approaches') and for short approaches, where low speed and an accurate touchdown point are at a premium ('carrier type approaches'), are also plotted in Fig. 3. It is clear that the speed control of the B.A.C. 221 in the approach configuration may be less than satisfactory for speeds below 160 kt, and should be significantly worse than that of the Fairey Delta 2.

3. *Description of the Simulator.*

The simulator is described in detail in Ref. 6. The single seat cockpit illustrated in Fig. 4, can be moved through +20 to −10 degrees in pitch and ±15 degrees in roll by hydraulic jacks[6]. The acceleration cues provided by the cockpit movement have previously been shown[6] to assist the pilot in controlling a simulated aircraft. Cockpit motion was used throughout the B.A.C. 221 simulation.

The external visual background used in the simulation is illustrated in Fig. 5. The optical projector[6] producing this display consists of a horizon ring mounted above the cockpit and driven in roll, pitch and yaw from the computer. The shadow of the horizon ring is cast onto a 15 ft radius dome surrounding the cockpit by a small filament lamp. In addition a perspex triangle attached to the projector is driven so as to form a shadow on the screen representing an infinitely long runway, seen during the approach. Pilots found the display realistic and were able to use it down to the initiation of the landing flare. However, from the start of the flare to touchdown the high nose-up attitude of the aircraft and lack of detail in the display made it impossible to judge the hold-off for landing.

The cockpits of both the B.A.C. 221 and Fairey Delta 2 aircraft are so confined that this may interfere with control of the aircraft, especially for larger pilots. An attempt was made to simulate these conditions by padding out the back of the seat of the simulator cockpit, and by fixing the rudder pedals in a position so close to the pilot that his knees were forced up round the control stick.

The layout of the instruments of the B.A.C. 221, Fairey Delta 2 and the simulator, are compared in Fig. 6. Several points of major dissimilarity must be mentioned as having a bearing on the validity of the results. An I.L.S. instrument, absent from the aircraft, was provided in the simulator because pilots had, in previous simulations, complained of being unable to follow an accurate glidepath in the simulator, using only the primary flight instruments and the external visual background. In this connection it should be noted that the Fairey Delta 2 aircraft has no vertical speed indicator.

Throughout the exercise considerable dissatisfaction was expressed about the position of the sideslip instrument in the simulator. In both aircraft the sideslip instrument is so positioned that the pilot will readily register its indication during a normal scan of the blind flying panel; further, the pilot is aware of changes in the indication on this instrument even when he is looking out of the cockpit. In the simulator, on the other hand, the slip instrument was located in such a position that it had to be scanned independently and pilots were frequently unaware of the slip indication, or of changes in the indication, when flying, either on instruments, or when using the external visual background. Full scale deflection of the aircraft instrument corresponds to ±5° of slideslip; in the simulator full scale deflection corresponded to ±10° of slip. Unfortunately it was not possible to change the scaling of the instrument, or to reposition it closer to the other instruments, in the time available for the tests.

Filtered white noise, representing a turbulence power spectrum, was introduced into the computer to represent the lateral and vertical components of atmospheric turbulence[6]. Except where noted in the text the turbulence level was 3 fps rms. Low altitude turbulence is likely to be 3 fps or less on some 240 days per year[7], and so this turbulence level was taken to represent reasonable operating conditions for a research aircraft. In general pilots found the turbulence presentation realistic, though one R.A.E. pilot felt the vertical component to be more pronounced than the horizontal one.

The general purpose analogue computer[6] was programmed to solve the flight equations in six degrees of freedom[8], over the range from 100 to 175 kt. Dynamic pressure varied correctly with speed and, where appropriate, non-linear variations of derivatives were simulated.

4. *Conduct of the Experiment.*

Pilots were asked to make straight in, visual approaches at 150 kt from 1500 ft on a 3° glide path. A raw I.L.S. instrument was provided to compensate for the visual and motion cues which in the simulator were poor in comparison with flight[6]. No specific instruction was given as to the method of control during the approach, but most pilots flew predominantly on instruments down to 400 ft, then predominantly on the external visual background to the initiation of the flare. Several approaches were flown 'in cloud'* down to 300 ft, but control of the approach on instruments only was found to be a much more difficult task.

The exercise comprised a total of 31 hours of simulation by three R.A.E. and two British Aircraft Corporation (B.A.C.) pilots, including 2 hours of preliminary assessment. One B.A.C. pilot had flown the Fairey Delta 2 about $2\frac{1}{2}$ years before the simulation. During the simulation the unmodified Fairey Delta 2 became serviceable and was flown by one of the R.A.E. pilots (pilot 'B' of Fig. 9) taking part in the exercise. Since the end of the exercise all but one of the pilots have flown the Fairey Delta 2 and two of the pilots have also flown the B.A.C. 221.

In addition to the principal subjects, three other R.A.E. pilots spent one hour each in the simulator.

To cover the possibility of errors in wind-tunnel data used, the more critical lateral derivatives of the B.A.C. 221 were varied during the simulation. Because of the difficulty of making accurate estimates of the inertias, the effects of fairly gross changes in these parameters was also investigated. Details of these changes, and of the range of centre of gravity positions, are given in Table 2, and the effects of the changes on handling are discussed in Section 5.2.

The Fairey Delta 2 was simulated to provide a basis for comparison of the B.A.C. 221. It must be noted, however, that the simulation of the Fairey Delta 2 was of a very much lower standard than is normally achieved on the Aero Flight simulator, due to lack of time and computing equipment. The representation of the aircraft was, nevertheless, considered good enough to make comparisons valid. The Fairey Delta 2 simulation is discussed in Sections 5.3 and 5.4.

The possible fitting of an engine nozzle designed to improve the high-speed performance of the B.A.C. 221 may reduce the maximum thrust available at low altitude and low speed to 60 per cent of the value given in Table 1. Pilots were asked to assess the safety of baulked landings, with the reduced thrust, at a range of speeds below 170 kt. The results of this exercise are discussed in Section 5.5.

5. *Discussion of Results.*

A simulation of this type, designed principally as a handling assessment, produces few quantitative results which can be analysed and discussed. Although an attempt was made to analyse the records of simulated flights statistically, no conclusive results were obtained from the analysis. In the limited amount of records available for analysis, the effects of changes in the assumed data were masked by the random variations in turbulence. For the most part, the only tangible result of this type of simulation is pilots' assessment, expressed as verbal appraisal and criticism. No attempt was made to associate such appraisal with the grades of a pilot opinion rating scale, such as the familiar Cooper scale, since a scale appropriate to the special requirements of a research aircraft was not felt to be sufficiently well established.

The results must be interpreted in the light of the role in which the aircraft is to be used. The B.A.C. 221 is a research aircraft which need not satisfy the more stringent handling requirements of, for example, a service aircraft; it is to be flown only by test pilots with above average skill, and can be restricted to operations in favourable weather conditions.

*An impression of flying through cloud is given by extinguishing the lamp on the visual display and replacing this by diffuse light in the dome.

5.1. *General Discussion.*

Pilots felt that the main impression gained from this simulation was that there should be few problems flying the B.A.C. 221, at least in the favourable meteorological conditions proposed for the first test flights. The aircraft was, however, sensitive to turbulence and to control inputs so that, even in still air, the pilot had to work throughout the approach to maintain the flight path. Control of pitch attitude was no problem, but speed control in turbulence required some attention. Lateral and directional control demanded constant concentration, a condition which was probably exaggerated on the simulator by the lack of sufficiently compelling cues as to the large amounts of sideslip developing as a result of lateral control. As sideslip built up, the rolling effect of the ailerons was reduced, until, at large sideslip angles, full aileron control would not roll the simulated aircraft towards the sideslip; this confirmed the predictions of Section 2, illustrated in Fig. 2. This characteristic caused the pilots some trouble in the simulator, but they were confident that, with improved sideslip information, 'instinctive'* use of rudder to reduce the sideslip would bring an improvement in lateral control. It should be noted here that no sideslipping motion cues were presented in the simulator.

Lateral control deteriorated as the turbulence level was increased until the aircraft was barely under control in turbulence of 6 fps rms.

Both the simulated Fairey Delta 2 and B.A.C. 221 were felt to represent aircraft which it would always be possible, if at times unpleasant, to fly. Pilots were agreed that the handling characteristics were acceptable for a research aircraft. Fig. 7 shows time histories of part of an approach in turbulence at 150 kt in the simulated B.A.C. 221. The elevator, aileron and rudder traces show that the pilot was working hard to achieve only very moderate control over angle of bank, sideslip and incidence. However, pilots were confident that they were in full control of the simulated aircraft during such approaches, and that they could increase their effort to gain more precise control for the flare and landing.

Approaching at speeds below 150 kt made the lateral task slightly more difficult, but the most noticeable effect on handling was in speed control which became increasingly difficult as the approach speed was reduced. The rapid increase in speed instability for speeds below 150 kt is shown in Fig. 3. At 135 kt, speed control was demanding sufficient attention to debase the pitch attitude and lateral-directional control. The high nose-up attitude of the simulated aircraft approaching at 135 kt also affected pitch attitude control, in that the pilot was reluctant to make nose-up pitch changes which would bring the nose of the aircraft above the horizon. Approaching at 160 kt, speed holding was very easy, enabling the pilot to concentrate his attention on pitch and lateral-direction control. Elevator and incidence time histories for simulated B.A.C. 221 approaches at 135 kt, 150 kt and 160 kt are shown in Fig. 8. The length of record (20 sec) is so short as to frustrate attempts to apply statistical techniques; however, the records strongly support the view that longitudinal control becomes increasingly difficult as the approach speed is reduced.

5.1.1. *Control gearings.* The elevator and aileron controls of both the Fairey Delta 2 and the B.A.C. 221 are fitted with variable gearing devices. The pilot can select, in flight, any aileron gearing between 1:1 (full stick travel gives maximum control surface movement) and 6:1 (full stick travel gives 1/6 maximum control surface movement), and any elevator gearing between 1:1 and 9:1.

For the simulated B.A.C. 221 pilots generally preferred an aileron gearing of 2:1, with the 1·5:1 gearing noticeably, but not significantly, worse. The 3:1 aileron gearing was, if anything, a little more pleasant for making small corrections, and for controlling small gusts, but pilots occasionally hit the aileron stops when controlling large gusts and when making large corrections. The 4:1 aileron gearing made control almost impossible because of the limited control power then available. The preferred aileron gearing was affected by changes in the value of l_v from the nominal value (*see* Section 5.2.3). With rms turbulence values of $4\frac{1}{2}$ fps and 6 fps the 2:1 aileron gearing became inadequate to control the larger gusts and the 1·5:1 gearing was necessary.

*'Instinctive', in this context, is used to imply that conscious judgement is not required, that is, that the situation requires a habitual response.

At the datum position of the centre of gravity the 2:1 elevator gearing was generally preferred, though two of the bulkier pilots found the stick to be uncomfortably close to them. An elevator gearing of 1·5:1 made the control slightly too sensitive, while gearings of 3:1 and 4:1 moved the stick uncomfortably close to the pilot. The optimum elevator gearing was, however, affected by the position of the centre of gravity (*see* Section 5.2.1).

It may be worth noting that the gearings used on the Fairey Delta 2 aircraft in the approach configuration are 2:1 for both elevator and aileron.

5.2. *Effect of Variations in the Characteristics of the B.A.C.* 221.

5.2.1. *Variations in the position of the centre of gravity.* The centre of gravity was varied over the range from 3·39 per cent $\bar{c}$ forward of the position for the datum case to 1·65 per cent $\bar{c}$ aft, the discrete values tested being shown in Fig. 9. Fig. 10 shows the curves of pitching-moment coefficient *versus* incidence at the extreme and datum positions of the centre of gravity. The effect of change in the centre of gravity on the lateral derivatives was ignored since they are within the 10 per cent variations discussed in Section 5.2.3.

Fig. 9 shows the pilots' comments on the centre of gravity variations. With the reduction in the longitudinal stability as the centre of gravity was moved aft, the simulated B.A.C. 221 became more difficult to handle, till at the aft ballast limit it was longitudinally unstable, and pilots felt that control might be lost at any instant. The additional concentration required for pitch attitude control resulted also in a debasement of lateral and directional control. Forward movement of the centre of gravity from the datum position made much less difference to the handling qualities of the simulated aircraft than aft movement, though progressively larger elevator movements were required for glide path corrections. At the forward ballast limit, a 1·5:1 elevator gearing was necessary for precise control. The greatest change resulting from the forward movement of the centre of gravity was in the stick position. As more back stick was needed to trim the aircraft the stick came uncomfortably close to the pilot and to the back elevator stop. At the forward ballast limit a 1:1 elevator gearing was needed to bring the stick into a comfortable position and to allow sufficient back stick for safe control.

5.2.2. *Variations in aircraft inertia.* The rolling, pitching and yawing inertias (with respect to body datum axes) were varied by ± 20 per cent. None of these changes made a significant difference to the handling of the simulated aircraft, and only three were distinguishable to the pilots from the datum configuration, namely:

1. Reduction in roll inertia, I_{xx}, by 20 per cent to 6728 slug ft^2. The simulated aircraft was slightly more lively in roll, though no less pleasant to fly.
2. Increase in yaw inertia, I_{zz}, by 20 per cent to 65 095 slug ft^2. This configuration required slightly harder work on the rudder to co-ordinate turns.
3. Decrease in both pitching and yawing inertias by 20 per cent to 39 831 slug ft^2 and 43 397 slug ft^2 respectively. The simulated aircraft seemed to be slightly more lively laterally and directionally, and consequently slightly less pleasant to fly.

Changing the product of inertia term, I_{xz}, is equivalent to changing the inclination of the principal inertia axes with respect to the body-datum axes. Increasing the inclination of the principal inertia axes from 1° 31′ to 2° 39′, nose down, made no detectable difference to the handling of the simulated B.A.C. 221.

5.2.3. *Variations in lateral derivatives.* Table 2 summarises the derivatives varied, and the range of the variations, while Figs. 11 and 12 show in more detail changes in the derivatives l_v, n_v and l_p. None of the changes in the lateral derivatives made the aircraft uncontrollable, though some increased the problems of lateral control.

The changes in the yawing moment due to rate of roll derivative, n_p, made no detectable difference to the handling. Changes in the yawing moment due to rate of yaw derivative, n_r, were detectable as a slight change in yaw damping but were considered to make no significant change in the handling.

Increasing the magnitude of the rolling moment due to rate of roll derivative, l_p, to $-0{\cdot}266$ in body axes (from $-0{\cdot}225$) reduced the rolling response to turbulence, while leaving perfectly adequate aileron response; pilots considered this damping the most satisfactory of the three values tested. Decreasing $(-l_p)$ to 0·184 made the simulated aircraft more lively in roll, but the difference was very hard to detect. Neither change was thought to make a significant change in handling. Fig. 13 shows the time histories of aileron angle for approaches at 150 kt in turbulence with three values of l_p. Statistical analysis of time histories of angle of bank and aileron revealed no consistent differences between the three levels of roll damping, at least over the length of record analysed (30 sec).

Fig. 11 shows the variation of the yawing moment due to sideslip derivative (in body axes), n_v, with incidence, for the datum case and for the two other cases considered. When n_v was reduced to zero the difference in handling was not marked, but the rudder appeared to be slightly more effective and aileron had to be held on for slightly longer periods of time when making corrections. It should be noted that a zero value for n_v in body axes corresponds to a value of $+0{\cdot}03$ for n_{v_s} in stability axes. An increase in n_v from the datum value of $+0{\cdot}015$ to $+0{\cdot}0293$ (body axes) made a barely detectable difference, but there was a feeling that less rudder was needed to co-ordinate aileron.

It may be of interest to note that after the completion of the simulation, but before the first flight of the aircraft, further wind-tunnel data became available which gave negative values for n_v in body axes, that is values lying outside the range studied in the simulation. These values are also shown in Fig. 11. The predicted rolling response to a step aileron input for the aircraft with negative n_v is shown in Fig. 2, and gave rise to some anxiety. To ensure that the predicted n_v for the first flight configuration of the actual aircraft should be not less than $+0{\cdot}015$ (equivalent to $+0{\cdot}045$ in stability axes), the centre of gravity was moved forward and the nose-wheel undercarriage doors were replaced by half doors, prior to the first flight; in the event, wind-tunnel measurements of n_v proved to be pessimistic.

Changes in the value of the rolling moment due to sideslip derivative in body axes, l_v, had the most marked effect on the handling of the simulated B.A.C. 221. Decreasing $(-l_v)$ to 0·1296 (Table 2 and Fig. 11) eased the problem of lateral control noticeably; lateral corrections could be made using smaller aileron inputs, and there was less build up of slideslip during the corrective manoeuvres. Changing the aileron gearing from 2:1 to 1·5:1 with decreased $(-l_v)$ made the simulated aircraft too sensitive to aileron control inputs. Increasing $(-l_v)$ to 0·1584 (Table 2 and Fig. 11) demanded larger aileron inputs. With the 2:1 aileron gearing pilots frequently hit the aileron stops. The combination of increased $(-l_v)$ and 2:1 aileron gearing was felt to be unacceptable for flight in turbulence. With increased $(-l_v)$ and 1·5:1 aileron gearing, sufficient control was available for large lateral corrections, but there was a tendency to overcontrol when making small adjustments. Increased $(-l_v)$ made lateral control significantly more difficult but, with 1·5:1 aileron gearing, by no means impossible.

Time histories of aileron angle for approaches in turbulence at 150 kt with the three values of l_v studied are shown in Fig. 14. Comparison of the mean modulus aileron angle, the mean modulus bank angle and the number of times bank angle exceeded 5° revealed no statistically significant differences between the three values of l_v, at least over the length of record analysed (45 sec).

5.3. *Comparison of the Simulated B.A.C.* 221 *and Fairey Delta* 2.

Table 1 and Fig. 1 compare the dimensional data of the B.A.C. 221 and Fairey Delta 2, while Figs. 15 to 20 compare some of the aerodynamic derivatives. Fig. 17 illustrates the principal differences between the two aircraft: namely the shallower slope of the curve of l_v *versus* incidence and the larger positive values of n_v of the Fairey Delta 2. Trim incidence for the Fairey Delta 2 on a 3° glide path at 150 kt is about 10° compared with about 12° for the B.A.C. 221.

Pilots found little to choose between the two simulated aircraft in controlling longitudinal motions, though speed control of the simulated Fairey Delta 2 was perhaps a little easier. Because the ailerons induced less sideslip on the simulated Fairey Delta 2 than on the simulated B.A.C. 221, lateral control of the Fairey Delta 2 was noticeably easier, requiring smaller aileron angles and less need to co-ordinate aileron inputs with rudder. The smaller sideslips developed in flying the simulated Fairey Delta 2 had two main consequences:

(i) Lateral control was less tiring, since less aileron was required and control was needed for only a short period of time.

(ii) There was less chance of the simulated aircraft flying into a large gust while aileron was being held on, and consequently less danger of an uncontrollable situation arising.
Despite these differences, the overall impression was that the handling characteristics of the two simulated aircraft were very similar, but that the Fairey Delta 2 was slightly easier to control than the B.A.C. 221.

5.4. *Comparison between the Simulated Fairey Delta 2 and the Actual Aircraft.*

Flight and simulator traces for the Fairey Delta 2 in two particular conditions, namely during an approach in moderate turbulence, and performing a sidestep manoeuvre on the approach, are available for comparison (Figs. 21 and 22 respectively). They show a general similarity, except in the use of rudder and in incidence angles. Though there is, as yet, no evidence to support the view, it seems likely that the differences between flight and simulator in rudder and in incidence are due to lack of adequate cues in the simulator, and do not reflect inadequacies in the flight equations used in the simulator. Nonetheless, the Fairey Delta 2 aircraft was thought, by the two pilots who had flown it, to be reasonably well represented by the simulation.

The simulated Fairey Delta 2 was, however, judged to be *easier* to fly than the actual aircraft. This is contrary to general experience since, because of poor motion and visual cues, pilots often find greater difficulty in flying a simulator. In this particular case it was thought that the simulated Fairey Delta 2 was easier to fly than the real aircraft for two main reasons:

(i) The Fairey Delta 2 aircraft in the approach configuration appears to have negative directional stability for small angles of sideslip. Pilots report that the aircraft appears to have two stable sideslipped conditions, one on each side of zero. When any lateral correction is made the aircraft sideslips to one of the stable positions, and any attempt to remove this sideslip tends to result in overshooting zero slip to the other stable position. There is also a considerable change in longitudinal trim with sideslip, and this accentuates the problems discussed in (ii) below. These characteristics were not represented on the simulator as they were not indicated by the available wind-tunnel data.

(ii) The power controls of the Fairey Delta 2 aircraft are not entirely satisfactory, and in particular the elevator control surface 'creeps' towards its final position over a period of a few seconds after a stick input. This characteristic was not represented on the simulator. Pilots report that it is very difficult to trim the aircraft in flight, so that approaches are generally made with the aircraft slightly out of trim. On the few occasions when long, trimmed approaches were achieved in flight, the longitudinal handling of the aircraft appeared to the pilot much more like that of the simulated Fairey Delta 2. Further, corrective elevator movements on the approach are made with such frequency that the control surface can seldom complete its 'creep' for one stick input before the next stick movement is made. As a result the pilot feels that the link between the stick and the control surface is not unique.

One of the pilots taking part in this simulator exercise first flew the Fairey Delta 2 two weeks after the end of the simulation. For this pilot, at least, the Fairey Delta 2 simulation served as a pre-flight exercise. He reported that his experience of the simulated aircraft was invaluable, and that the characteristics of the Fairey Delta 2 were well represented, but thought that there were differences in detail between the aircraft and the simulation. Extracts from his notes, made after conversion to the aircraft, are appended to this Report (Appendix A).

Overall, pilots thought the simulated B.A.C. 221 was slightly more difficult to fly than the simulated Fairey Delta 2, but slightly less difficult to fly than the Fairey Delta 2 aircraft.

5.5. *Reduced Thrust Baulked Landings on the B.A.C.* 221.

Reducing maximum available thrust to 60 per cent also reduced the throttle sensitivity to 60 per cent, and this increased the problems of speed control during approaches at speeds below 150 kt. No problems were experienced in overshooting from baulked landings at speeds down to 140 kt; loss of height from the initiation of the overshoot was about 10 ft. When overshoots were initiated at 130 kt the simulated aircraft took rather a long time to climb away, and there was a tendency to over-rotate, so that speed built up very slowly. Pilots considered that, with this reduced thrust, overshoots at 130 kt were only marginally safe and should not be initiated below about 100 ft. Overshoots initiated at 125 kt would be dangerous below about 400 ft.

6. *Conclusions.*

The handling characteristics of the B.A.C. 221 in the approach configuration, as represented by this simulation, were found to be satisfactory for its role as a research aircraft. The simulated Bristol 221 had characteristics similar to those of the Fairey Delta 2. Pitch attitude control presented no problems, and speed control was good on approaches at speeds of 150 kt or more, but deteriorated as the approach speed decreased. Lateral-directional control required constant attention; the large amounts of slideslip which built up whenever aileron was used had to be countered with rudder.

Pilots found the optimum gearing of both aileron and elevator to be 2:1, that is, full stick deflection gives $\frac{1}{2}$ maximum control surface movement.

Of the variations in the characteristics of the simulated B.A.C. 221 summarised in Table 2, only the variation of the rolling moment due to sideslip derivative, l_v, made a significant change in the handling characteristics. Though increasing $(-l_v)$ to 0·1584 (from 0·144) debased the lateral-directional control of the simulated aircraft, the handling was still considered satisfactory, at least with 1·5:1 aileron gearing.

Baulked landings with the maximum thrust reduced to 60 per cent were safe when initiated at 140 kt and above, and possible, though increasingly dangerous, when initiated at speeds down to 125 kt.

7. *Postscript Comparing the Simulated B.A.C.* 221 *with the Aircraft.*

The first flight of the B.A.C. 221 took place in April 1964, four months after the completion of the simulation. The first flight by an R.A.E. pilot took place 9 months after the simulation and it was also nine months after the simulation before the aircraft was first manoeuvred at speeds below 170 kt with undercarriage down and nose droped, i.e. in the regime covered by the simulation.

While the long time interval and intervening flight experience, (particularly experience in the Fairey Delta 2), make detailed comparison of the simulation with flight very difficult, the general impression was that the handling characteristics of the aircraft and the simulated B.A.C. 221 were fairly similar. The aircraft exhibited the sensitivity to lateral turbulence, the need to use rudder with aileron, and the speed instability predicted by the simulation. In particular, with the B.A.C. 221 there were none of the discrepancies between the predicted and actual handling characteristics which marked the comparison between the simulated and the actual Fairey Delta 2 (*see* Section 5.3 and Appendix A). One may, therefore, conclude that the simulation represented all the significant characteristics of the aircraft faithfully, in form if not in degree, and thus, that the handling assessments of the simulation had a useful degree of validity.

No.	*Author(s)*	*Title, etc.*
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2	R. Rose	Flight measurements of the low speed drag in the approach configuartion of a 60° Delta wing research aircraft (Fairey ER.103). R.A.E. Tech. Note No. Aero 2599, (A.R.C. 21183). January 1959.
3	R. Rose	Flight measurements of the Dutch roll characteristics of a 60° Delta wing aircraft (Fairey Delta 2) at Mach numbers from 0·4 to 1·5 with stability derivatives extracted by vector analysis. A.R.C. C.P. 653. March 1961.
4	F. W. Dee	Flight measurements at subsonic speeds of the aileron rolling power and lateral stability derivatives l_v and y_v on a 60° Delta wing aircraft (Fairey Delta 2). A.R.C. C.P. 739. June 1963.
5	D. Lean and R. Eaton ..	The influence of drag characteristics on the choice of landing approach speeds. A.R.C. C.P. 433. April 1957.
6	D. H. Perry and J. M. Naish ..	Flight simulation for research. J. R. aero. Soc., Vol. 68, No. 646. October 1964.
7	J. K. Zbrozek	The relationship between the discrete gust and power spectra presentations of atmospheric turbulence with a suggested model of low-altitude turbulence. A.R.C. R. & M. No. 3216. March 1960.
8	R. M. Howe	Co-ordinate systems for solving the three-dimensional flight equations. WADC T.N. 55–747. June 1956.

APPENDIX

Comparison of the Behaviour of the Simulated Fairey Delta 2 with initial Impressions obtained in Flight by Flt. Lt. C. C. Rustin, R.A.E. Bedford.

As part of a simulator programme to assess the handling qualities of the B.A.C. 221 prior to first flight, the Fairey Delta 2 was also simulated to provide a reference for comparison with existing flight experience. For this particular pilot, however, initial conversion onto the Fairey Delta 2 aircraft did not take place until two weeks after the end of the simulation programme, so that for him, at least, the Fairey Delta 2 simulation was in the nature of a pre-first flight exercise. The following comments are extracted from notes made after his conversion onto the aircraft:

After three conversion sorties in the Fairey Delta 2 aircraft the overall impression was that the simulator had reproduced the general dynamic characteristics of the aircraft quite well but that, nevertheless, the simulated aircraft did not feel completely like the aircraft. The differences are largely in detail and as a whole it was considered that the simulator provided valuable pre-flight experience, so that the peculiar handling characteristics of the Fairey Delta 2 did not come as a surprise. The differences between the handling in flight and in the simulated aircraft were principally:

(1) The aircraft felt much more lively and more like a small aeroplane than the simulator.

(2) The aircraft seemed to develop sideslip more frequently and for longer periods either side of zero.

(3) In the aircraft the sideslip was more difficult to control smoothly and demanded a higher rudder work load.

(4) In the aircraft large sideslip angles led to loss of aileron control, as in the simulator, but this was more disturbing.

(5) In the aircraft there was a marked change of longitudinal trim with sideslip. This was not detected at all in the simulator.

These apparent differences were thought to arise partly because of actual differences in the control and aerodynamic characteristics represented, but largely because motion cues available in the air were not fully or accurately reproduced in the simulator. The most significant motion of the Fairey Delta 2 in flight was its directional behaviour with continuous but random sideslips. Although the sideslip behaviour was the predominant feature, its occurrence affected the lateral control principally through its effect on roll power. With large sideslip angles it was not possible, using ailerons alone, to roll the aircraft towards the sideslip.

The sideslip gauge in the simulator was scaled to show 5° at only half deflection as against full scale in the aircraft. The sideslip gauge was relatively a long way from the rest of the flight instruments in the simulator and did not readily fall into the normal scan pattern. Thus in the simulator if a random sideslip occurred but was not observed on the sideslip gauge it could well have passed unnoticed if no lateral correction was required during the period of slip. In the aircraft sideslip and the random lateral and directional behaviour could be easily detected by:

(a) The pronounced yawing motion of the aircraft. It would be difficult to say how much of this was felt through a direct yawing acceleration and how much through a lateral acceleration due to the sideslip.

(b) At slip angles near 5° the air flow could be heard buffeting on the cockpit canopy.

(c) The sideslip needle was nearly always in the field of vision (visual and instrument flight) and showed full scale deflection at 5°. Instruments at full scale tend to attract more attention.

(d) There was quite a marked change of longitudinal trim with sideslip. This drew attention to the fact that something was happening even if the slip had not been noticed.

(e) When close to the ground near to the flare point the slip could be detected by reference to the lines of motion on the ground.

Thus in the aircraft any yaw produced either as a result of turbulence or aileron inputs was immediately detected. This had two main manifestations:

(1) The aircraft felt more untidy directionally in flight than in the simulator.

(2) Errors could be spotted and corrections applied more rapidly in flight than in the simulator.

In general the motion of the aircraft felt more lively about all axes and particularly the longitudinal motion which was felt through the seat of the pants and was not obvious visually. Speed holding on the approach was slightly better in the aircraft than in the simulator and smaller throttle movements were required. This was probably because:

(a) the engine reponse was more sensitive in the aircraft, and

(b) the aircraft's physical response to throttle movements could be easily detected through longitudinal accelerations.

The visual cues available in the aircraft were obviously better than those in the simulator using the shadowgraph display. Approaches in the aircraft were primarily visual whereas simulator approaches were essentially instrument. The improved visual display of the real world, which gives better attitude information, again led to the initial feeling that more was happening to the aircraft. Equally, however, it was much easier at any stage to assess the progress of the approach and thus although in general the work load was higher in the aircraft it did not feel proportionally more difficult.

In conclusion it may be stated that these differences, which at first felt marked, soon appeared to lessen as experience was gained, and in fact were largely differences only in detail. The actual dynamic motions of the aircraft were fairly well represented in the simulator, so that the peculiar handling characteristics did not come as a surprise, although the aircraft felt somewhat different. The simulator exercise was thus considered to have provided invaluable pre-flight experience.

The overall effect of the lack of motion cues and of the control characteristics was to make it feel as though the aircraft was more untidy laterally and directionally, and generally more lively especially longitudinally. Although demanding more effort, the aircraft was not significantly more difficult to fly.

TABLE 1

Dimensions and Inertia Data for the B.A.C. 221 and Fairey Delta 2 Aircraft Pertinent to the Simulation.

		B.A.C. 221	Fairey Delta 2
WING			
Area	S	446·7	360 ft^2
Span	b	25	26·83 ft
Aerodynamic mean chord	$\bar{\bar{c}}$	21·01	16·75 ft
Geometric mean chord	$\bar{c}$	17·87	13·42 ft
WEIGHT, etc.			
All-up weight on approach	W	16 000	12 500 lb
Mass on the approach	m	496·9	389 slug
Maximum available thrust	T	9500	9500 lb
Maximum thrust (baulked landing)		5700	— lb
Centre of gravity position (forward of Hunting datum position)		164·62	134·40 inch
INERTIAS with respect to body axes			
Rolling moment of inertia	I_{xx}	8410	6600 slug ft^2
Pitching moment of inertia	I_{yy}	49 789	24 800 slug ft^2
Yawing moment of inertia	I_{zz}	54 246	33 000 slug ft^2
Product of inertia	I_{xz}	1200	600 slug ft^2
Inclination of the principal inertia axes to the body datum axes		1° 31′	1° 19′ nose down

TABLE 2

Parameters varied in the B.A.C. 221 Simulation

	Values at 12° incidence		
	Maximum	Datum	Minimum
Rolling moment due to sideslip derivative, l_v (*see* Fig. 11)	−0·1296	−0·1440	−0·1584
Rolling moment due to rate of roll derivative, l_p (*see* Fig. 12)	−0·184	−0·225	−0·266
Rolling moment due to rate of yaw derivative, l_r	0·0836	0·0760	0
Yawing moment due to sideslip derivative, n_v (*see* Fig. 11)	0·0293	0·0150	0
Yawing moment due to rate of roll derivative, n_p	0·003	0·003	0
Yawing moment due to rate of yaw derivative, n_r	−0·4170	−0·4335	−0·4500
Rolling inertia, I_{xx} (slug ft^2)	10 092	8410	6728
Pitching inertia, I_{yy} (slug ft^2)	59 747	49 789	39 831
Yawing inertia, I_{zz} (slug ft^2)	65 095	54 246	43 397
Product of inertia, I_{xz} (slug ft^2)	2102	1200	1200
Inclination of principal inertia axes (nose down)	2° 39′	1° 31′	1° 31′
Centre of gravity (per cent of $\bar{\bar{c}}$ from datum) Figs. 9 and 10	+3·39% fwd	—	−1·65% aft

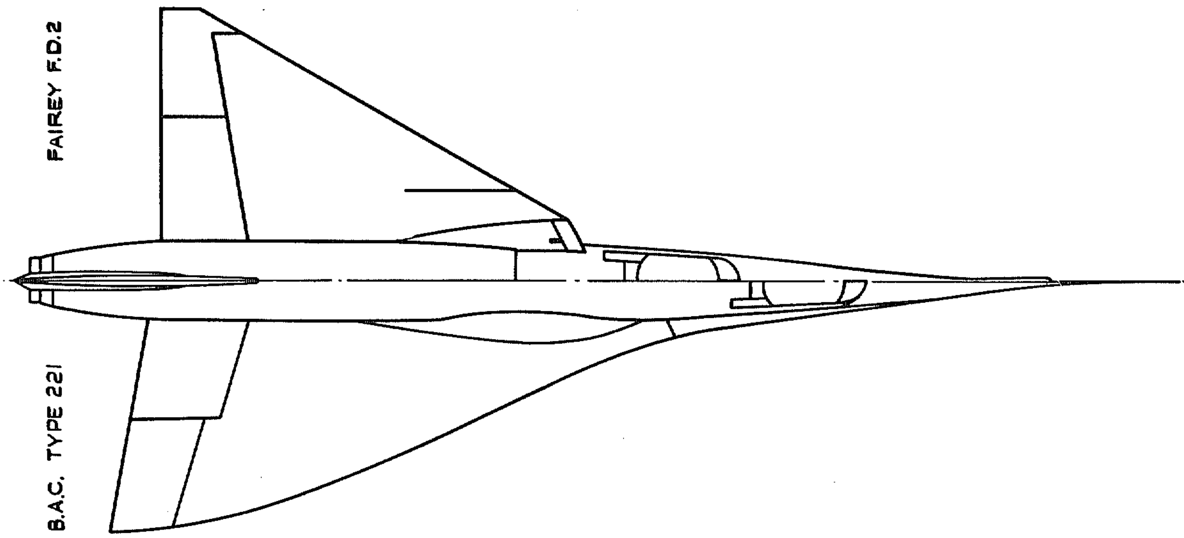

FIG. 1. Comparison of Fairey Delta 2 and B.A.C. 221 plan views.

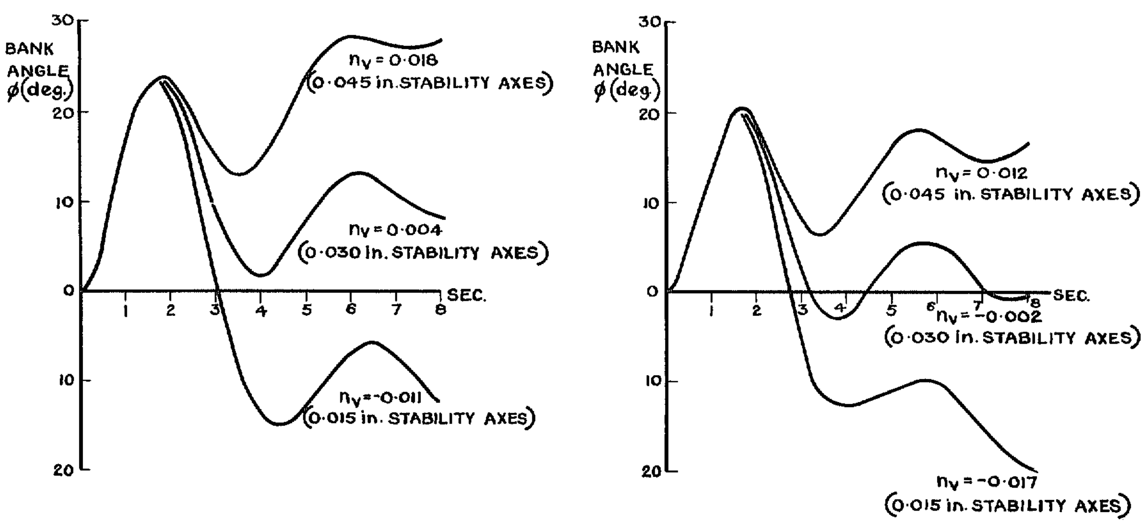

FIG. 2(a) l_v = -0·128 FIG. 2(b) l_v = -0·155

FIG. 2. B.A.C. 221 response to a 3° step aileron input for several values of l_v and n_v in body axes (analogue computer study).

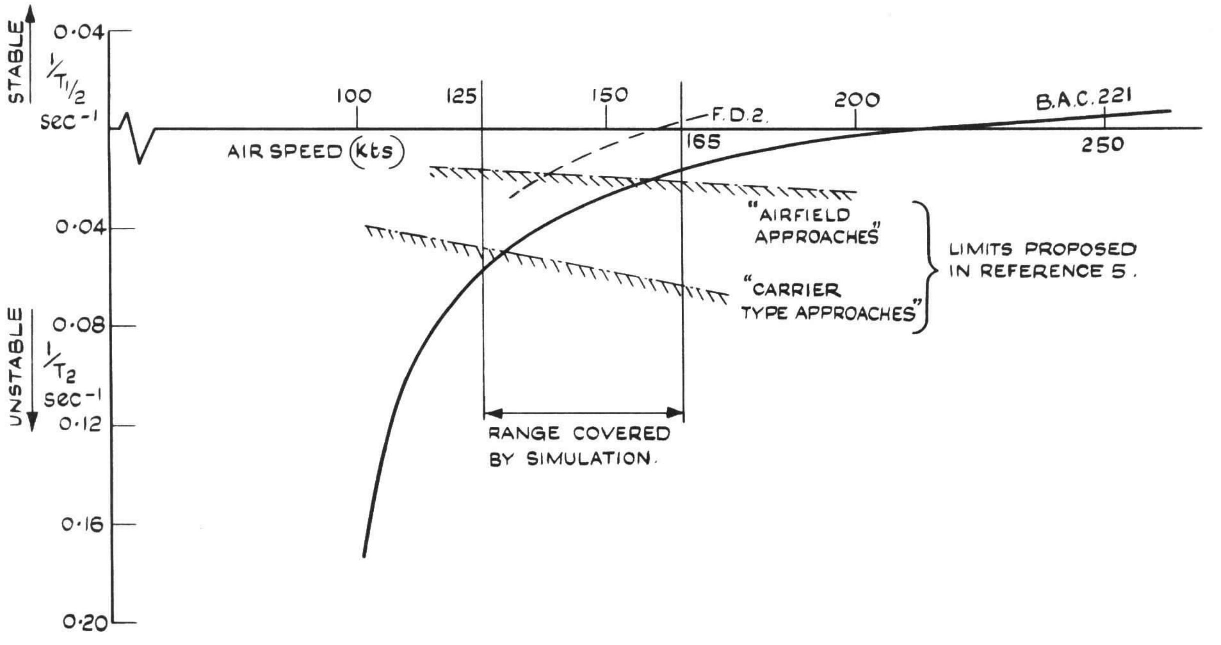

FIG. 3. Variation of speed stability time constant with speed for the B.A.C. 221.

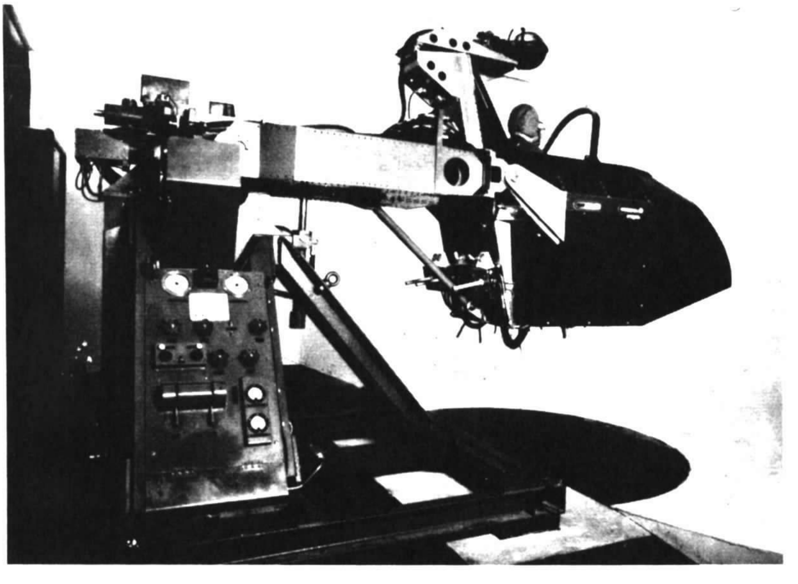

FIG. 4. Side view of cockpit and moving mechanism of Aero Flight simulator.

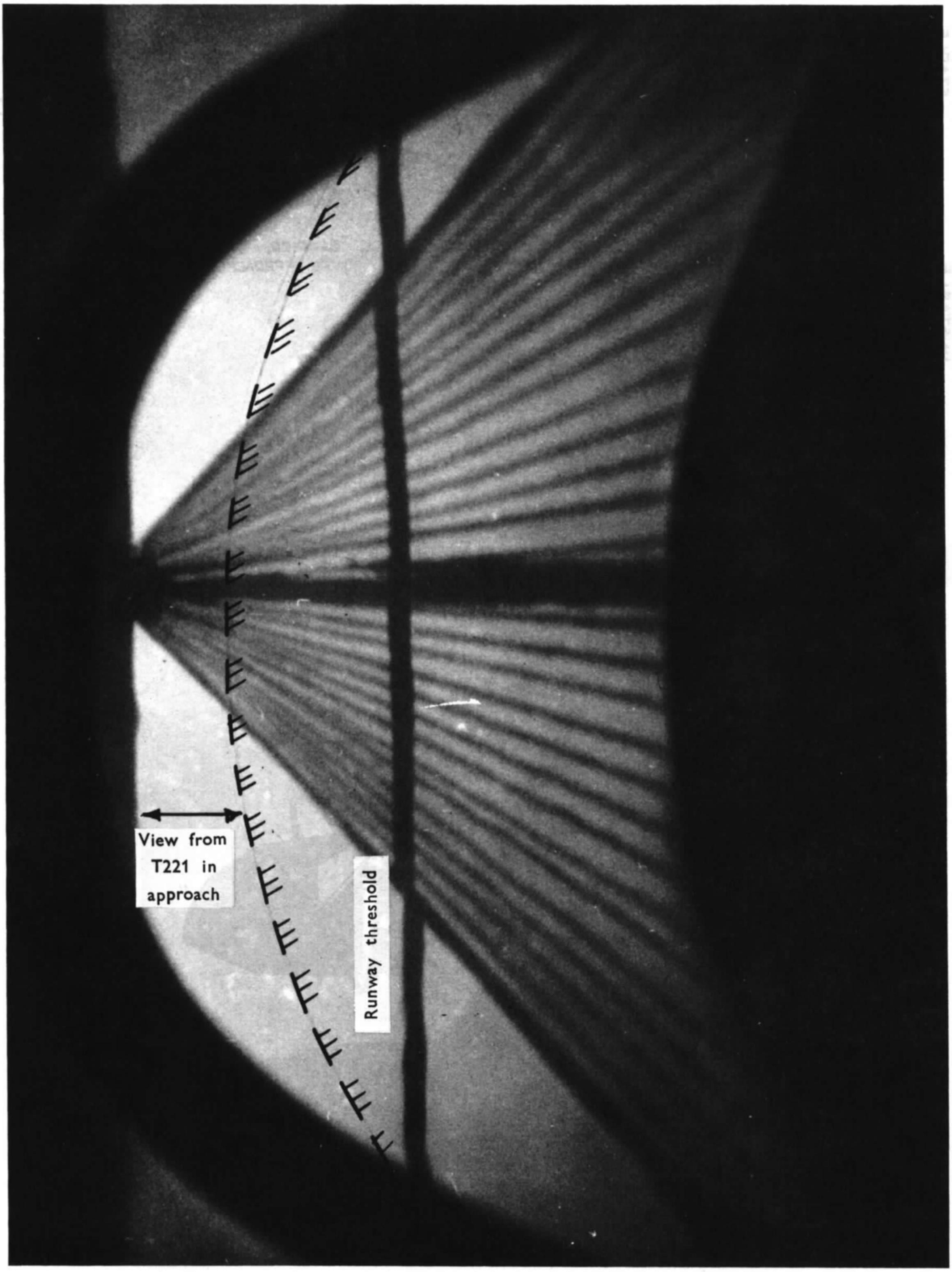

FIG. 5. Runway display showing view from B.A.C. 221 during the approach.

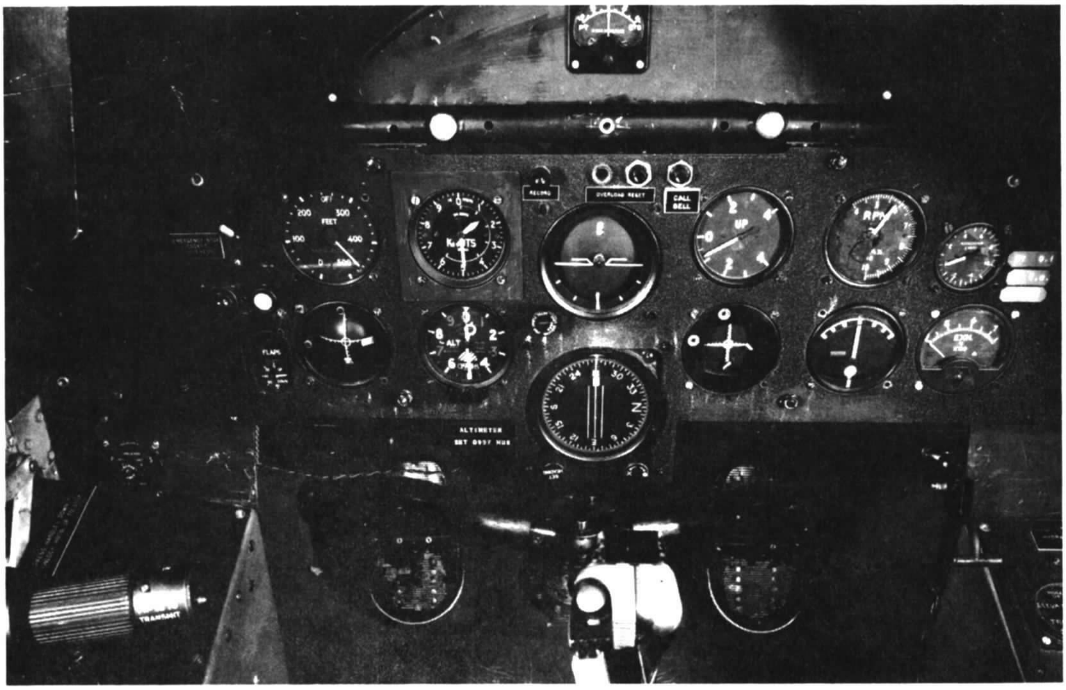

FIG. 6a. Simulator.

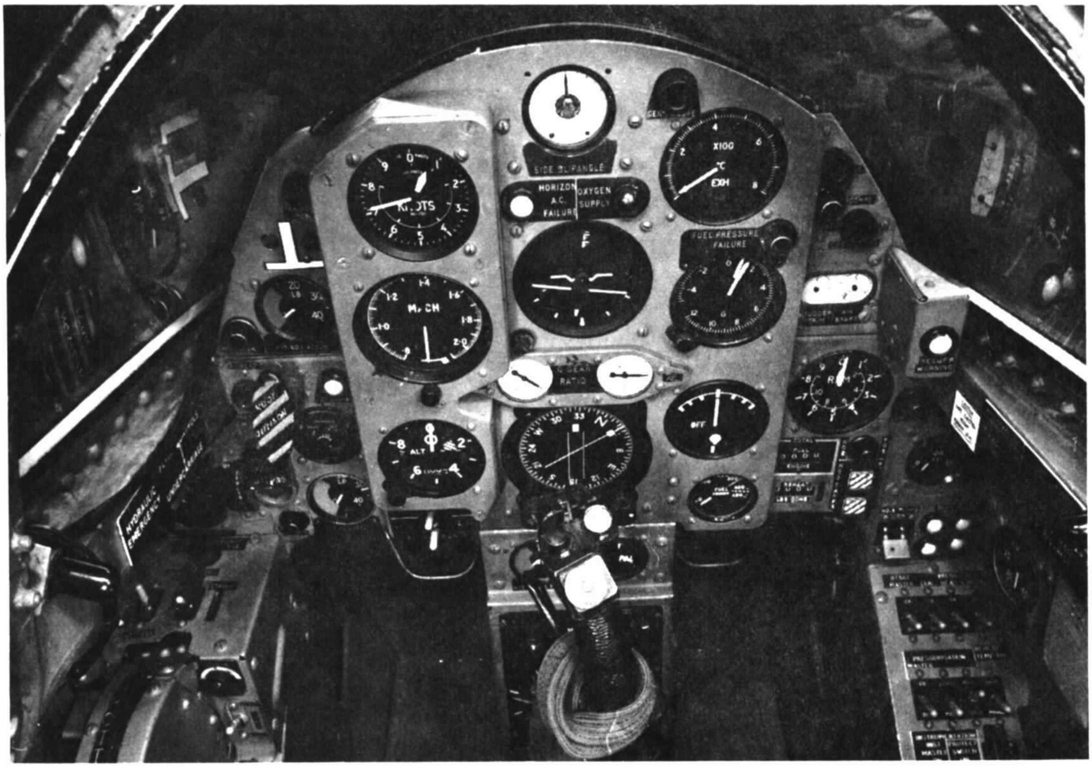

FIG. 6b. Fairey Delta 2 aircraft.

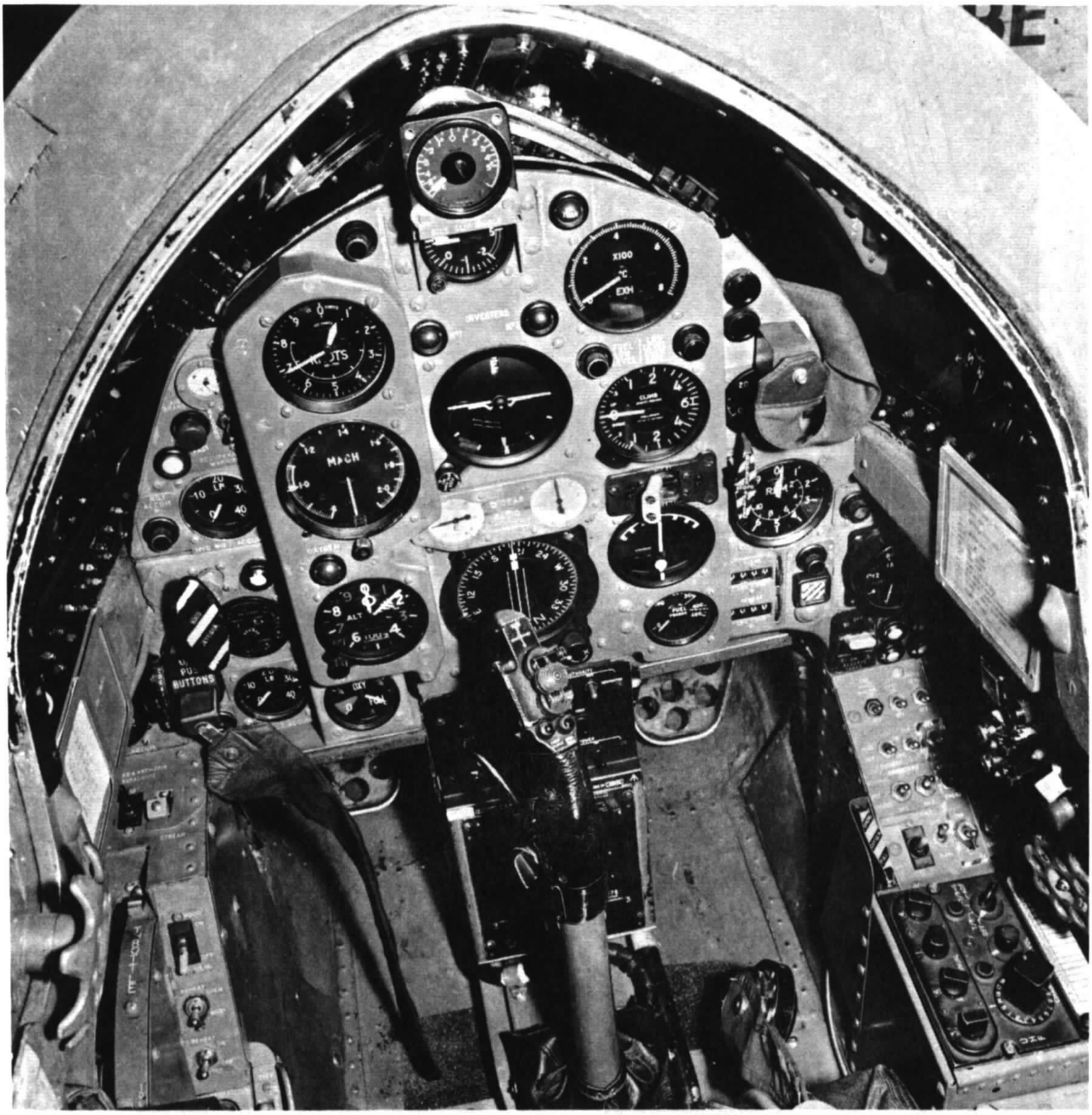

FIG. 6c. B.A.C. 221 aircraft.
FIG. 6. Instrument panel layouts.

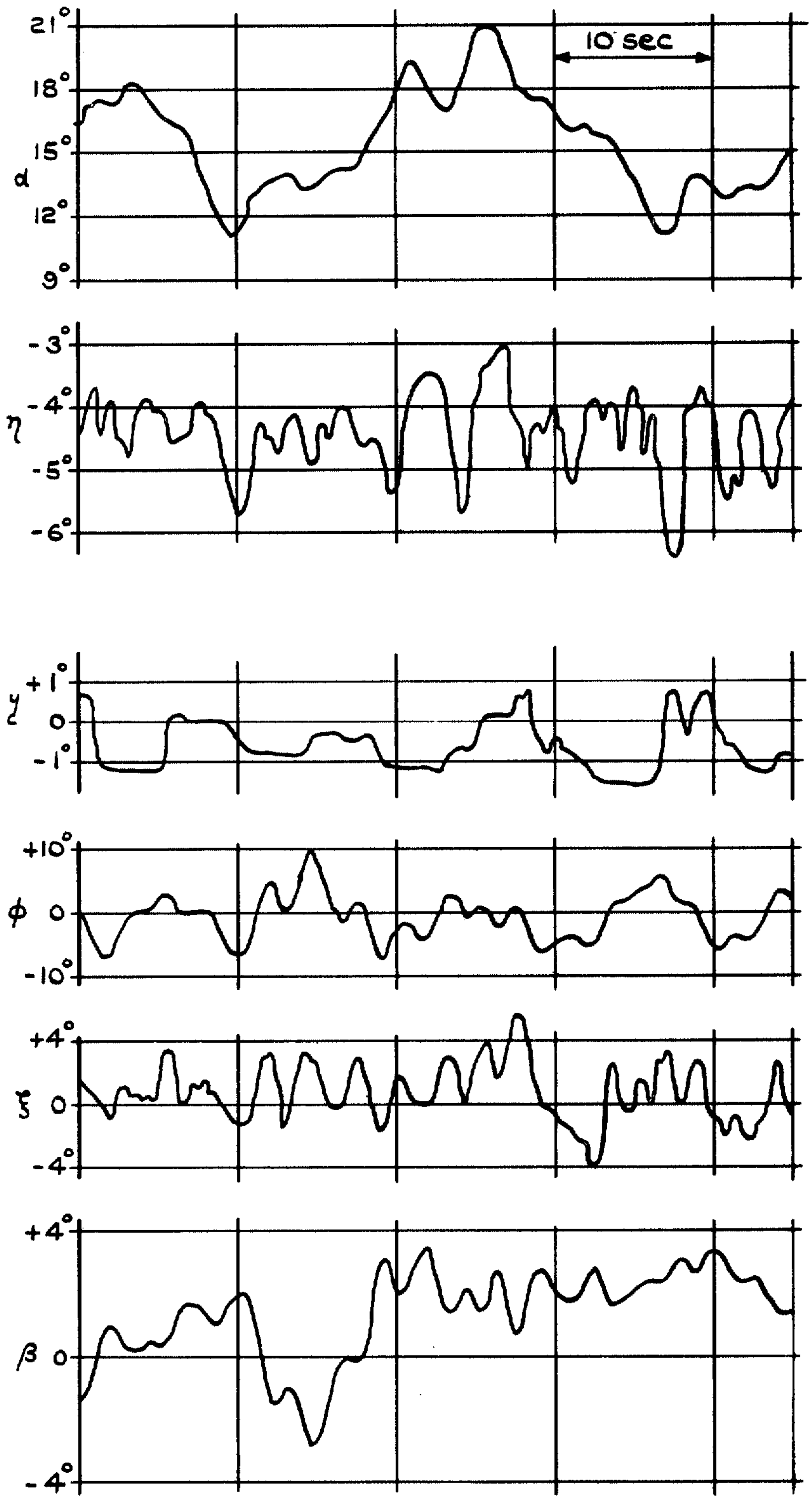

FIG. 7. Part of simulated B.A.C. 221 approach in turbulence at 150 kts.

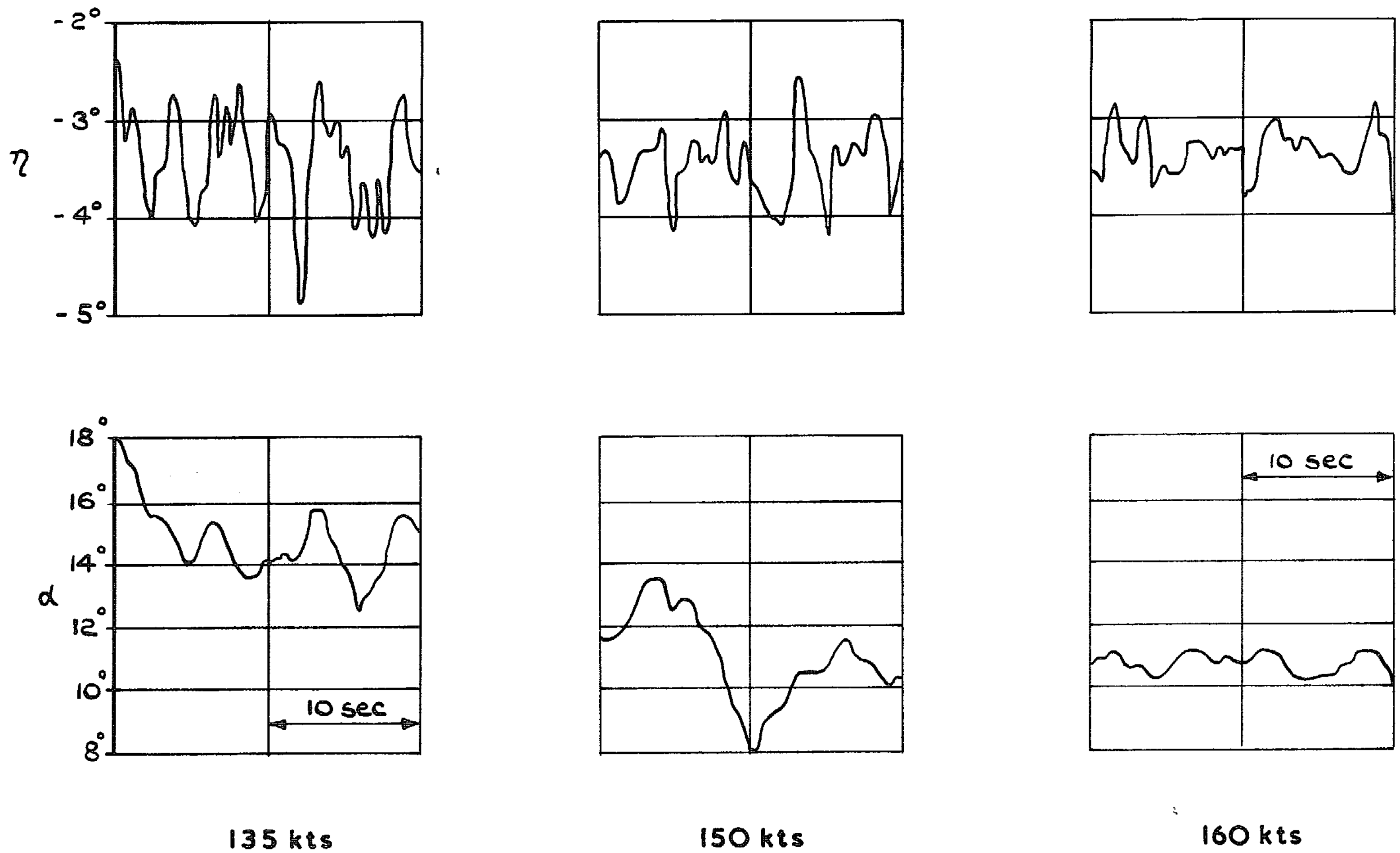

FIG. 8. Elevator and incidence time histories for the simulated B.A.C. 221 approaching at 135 kts, 150 kts and 160 kts.

ELEVATOR GEARING	PILOT	C.G. POSITION AS A PERCENTAGE OF $\bar{\bar{c}}$ FROM SIMULATOR DATUM AT 164·5 INCH							
		AFT		SIMULATOR DATUM	FORWARD				
		1·65% BALLAST LIMIT	0·56%		0·68%	1·36%	2·03%	2·71%	3·39% BALLAST LIMIT
2:1	A	MAY LOSE CONTROL AT ANY TIME; VERY RESPONSIVE TO TURBULENCE	MORE SENSITIVE TO TURBULENCE BUT NO MORE SENSITIVE TO ELEVON THAN DATUM CONDITION	BEST GEARING FOR DATUM C.G.	LONGITUDINAL CONTROL BETTER THAN DATUM C.G., STICK POSITION LESS COMFORTABLE	MORE SLUGGISH LONGITUDINALLY THAN DATUM C.G. STICK POSITION SLIGHTLY AWKWARD	← ELEVATOR GEARING IS UNSATISFACTORY - STICK IS TOO CLOSE TO THE PILOT → (spans 2·03% to 3·39%)		
2:1	B	—	—	NO STRONG PREFERENCE FOR 1·5:1 OR 2:1 GEARING	PITCH RESPONSE MAY BE MORE SLUGGISH THAN DATUM C.G. STICK POSITION UNCOMFORTABLE	← ELEVATOR GEARING IS UNSATISFACTORY - STICK IS TOO CLOSE TO THE PILOT → (spans 1·36% to 3·39%)			
2:1	C	TENDENCY TO OVER CORRECT AND FOR AN OSCILLATION TO BUILD UP: CAN BE CONTROLLED WITH SUFFICIENT CONCENTRATION	CONTROLLABLE AT 150 kts BUT UNPLEASANT AT 140 kts AND ALMOST IMPOSSIBLE AT 135 kts: EASY TO RECOVER BY DROPPING THE NOSE	STICK IS A LITTLE TOO CLOSE TO THE PILOT NO PROBLEMS IN APPROACHING AT SPEEDS DOWN TO 135 Kts	—	—	—	—	—
1·5:1	A	← ELEVATOR GEARING TOO SENSITIVE → (spans 1·65% to 0·56%)		BETTER THAN 1:1 GEARING. LESS GOOD THAN 2:1 GEARING (DATUM C.G.)	NO COMMENT	NOTICEABLY BUT NOT MARKEDLY BETTER THAN 2:1 GEARING	← STICK TOO CLOSE TO THE PILOT → (spans 2·03% to 3·39%)		
1·5:1	B	—	—	NO STRONG PREFERENCE FOR 1·5:1 OR 2:1 GEARING	STICK MORE COMFORTABLY SITUATED THAN WITH 2:1 GEARING - THIS GEARING IS PREFERRED	RATHER LIKE DATUM C.G. WITH 2:1 GEARING	VERY LITTLE DIFFERENT FROM 1·36% $\bar{\bar{c}}$ WITH THIS GEARING	NOTICEABLY BUT NOT SIGNIFICANTLY MORE SLUGGISH THAN 2·03% $\bar{\bar{c}}$ STICK TOO FAR BACK	SLUGGISHNESS IS NOT MUCH PROBLEM; STICK POSITION IS THE WORST FEATURE
1:1	A	—	—	VERY SENSITIVE - THERE IS A TENDENCY TO OVER CONTROL	FAIRLY PLEASANT	FAIRLY PLEASANT, PERHAPS OVER-SENSITIVE BUT THE BEST GEARING FOR THIS C.G.	VERY LITTLE DIFFERENT FROM 1·36% $\bar{\bar{c}}$ WITH THIS GEARING	CONTROL IS LESS PRECISE, LESS PLEASANT AT THIS C.G.	IF ANYTHING SLIGHTLY BETTER THAN 2·71% $\bar{\bar{c}}$ C.G. AT THIS GEARING
1:1	B	—	—	—	← ELEVATOR GEARING IS TOO SENSITIVE → (spans 0·68% to 2·03%)			NO COMMENT	STICK POSITION BETTER BUT CONTROL MAY BE TOO SENSITIVE

FIG. 9. Pilots' comments on variations in centre of gravity position.

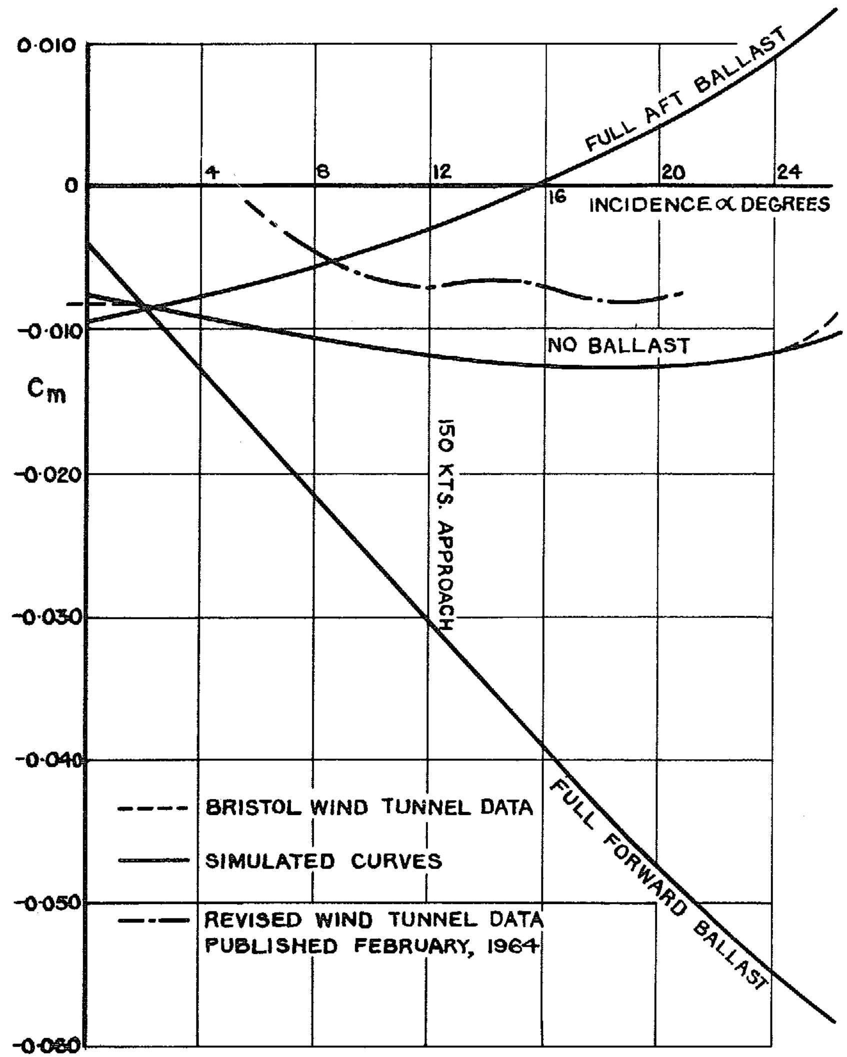

FIG. 10. Pitching-moment coefficient *versus* incidence: B.A.C. 221.

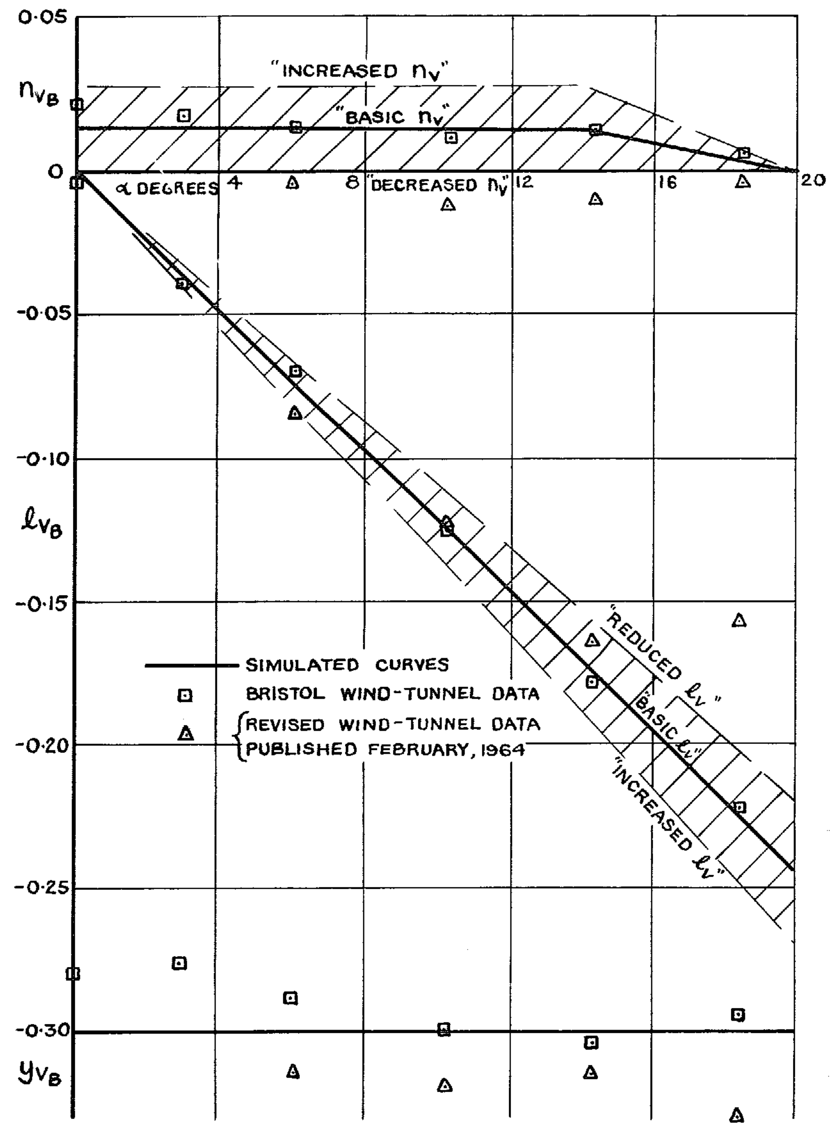

FIG. 11. Sideslip derivatives in body axes: B.A.C. 221.

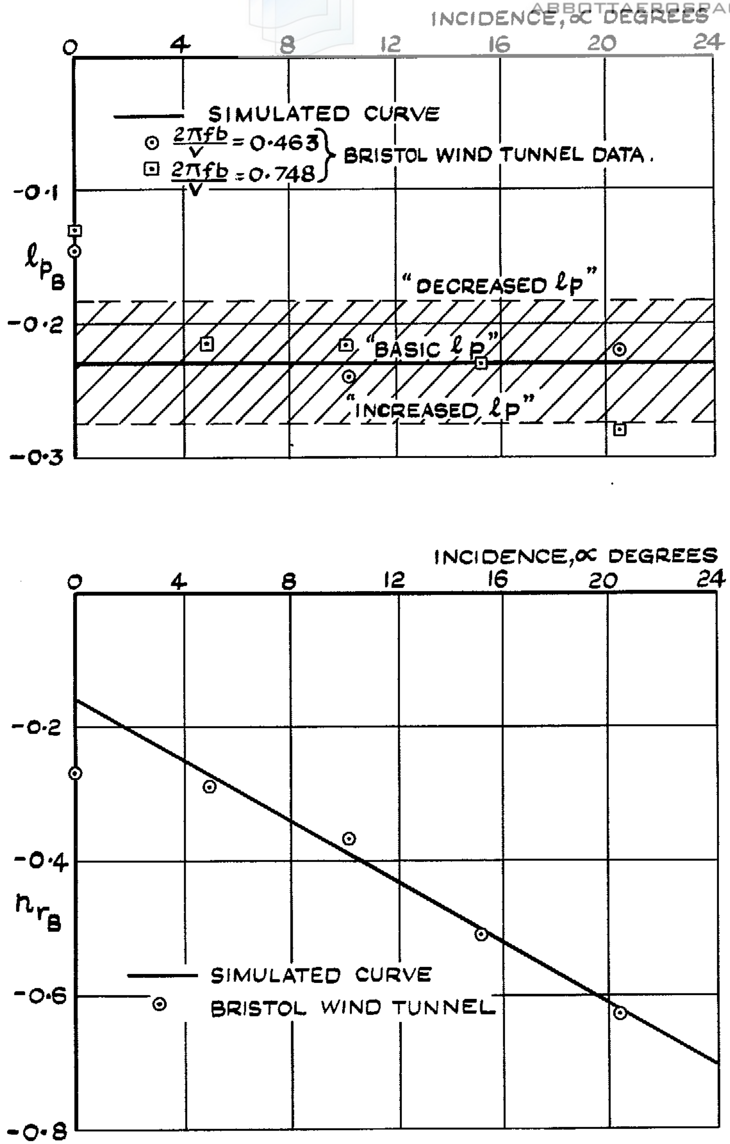

FIG. 12. Damping derivatives, l_p, n_r in body axes: B.A.C. 221.

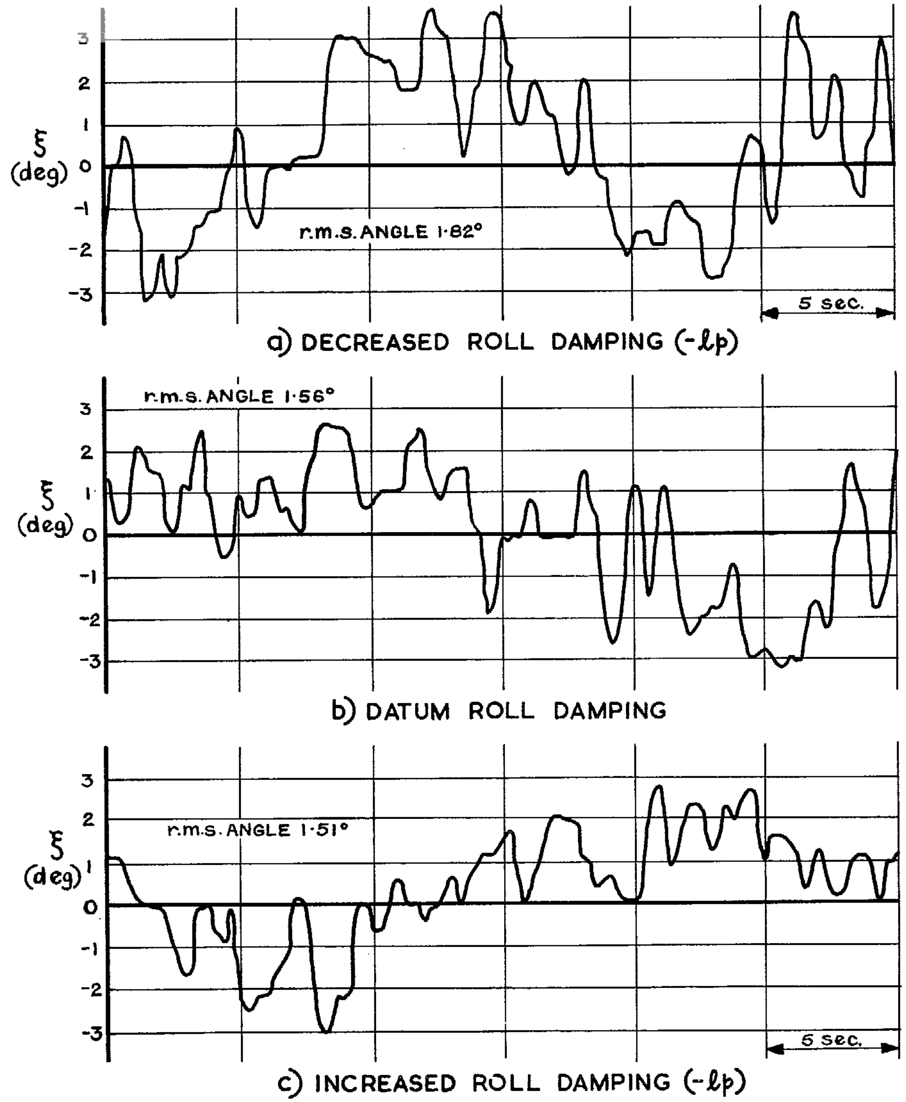

FIG. 13. Aileron time histories for three values of l_p for simulated B.A.C. 221 approaches at 150 kt. in turbulence.

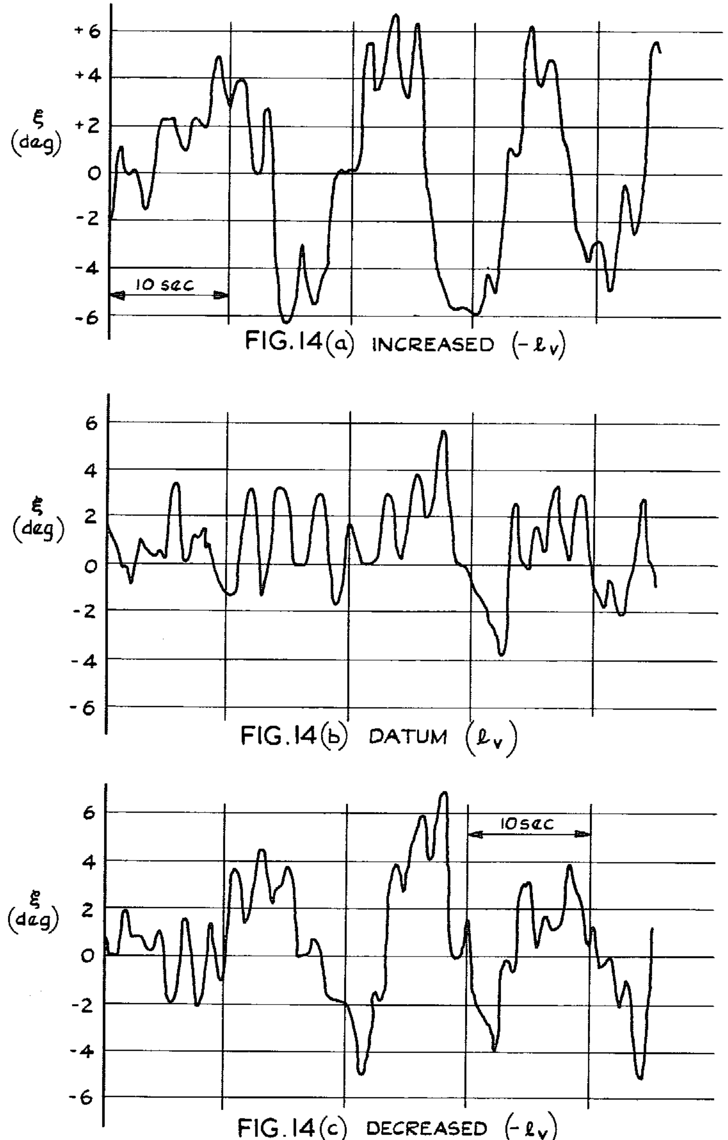

FIG. 14. Time histories of aileron angle for simulated B.A.C. 221 approaches in turbulence at 150 kt. with three values of l_v.

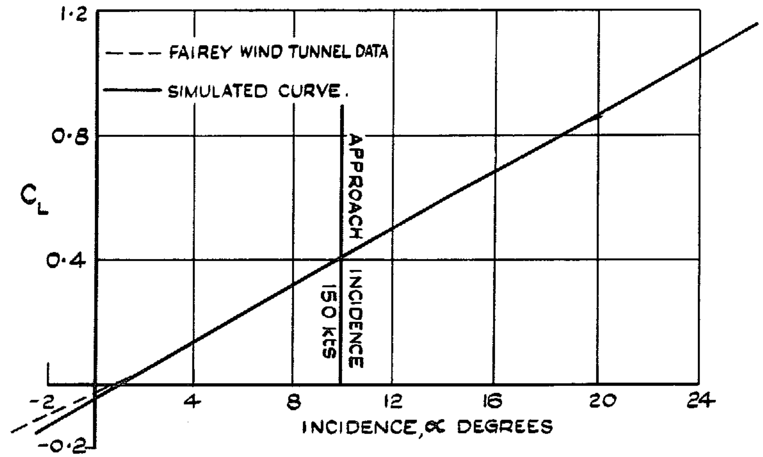

FIG. 15a. Lift coefficient *versus* incidence; Fairey Delta 2.

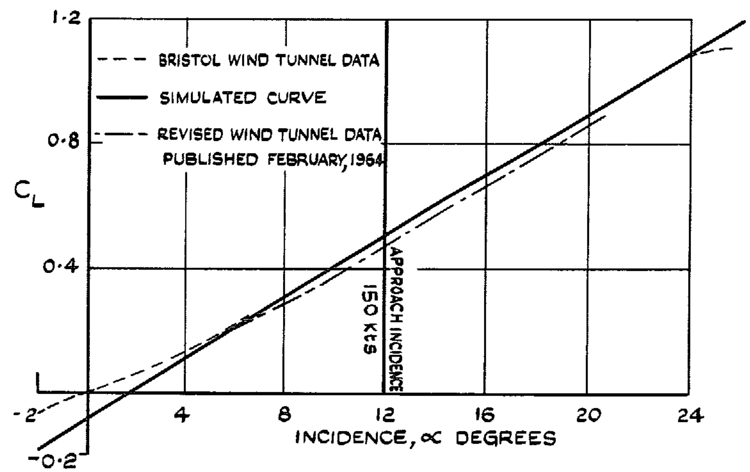

FIG. 15b. Lift coefficient *versus* incidence; B.A.C. 221.

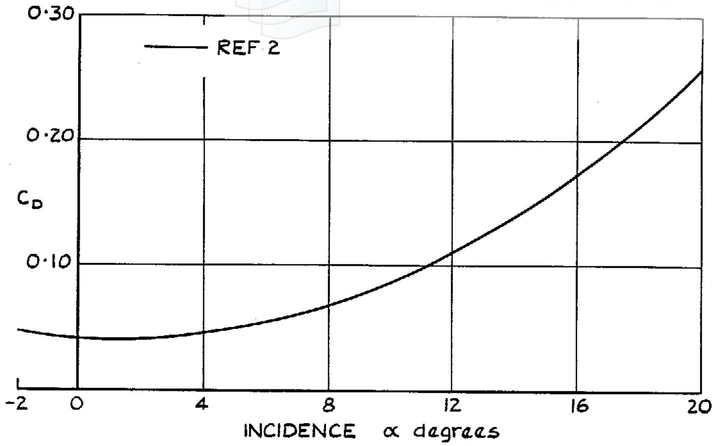

FIG. 16a. Drag coefficient *versus* incidence: Fairey Delta 2.

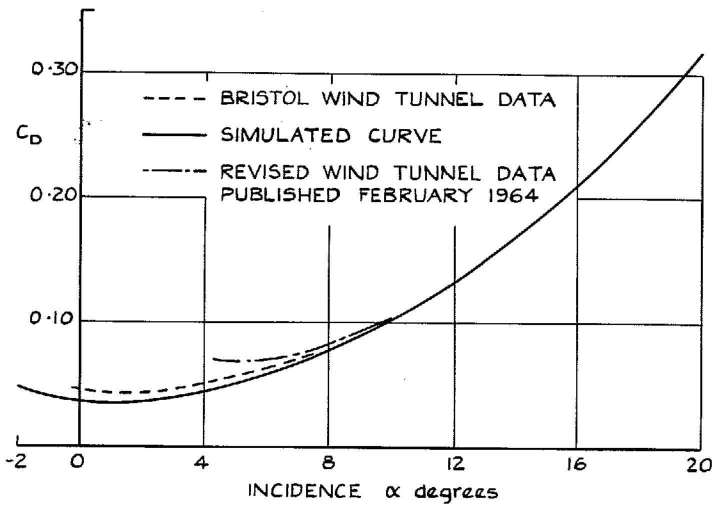

FIG. 16b. Drag coefficient *versus* incidence: B.A.C. 221.

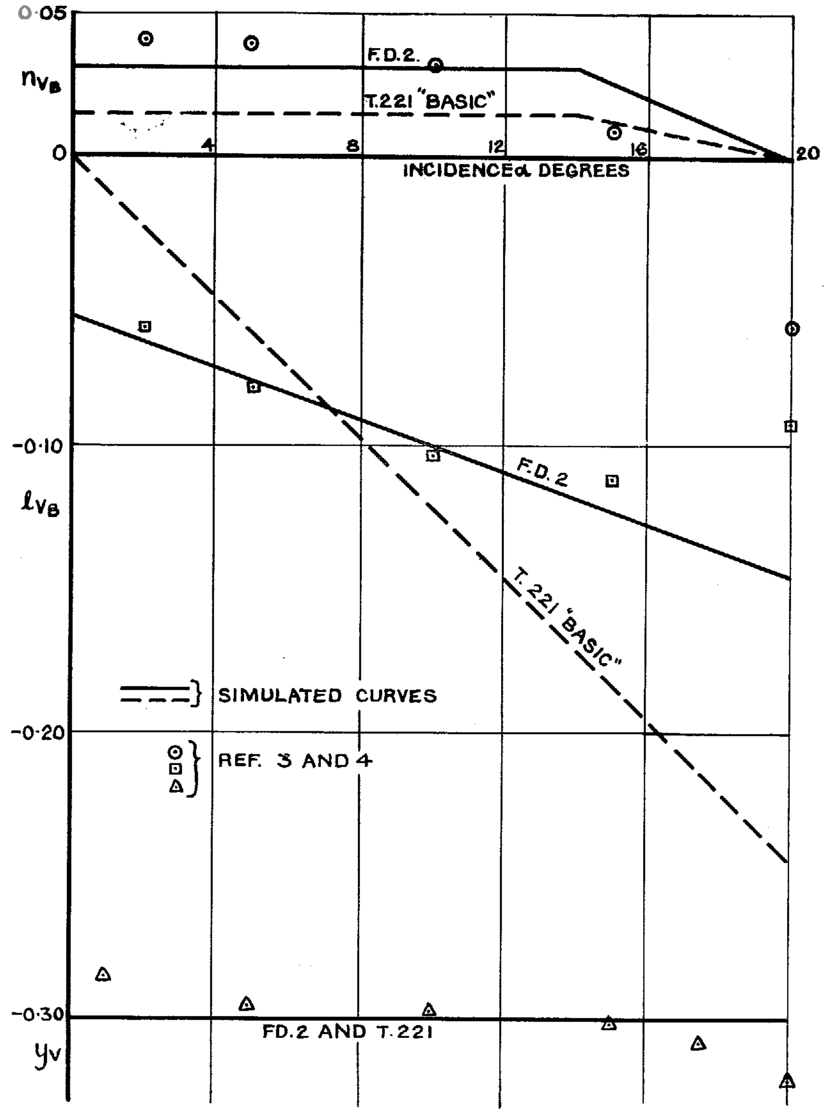

FIG. 17. Sideslip derivatives in body axes: comparison of Fairey Delta 2 and B.A.C. 221.

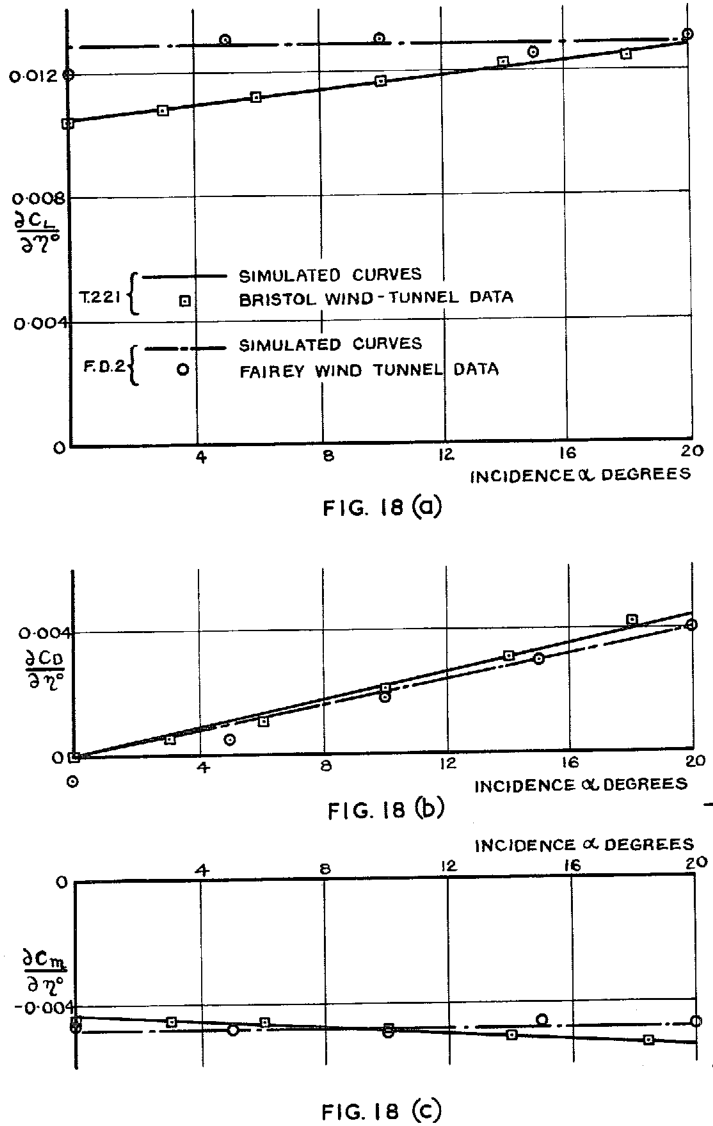

FIG. 18. Elevator derivatives.

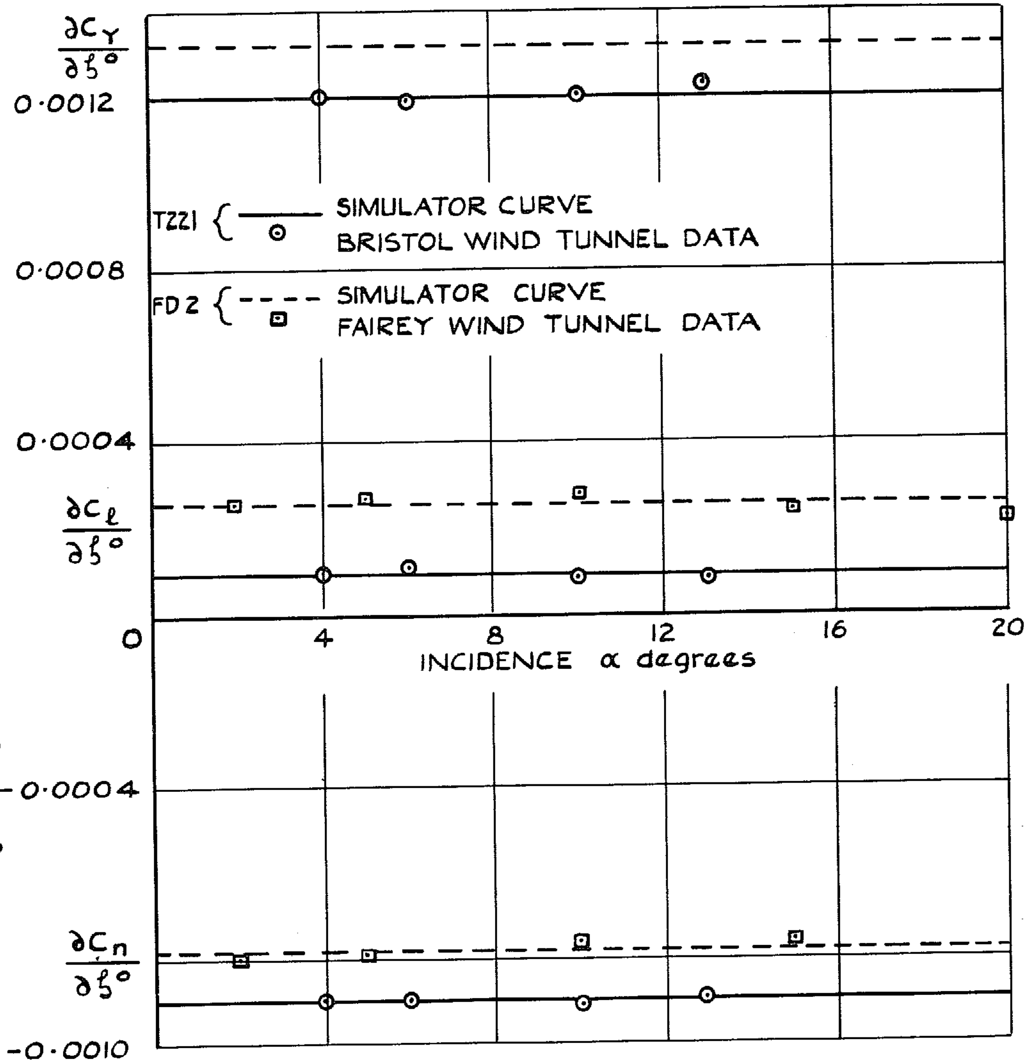

FIG. 19. Rudder derivatives in body axes.

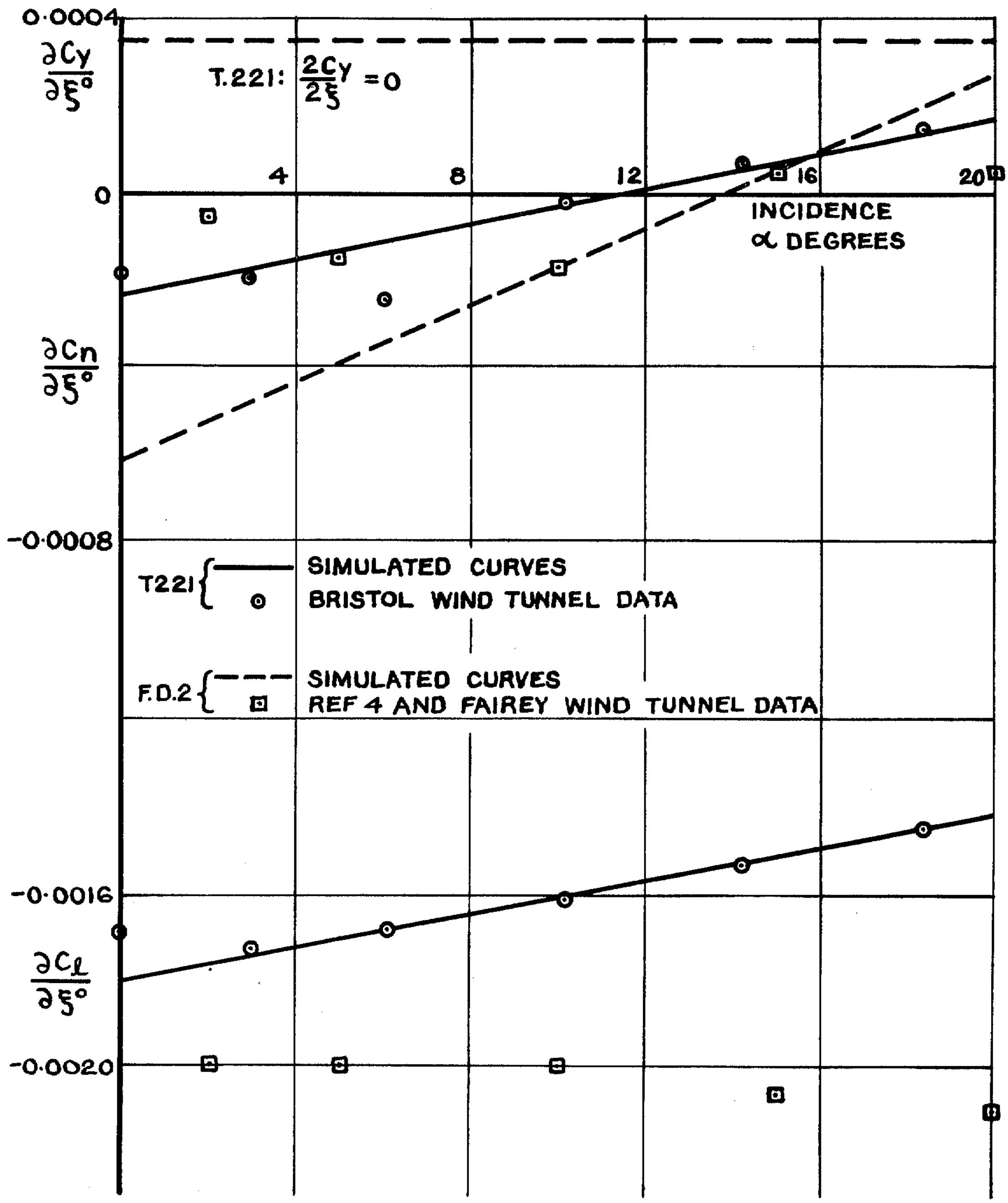

FIG. 20. Aileron derivatives in body axes.

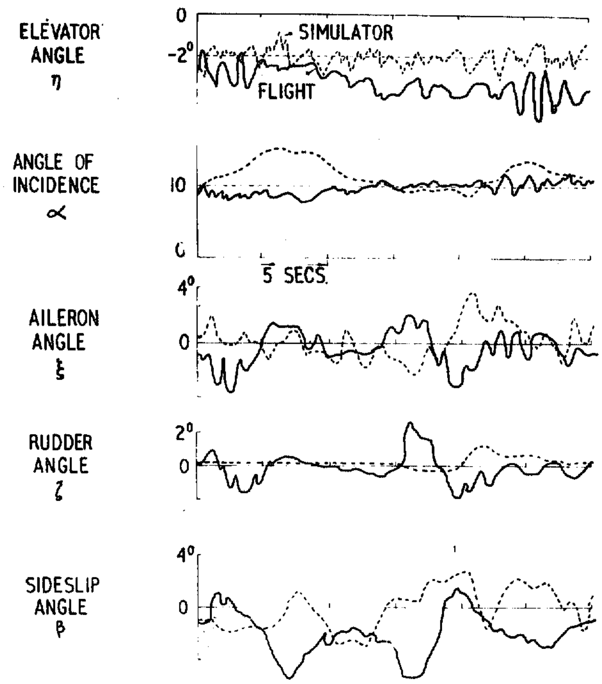

FIG. 21. Flight and simulator approaches of F.D.2.

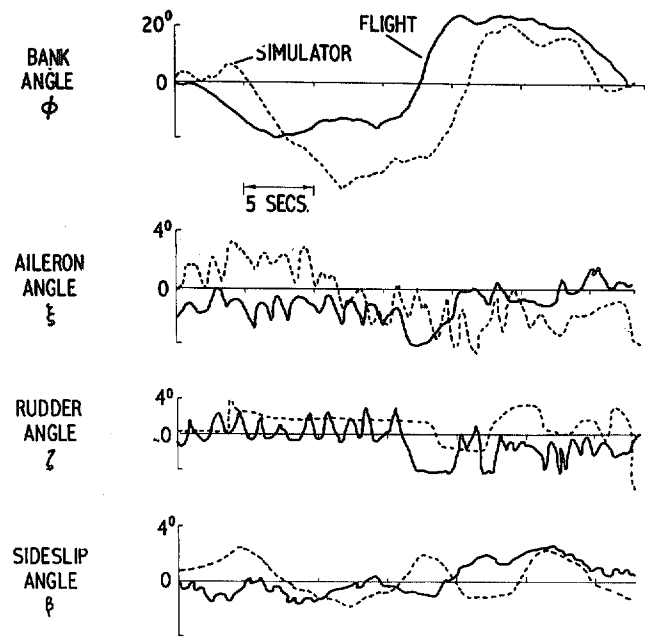

FIG. 22. Flight and simulator sidestep manoeuvre on F.D.2.

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