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A Piloted Simulator Study of a Slender-Wing Research Aircraft (HP 115)

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Summary.

The HP 115 slender-wing research aircraft was represented on the Aero Flight piloted research simulator. Comparisons of the handling of the simulated and the actual aircraft were made, based on the subjective opinion of six experienced test pilots and on recorded time histories.

As a separate exercise a variety of visual and motion cues was made available to the pilots. Their subjective opinion and measurements of their ability to maintain wings level when subjected to step sidegusts, were used to assess the value of the several cues.

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1. *Introduction.*

The Handley-Page HP 115 is a slender-wing research aircraft, built to investigate the aerodynamic characteristics and handling qualities of a slender-wing design at low airspeeds. The aircraft is shown in Fig. 1 and is described in detail in Ref. 1. Model tests and analytical studies predicted that a slender-wing design, while offering advantages in supersonic cruise, might suffer from handling problems, particularly at low airspeeds. The HP 115 was built to study these problems and conventional handling criteria, applied to wind-tunnel measurements of derivatives, predicted that this aircraft too would have handling problems. The considerable flying experience in the aircraft since it first flew in August 1961 has shown these fears to have been largely unjustified[2,3], at least in the case of the HP 115. This underlines the fact that there are still areas where conventional handling criteria do not adequately predict the behaviour of new aircraft designs. Piloted flight simulation offers the possibility of assessing directly the handling characteristics of an aircraft and so of checking the validity of assessments based on existing handling criteria for a novel configuration.

A previous simulation of the HP 115 made by the firm before the first flight, using a very simple attitude display and without cockpit motion or realistic control forces[2], provided interesting experience but required, in the words of the pilot concerned, 'a mixture of intuition and intelligence . . . in drawing the conclusions[3]'. Thus the pilot had to judge whether the problems that arose were due to the characteristics of the aircraft or to inadequacies in the simulation. In view of the continuing interest in the slender-wing concept, it was decided to simulate the HP 115 on the Aero Flight simulator to establish a comparison with flight and to see whether a more sophisticated simulation could faithfully represent the behaviour of this unorthodox design.

There are two main factors which might affect the validity of a simulation, on the one hand the aerodynamic and inertia data used to programme the computer, and on the other the visual and motion cues available to the pilot. For the present experiment, interim flight test data were available[1] to supplement the wind tunnel and estimated data used in the pre-flight simulation. An external visual background and cockpit motion in pitch and roll were used throughout the simulator trials for comparison with flight. No yawing motion was available so the tasks to compare the simulation with flight were chosen to exclude, as far as possible, situations in which the aircraft would have appreciable yawing motion. At one stage, as part of a continuing programme to establish the effects of motion and visual cues, several alternative visual displays were presented to the pilot and various signals were used to position the cockpit.

The object of this experiment was to assess whether it was possible to simulate the HP 115 in such a way that the simulated aircraft could be controlled in the same way as the actual aircraft, without any special flying techniques. Thus subjective pilot opinion formed an invaluable complement to more quantitative comparisons in judging the success of the simulation.

2. *Description of the Simulator.*

The Aero Flight simulator consists, essentially, of a general purpose analogue computer, and a moving-base, single-seat cockpit, with provision for several kinds of external visual background. The cockpit is illustrated in Fig. 2 and the simulator is described in detail in Ref. 4. For the HP 115 simulation, the computer was programmed to represent six degrees-of-freedom of motion, with correct variation with dynamic pressure and incidence from 130 to 50 kt. The equations of motion used are detailed in the Appendix. Atmospheric turbulence, represented by filtered white noise[4], was used during the exercise and was considered by the pilots to give a realistic impression.

The simulation of the HP 115 posed some problems in programming the equations of motion on the computer, in providing the pilot with satisfactory sensory information, and in representing the characteristics of the mechnical control linkage. These problems are discussed in the remainder of this section.

2.1. *Aerodynamic Representation.*

Reference dimensions and inertia data pertinent to the HP 115 simulation are given in Table 1. For the most part flight measured values of derivatives were used in the simulation. This does not, however, preclude the possibility of differences between the dynamic and static behaviour of the simulated and the actual aircraft, for three main reasons.

(i) Flight results were obtained at speeds down to about 60 kt (incidence about 24°) and since the simulation was intended to cover speeds down to 50 kt (incidence about 30°) aerodynamic data had to be extrapolated in this region.

(ii) In the second place the forces and moments measured on the aircraft are assumed to be the algebraic summation of certain parameters. That is to say a mathematical model of the forces and moments is assumed, and the values of the derivatives extracted will depend on the form of the model. If, for example, the lateral derivatives are extracted from measurements of a rudder-induced Dutch roll, and the same model is used to programme the computer, then the computed Dutch roll motion should be correct, but other computed motions, for instance the response to an aileron step, may be rather different from the motion of the actual aircraft.

The model used to derive the flight measured values of the lateral derivatives[1], and to programme the computer (*see* Appendix), was based on the usual assumptions of lateral stability theory. In particular it was assumed.

(a) that the aircraft behaved as a linear system, that the disturbances were small, and that their squares and products were negligible, and

(b) that the rolling moment due to rate of change of sideslip derivative, $l_{\dot{v}}$, was negligible.

While it is beyond the scope of this work to question these assumptions, several points require some consideration:

(a) There is a difference between the value of the sideforce due to sideslip derivative, y_v, extracted from flight Dutch rolls and the value based on flight-measured steady sideslips (Fig. 3).

(b) The Dutch roll oscillation of the HP 115 is divergent at low airspeeds for small amplitude oscillations, but the oscillation stabilises at bank amplitudes in the region of ±30°[1]. Flight measurements of damping at small amplitudes were used to programme the computer. Thus, while the computed motion had almost the same Dutch roll characteristics as the aircraft for small amplitude oscillations, in terms of period, damping and Dutch roll ratio, as shown in Fig. 4, there was no evidence of the oscillation stabilising.

(c) Following the first high acceleration in roll due to a step aileron input with rudder fixed, the mean roll acceleration of the actual aircraft falls to zero, with very marked hesitations in the rate of roll at intervals corresponding to the period of the superimposed Dutch roll oscillation. In the simulated aircraft the hesitations were less marked and the mean rate of roll went on increasing. Flight and simulator traces of the response to a step aileron input are compared in Fig. 5.

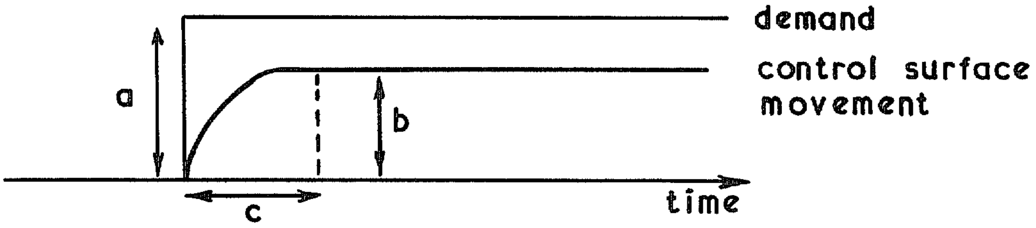
Despite these reservations, and in the absence of better data, the computer was programmed using the usual force and moment equations (*see* Appendix), which had been assumed in extracting the derivatives from flight test results.

(iii) A third possible source of difference between the simulated and the actual aircraft is that, due to lack of computing equipment, a certain amount of simplification was unavoidable. The degree of simplification of the equations of motion used in this exercise is detailed in the Appendix. Further, the variation of some derivatives with respect to incidence was linearised. The mathematical representations of derivatives are given in the Appendix where the degree of linearisation and the extrapolation from 24° to 30° incidence can be clearly seen. The extent of this linearisation can be gauged from Figs. 6 to 9, and the effect on the static and dynamic behaviour of the simulated aircraft is shown in Figs. 4 and 10. The effect can be seen to be small, at least in the speed range 130 to 50 kt (C_{L_a} 0·17 to 1·21 in level flight).

2.2. *Controls and Displays.*

Having achieved an acceptable representation of the aircraft motions, two closely related problems remained. Attention must be given to the representation of the pilot's controls, and to the sensory information, both visual and kinaesthetic, presented to him. It is of prime importance that the pilot be able to control the simulated aircraft in essentially the same way as he controls the real aircraft, without having to learn any special techniques.

The HP 115 has manual spring tab elevons and manual rudder[2]. The aircraft instrumentation measured control-surface movement, but did not measure stick position. There was no exact knowledge of the effect of control circuit flexibility on the relationship between stick and control surface so a few initial trials were made with a simple 1:1 stick-to-control surface linkage. However, pilots considered that the lateral handling of the simulated aircraft was not fully representative so a relationship was chosen of the form indicated in the figure;



The diagram represents the response of the control surface to a step stick input. The rise time *c* was represented by a simple first order time lag with time constant $\frac{1}{3}$ second: this lag was applied to both aileron and elevator inputs. An unpublished Handley-Page report suggested that, at 120 kt, for full stick deflection, $b/a = 10/14$. It was assumed that this ratio varied with dynamic pressure so that at 60 kt $b/a = 13/14$ and, in the absence of any further information, aileron was represented as

$$\xi \text{ control surface} = (1{\cdot}22 - 6{\cdot}18 \times 10^{-3}\, q)\left(\frac{1}{1+\frac{1}{3}s}\right) \xi \text{ stick}$$

where q is the dynamic pressure in lb/ft^2. Elevator was represented using the simple time lag but was independent of dynamic pressure.

The control forces used on the simulated aircraft were based on flight measurements. The elevator force used was 19 lb per g at all speeds, the aileron force was 4 lb/in at 80 kt, varying with dynamic pressure to 7 lb/in at 140 kt, and the rudder force was 90 lb for full scale deflection at all speeds.

The instrument panel of the simulated aircraft contained an artificial horizon, a gyro-compass, an airspeed indicator, a vertical speed indicator, an altimeter, and a turn and slip meter. These are the elements of a conventional blind-flying panel and are essentially the same as the instruments in the HP 115 aircraft.

For the simulator/flight comparison described in Section 3 a contact analogue visual display, and cockpit attitude motion, (*see* Section 4.1 for a description of these cues) were used. Following the comparative study, the effect on handling of changing the motion and visual cues was investigated.

It is generally accepted that, when visual flight is simulated, some form of external visual background is necessary, but most practical systems lack one or more of the cues which a pilot may use when controlling an aircraft in visual flight. While there is no complete understanding of the problem, it seems likely that peripheral information and ground detail will be important cues, and an attempt was made, during this simulation, to gain some idea of the value of an external visual background lacking one or both of these cues. The types of visual background used and the results of this work are discussed in Section 4 of this paper. It should be stressed that the relative importance of the cues may vary with the imposed task and with the dynamic behaviour of the particular aircraft.

There is less general agreement about the value of cockpit motion as an aid to realistic simulation, but previous experience with the Aero Flight simulator[5] suggests that kinaesthetic cues may be at least as important as visual cues. Consequently several different signals were used to position the pitching and rolling modes of the cockpit. The nature of the signals and the results of the tests are also discussed in Section 4. As is the case with visual cues, the results obtained in this exercise may depend on the task and on the behaviour of the simulated aircraft.

3. *Comparison of the Simulated with the Actual Aircraft.*

The primary aim of this exercise was to simulate the HP 115 with such accuracy that pilots could 'fly' the simulated aircraft as they would the actual aircraft, without having to learn any special techniques. Qualitative pilot opinion, therefore, constitutes a most important part of the results. Of equal importance is the comparison of trace records of parameters defining the dynamic behaviour measured in flight and on the simulator. The contact analogue display, and the cockpit positioned by pitch and roll attitude signals, were used throughout this part of the trials aimed at flight/simulator comparison. It is worth mentioning that the decision to use a visual display and cockpit motion was justified later in the simulation exercise when a comparative study of visual and motion cues was made; this study is described in Section 4. The contact analogue display may not have provided the best visual cue but it was almost as good as any of the other displays available. Pitch and roll attitude signals did provide the best motion cues.

Six pilots took part in the simulator exercise and they were encouraged to make comprehensive handling manoeuvres over the full range of speeds simulated, before expressing qualitative opinions. Quantitative comparisons of flight and simulator time histories were made on the basis of several specific tasks, for example on the use of ailerons to control the divergent Dutch roll. Where pilots felt that a difference existed between simulated and actual characteristics, an additional task was devised to provide quantitative support for the qualitative opinion.

As the principal interest of the experiment was handling, the comparisons between flight and simulator were clearly more meaningful when the nature of the motion was similar in the conditions compared. It then mattered little if such parameters as speed and incidence were precisely comparable. In Figs. 11, 12 and 13 the comparisons are valid if the Dutch roll is divergent whatever the exact values of speed and incidence, while in Figs. 15 and 16 the small differences in initial incidence would not materially affect the results.

For various reasons, the bulk of the flight testing for quantitative comparison with the simulation took place 15 months after the simulator exercise. This quantitative comparison in the HP 115 aircraft was carried out by pilots C and F (*see* Table 2). Pilot F had not flown the aircraft at the time of the simulator exercise, so the results of quantitative comparisons based on his work may be of less value than would otherwise have been the case.

Although six degrees-of-freedom were used throughout the simulation, pilots tended to explore the lateral handling while holding constant flight path and speed, and to explore the longitudinal handling while maintaining wings level and zero sideslip. This division has been retained in the following discussion of the results. As noted earlier, directional characteristics and rudder usage were not the subject of special attention, because of the absence of motion in the yawing plane.

3.1. *Comparison of the Lateral Handling.*

There were some differences in the handling of the simulated and the actual aircraft in early trials when a simple 1:1 relationship between the control stick and elevons was being represented. As discussed in Section 2.2 a modification was made to represent the spring-tab elevons and after this the comparison of the simulated and actual handling characteristics showed very good agreement. In every important aspect the pilots who had flown the HP 115 aircraft considered that the lateral handling of the simulated and the actual aircraft were very similar. Such differences as did exist were of such a minor nature that they in no way detracted from the validity of the simulation. It should be remembered, however, that the comparisons excluded those manoeuvres in which yawing motion would be significant since the simulator cockpit had no yaw motion.

Because the lateral handling of the simulated aircraft was so similar to the actual aircraft, only one task was set for quantitative comparison. The most difficult lateral task in the aircraft is the control of the Dutch roll oscillation at speeds below about 60 kt, when it has become divergent. Figs. 11 and 12 compare simulator and flight recoveries, by pilots C and F respectively, at constant speed using ailerons. The first 7 seconds or so of the manoeuvres flown by pilot C (Fig. 11) are very similar, but after that time the simulated rate of roll remains oscillatory and the flight rate of roll does not. At least part of this difference in the latter parts of the two records is thought to be due to slightly inferior motion and visual cues of the simulated aircraft, which made it more difficult for the pilot to detect very small angles of bank and rates of roll. The comparison in Fig. 12 is slightly less favourable, since the simulated aileron angle is rather smaller and the oscillation persists somewhat longer. However, at the time when the simulator record was made, pilot F had had less than 2 hours experience in the simulated aircraft and he had not then flown the HP 115 aircraft.

Because the control of the divergent Dutch roll is a fairly critical handling task, there tend to be significant differences in the techniques used by different pilots. A comparison of Figs. 11 and 12 shows that pilots C and F, though both controlled the oscillation, did so in recognisably different ways. Pilot C to all intents stopped the oscillation in one cycle (Fig. 11), while the oscillation persisted for three or more cycles when pilot F was in control (Fig. 12). Moreover, each pilot used the same technique in the simulated, as in the actual, aircraft with very similar effects, so that, at least for this task, the pilots were not having to learn new techniques to fly the simulated aircraft, and so were achieving the primary aim of the exercise.

The simulator records for the comparisons in Figs. 11 and 12 were made with cockpit pitch and roll attitude motion and a contact analogue visual background (*see* Section 4 for a fuller discussion of cues). One of the 'three other pilots' of Table 2 attempted to control the divergent Dutch roll using ailerons with (a) cockpit motion and contact analogue display, (b) cockpit motion without an external visual reference, and (c) contact analogue display without cockpit motion. He found that he could not control the simulated aircraft without cockpit motion at speeds where the Dutch roll became divergent. Records of aileron angle and rate of roll obtained with the contact analogue display and with no external display (but both with cockpit motion) are compared in Fig. 13, and show that the handling is considerably debased when the pilot has no external visual reference.

The differences between the simulated and the actual rolling response to ailerons, discussed in Section 2 and illustrated in Fig. 5, gave rise to some differences in handling and particularly in the handling of the simulated aircraft in turbulence, when larger aileron inputs were required. As a result lateral control was somewhat less precise in the simulated than in the actual aircraft when flying through disturbed air.

3.2. *Comparison of the Longitudinal Handling.*

At speeds between 50 and 130 kt, pilots considered that the longitudinal handling characteristics of the simulated aircraft were very similar to those of the actual HP 115. Two tasks were set: the first was a speed reduction in level flight, and the second was the control of the divergent Dutch roll by reducing incidence to bring the aircraft into a condition in which the oscillation was damped. This latter task was chosen because the pilots felt that there was some difference between the simulated and the actual aircraft when the task was performed.

In Fig. 14 typical time histories of elevator, incidence and airspeed recorded in flight and on the simulator by the same pilot, are compared. Pilot F maintained constant height while decelerating from 120 to 90 kt. The flight and simulator records of both the time taken for the manoeuvre and the magnitude and nature of the elevator movements are very similar. The simulator results were obtained with the contact analogue display and with pitch and roll attitude cockpit motion. It may be of interest to note that the minimum-drag speed of the simulated aircraft was about 100 kt and that the throttle was represented with a first order time lag with time constant 0·22 second.

Only one task showed up a difference in handling between the simulated and the actual aircraft, and results for it are shown in Figs. 15 and 16. The Dutch roll of the HP 115, which is divergent at high angle of incidence, is fairly well damped at low incidence (*see* Fig. 4), so the divergent oscillation can be damped out by pushing forward on the control stick to reduce the incidence. It can be seen from Fig. 15 that pilot C has used rather less than half the forward elevator movement in the simulator that he used in flight, with the result that the rate of roll of the simulated aircraft reduced much more slowly. However, the initial rate of roll was much lower in the simulated case and the pilot may have felt less urgency in dealing with it. The difference in elevator movements is somewhat less marked with pilot F in Fig. 16, but the resulting rate of roll decay is again much less rapid in the simulated aircraft. Both pilots were reluctant to push the nose of the simulated aircraft as far down as they would in flight. They compared 'flight' in the simulated aircraft with actual flight in cloud, when pilots are equally reluctant to make large changes in aircraft attitude. In those circumstances, pilots prefer to stay close to an established trimmed condition. Some of the difference between simulator and flight traces may be due to differences in the Dutch roll damping, as shown in Fig. 4.

3.3. *Summary of Comparisons.*

Comparison of the simulated with the actual HP 115, based on pilot subjective opinion and quantitative comparison of recorded time histories, showed good agreement. The pilots were able to fly the simulated aircraft as they did the actual aircraft without having to learn any special techniques. Such differences as did exist were thought to be due to inaccuracies in the aerodynamic representation and to slightly inferior visual and motion cues available to the pilot of the simulated aircraft.

It should be remembered that the simulator cockpit was positioned in pitch and roll, throughout the comparative trials, by pitch and roll attitude signals from the computer. The contact analogue display was used in all these simulated flights. The next Section discusses the significance of these cues on the handling assessment.

4. *Effect of Varying Motion and Visual Cues.*

It is generally accepted that some form of external visual background, or 'real-world' display, increases the realism of a simulation, that is to say that it enables the pilot to fly the simulated aircraft more nearly in the same way as the real aircraft without having to learn any special techniques. Little is known, however, of the way in which a pilot uses external visual information. Simulator displays in current use tend to be limited in one or more ways, for example by having a limited angle of view or no ground detail. At this time there is little experimental data to aid the simulator designer, so during the HP 115 simulation some time (Table 2) was made available to explore the problem. It must be emphasised that this experiment used very simple displays and was intended only to clarify ideas for a more complete experiment at a later date.

Though there is less general agreement on the value of cockpit motion in increasing the realism of simulation, experience with the Aero Flight simulator[5,6] suggests that, in some cases at least, cockpit motion may be a most valuable aid. Again, the purpose of varying motion cues in the HP 115 simulation was largely to clarify ideas on the subject. The pilots who flew the 24 combinations of motion and visual cues used are shown in Table 3 (*see* also Table 2).

Four pilots (pilots B, C, D and E of Table 2) took part in this exercise. They were asked to fly the simulated HP 115 straight and level at between 80 and 90 kt through turbulence likely to be associated with low altitude and a mean head wind of 5 kt (vertical and longitudinal components 1·6 ft/s rms, lateral components 2 ft/s rms). The simulator operator then introduced a 10 ft/s step sidegust. The value of the visual and motion cues were assessed from measurements of the magnitude of the first angle of bank and of the first aileron input following the sidegust, and from the time for the pilot to respond to the gust. The several cues are described in Section 4.1 and the results are discussed in Section 4.2.

4.1. *The Motion and Visual Cues.*

The cockpit is free to move $-10°$ to $+20°$ in pitch and $\pm 15°$ in roll. The pilot's position is on the roll axis and about 6 ft ahead of the pitch axis[4]. Signals for the motion system come from the computer. The frequency responses of the cockpit and of the visual displays discussed below are given in Ref. 4.

Two different external backgrounds were used. The first, a simple horizon with no ground detail, called a 'skyscape' display, is produced by a point filament lamp inside a small transparent plastic sphere. It casts the shadow of a simple cloud/sky picture painted on the sphere onto a 15 ft radius spherical dome surrounding the cockpit[4] (*see* Fig. 17a) and is driven in roll, pitch and yaw by the computer. The pilot's eye coincides with the centre of the dome and the projector is mounted about 2 ft above his head.

The second visual display is electronically generated and is presented to the pilot on a cathode ray tube[4]. This display, called a 'contact analogue' display, gives the impression of flight along the diagonals of rectangular fields (*see* Fig. 17b), and it is pitched, rolled and yawed by signals from the computer.

4.1.1. *Motion cues.* Results of previous simulations[5,6] had indicated that, in some cases at least, cockpit motion added considerably to the validity of the simulation. In this exercise five different combinations of signals were used to position the cockpit and a sixth case was provided by fixing the cockpit.

Pitch and roll attitude were obvious cases for study and had been used, with good results, in previous simulations. However, it is a fundamental failing of the use of a simple roll attitude signal, that when the cockpit is banked the pilot feels a sideforce which is spurious since it would not occur in the same circumstances in actual flight. Roll 'washout' is one method of overcoming this failing. The effect of roll washout is to reduce the sideforce felt by the pilot in a steady banked turn in the simulator, by gradually restoring the cockpit to the wings-level position. Since the pilot feels sideforce when the simulator cockpit is banked a further case to be studied was the use of a signal proportional to the actual sideforce to position the cockpit in bank.

In an earlier simulation[8] a discrepancy had been found between flight and simulator incidence traces and it had been suggested that this was due to a lack of appreciation of normal acceleration. It was not, however, possible to provide a pure normal acceleration cue at the cockpit, and instead a normal acceleration signal was used to position the cockpit in pitch. (Note: for the pilot to experience true normal acceleration a height signal would be required to position the cockpit.) The pilot is seated some 6 ft from the centre of rotation in pitch of the cockpit so that changes in the pitch signal to the cockpit move the pilot vertically. Transient changes in normal acceleration can thus be transmitted to the pilot by pitching the cockpit although, clearly, sustained normal acceleration cannot be simulated. The fixed cockpit was also used because it was by no means certain that the cockpit motions used would improve the validity of the simulation.

The six motion cues used (Table 3) were:

(a) no motion—fixed base simulation;

(b) pitch and roll attitude—a pitch attitude signal positioned the cockpit (e.g. 10° pitch attitude moved the cockpit 10°), and $\frac{1}{2}$ the roll attitude was used (e.g. 10° roll attitude moved the cockpit 5°);

(c) pitch attitude, roll with washout—the pitch signal was the same as in (b), but the roll signal was allowed to leak away with a time to half-amplitude of $5\frac{1}{2}$ seconds;

(d) pitch attitude with normal acceleration g, roll attitude—the roll signal was the same as in (b), but a normal acceleration signal was added to the pitch attitude signal, scaled so that $\frac{1}{2}\,g$ excess moved the cockpit through 20° in pitch;

(e) pitch attitude with normal acceleration g, roll with washout; and

(f) pitch attitude and sideslip—the pitch signal was the same as in (b), but a sideslip signal positioned the cockpit in roll, scaled so that 10° of sideslip moved the cockpit through 15° in roll, giving the correct sideforce at 85 kt.

It took only a few seconds to change motion cues so that, once a visual configuration had been set up, all the motion cues were assessed before the visual configuration was altered. The motion cues were presented in random order so that the effects of learning would be minimised.

4.1.2. *Visual cues.* Five visual arrangements were available in all (Table 3):

(a) the simple horizon with no ground detail and unrestricted view in the horizontal plane (180° + Skyscape)—the view in the horizontal plane was in excess of 180° included angle and was in practice limited only by the pilot's peripheral vision;

(b) the simple horizon with no ground detail with 95° of view in the horizontal plane (95° Skyscape);

(c) the simple horizon with no ground detail with 35° of view in the horizontal plane (35° Skyscape); and

(d) the electronically generated display (contact analogue)—the cathode ray tube afforded 35° of view in the horizontal plane.

It took about 5 minutes to mask the cockpit to change the angle of view of the Skyscape display, and all three Skyscape views were simulated in a single session lasting about one hour. On the other hand it took about a day to replace the Skyscape display by the contact analogue display and, in view of this, all the trials using the Skyscape display were completed before the change was made. As a result the comparison of the two types of display was rather indirect and may have tended to favour the contact analogue display, since the pilots were more familiar with the simulated aircraft and the task when they assessed it. In fact only two of the four pilots (pilots B and C) were free to take part in the exercise using the contact analogue display (*see* Table 3).

Experience in past simulations[5] strongly supported the view that an external visual background improved the validity of the simulation. It was assumed that this would still be true for the simulated HP 115 and, consequently, some background was always present in the systematic study of cues. Nonetheless, a few trials were made with no visual background to confirm that the assumption was valid.

4.2. *Discussion of Results.*

The results are based on 687 step sidegusts and on subjective pilot opinion of the handling qualities in turbulence. Nine parameters, based on bank angle, aileron angle, sideslip and on combinations of these three, were studied for evidence of statistically significant differences amongst the combinations of visual and motion cues. Rudder was not included since it was rarely used during this exercise because the cockpit motion was limited to pitch and roll. Yawing motion is now being added to the simulator, and further tests to cover rudder control will be made later.

Systematic differences amongst the cues could be detected with only three of the parameters, which are detailed below. In the case of the six other parameters, differences due to the random turbulence, or perhaps to different piloting techniques, disguised systematic differences in performance amongst the cues.

(a) The first bank angle peak following the step sidegust. The magnitude of the peak was expressed as a proportion of the magnitude of the corresponding peak of the unpiloted response of the simulated aircraft to the 10 ft/s step sidegust.

(b) The magnitude of the first aileron input following the sidegust expressed as a proportion of the available aileron.

(c) The time elapsed between the sidegust and the first aileron input as a proportion of the period of the Dutch roll oscillation.

The use of proportions in expressing these parameters is not intended to imply that the results have general applicability. Further tests on simulated aircraft with widely varying characteristics would be required before any such claim could be presented. However it seemed sensible, in anticipation of such experiments, to report the results of this exercise in non-dimensional form.

When the relative amplitude of the first aileron input was considered there was an apparent effect of learning, as shown in Fig. 18. No learning effect could be detected either in the relative magnitude of the first bank angle peak (Fig. 19) or in the time to respond to the step sidegust. Nonetheless, it was felt that any effect of learning on the results could be reduced by confining the analysis to the middle group of results, as shown in Figs. 18 and 19, and discarding the first set of Skyscape results and the second set of contact analogue results.

Pilot comment on the motion and visual cues was recorded during and immediately following the exercises to which they refer.

4.2.1. *Motion cues.* Fig. 20 shows the variation with motion cues in the relative magnitude of the first aileron input, the relative time to respond to the step sidegust, and the relative magnitude of the first bank angle peak. The centres of the diamonds are at the mean values and the tips represent the $\pm 2\sigma$ points (95 per cent confidence limits). The results were obtained by averaging over all pilots and visual cues.

Taken together the three parts of the figure indicate that with no motion the pilot's response is worse than with any of the motion cues—that is to say that the aileron input is smaller and is applied later. The results are not significantly different, however, except that the mean bank angle with no motion is greater than the mean bank angle with pitch and roll attitude motion at the 5 per cent level (Student t test) of significance. Pilot opinion supported the view that a fixed cockpit was less satisfactory than any of the motion cues.

When the simulator cockpit was positioned in roll by a signal proportional to sideslip angle, the variance in the relative magnitude of the first bank angle peak was very much greater than for the five other motion cues (significant at the 1 per cent level). There was nothing in the relative magnitude of the first aileron input, nor in the relative time to respond, to explain the wide variation in bank angle. Pilots commented, however, that the sideslip cue gave rise to misleading sensations which conflicted with the visual evidence and made it difficult to phase aileron inputs.

The pilots disliked the 'normal acceleration' cue and felt that it reduced the realism of the simulation, although without affecting the performance of the task. None of the pilots was very specific about the way in which the 'normal *g*' was unrealistic, but one suggested that the gusts were too 'sharp-edged'. This seems a reasonable complaint when it is recalled that the cockpit was positioned by normal acceleration and not by height, as it should have been for the pilot to experience true normal acceleration. The 'normal acceleration' cue was introduced in an attempt to make the control of incidence in the simulator similar to an aircraft but there was no noticeable difference in the incidence traces with or without the 'normal acceleration' cue. Pilots felt that the 'washing-out' of the roll attitude signal made no practical difference to the realism of the simulation, at least for this exercise, where they were concentrating on maintaining wings level.

In general the motion cues based on pitch and roll attitude signals to the cockpit (including those with 'normal *g*' and roll washout) were equally effective when performing the task and made the simulated aircraft feel like the real thing, except for the 'normal *g*' cue which was rather unrealistic. Although the motion based on pitch attitude and sideslip angle was less satisfactory, pilots preferred it to no motion at all. With the cockpit fixed there was a feeling of detachment, and a special technique had to be learned to control the simulated aircraft.

4.2.2. *Visual cues.* Fig. 21 shows the variation with visual cues in the relative magnitude of the first aileron angle, the relative time to respond to the step sidegust, and the relative magnitude of the first bank angle peak. The centres of the diamonds are at the mean values and the tips represent $\pm 2\sigma$ points (95 per cent confidence limits). The results were obtained by averaging over all pilots and motion cues.

The pilots felt that the visual cues were less important than motion cues, and that when satisfactory motion cues were provided (i.e. cues based on pitch and roll attitude) changes in the peripheral view or in the ground detail had only small effects on the realism of the simulation, and on the performance of the task. This pilot opinion is supported by the results shown in Fig. 21, where there is no clear-cut difference amongst the cues although there is, perhaps, some indication that the Skyscape display with 35° view in azimuth is rather worse than the others—the relative magnitude of the first aileron input is lower (significant at the 5 per cent level) and the variance of the first bank angle peak is greater (significant at the 0·1 per cent level).

Pilots compared the visual cues in two parts. Firstly they compared the Skyscape with 35° view with the contact analogue display (which also had 35° view in azimuth), and secondly they compared the three views of the Skyscape (included angles of 35°, 95° and 180°+). The Skyscape with 35° view was considered to be worse than the contact analogue because, although the angular view was the same, the information from the contact analogue display was much more compelling. This difference was thought to arise out of physical differences between the displays rather than because of the ground detail provided by one of them. The contact analogue display was fairly bright and was mounted about 2 ft from the pilot. Pitching and rolling of the display caused changes in the light level in the cockpit and so it was apparent to the pilot that a change had occurred even when his attention was on something else. The Skyscape display, on the other hand, was projected onto a dome 15 ft from the pilot and the level of illumination was very low, so that changes in pitch and roll could easily be missed.

Comparing the three views of the Skyscape display, pilots felt that the addition of some peripheral view (95° included angle) improved their performance and the realism of the simulation. However, further increasing the peripheral view to 180°+included angle, was felt to detract from the realism of the display, although it did not debase the performance of the task. With 180°+view the pilots were conscious of the horizon rushing up and down when the simulated aircraft was rolling, and they tended to overcontrol as a result. They felt that the peripheral horizon was too close and consequently too compelling.

The few trials without an external visual display supported the view that any of the four visual cues was better than no external view.

4.2.3. *General results.* The flying task was realistic only when motion cues based on pitch and roll attitude were provided. The best combination of cues was the Skyscape with 95° view and any one of pitch and roll attitude motion, pitch attitude and roll with washout, pitch attitude with 'normal *g*' and roll attitude, and pitch attitude with 'normal *g*' and roll with washout. These motion cues with either 180°+ Skyscape or contact analogue display were slightly less satisfactory, and with 35° Skyscape the simulated aircraft was slightly more difficult to handle. With the cockpit fixed or with pitch attitude and sideslip motion, with any view the simulated aircraft did not feel like the actual aircraft. The worst possible combination of cues was fixed cockpit and the Skyscape with 35° view. The absence of yawing motion made it impossible to study directional aspects in a satisfactory manner, and it is hoped that these will be the subject of further tests.

5. *Conclusions.*

The HP 115 slender-wing research aircraft was simulated on the Aero Flight simulator using the complete equations of motion. The primary purpose of the exercise was to compare the handling of the simulated and the actual aircraft in the speed range from 50 to 130 kt. The comparisons have been based on pilot opinion, formed in general flying over the full speed range, together with recorded time histories of specific tasks. An external visual background and cockpit motion in pitch and roll were used in the comparative studies.

The handling of the simulated aircraft was very similar to that of the actual aircraft. This excellent agreement was obtained only after some effect of the aircraft's spring-tab had been included in the simulated linkage between the control stick and elevon, emphasising that the representation of the pilot's controls can be at least as important as the correct aerodyanmic representation.

An experiment comparing four visual and six cockpit motion cues was included in this exercise. Pilots were asked to fly straight and level between 80 and 90 kt through turbulence, and step sidegusts were introduced at intervals by the simulator operator. The results indicated that with good motion cues the nature of the external visual background was not very important. Of the six motion cues used those based on pitch and roll attitude were shown to be best. These results apply only to the simulated HP 115 performing a specific task and before any general conclusions could be drawn a more comprehensive exercise, using different simulated aircraft characteristics and a variety of tasks, would have to be conducted. The effects of yawing motion on simulator assessments of directional characteristics, also require study.

As a result of this exercise it is felt that the simulation of future slender-wing designs could be undertaken on the Aero Flight simulator facility with cautious optimism.

LIST OF SYMBOLS

b	Wing span (*see* Table 1)	
$\bar{\bar{c}}$	Aerodynamic mean chord (*see* Table 1)	
C_D	Drag coefficient	
C_L	Lift coefficient	
C_{L_a}	Total lift coefficient $= mg/\frac{1}{2}\,\rho\,V^2\,S$	
C_{L_T}	Trimmed lift coefficient	
C_m	Pitching-moment coefficient	
d	Moment arm of thrust about the *cg* (8 in)	
g	Acceleration due to gravity (32·2 ft/sec^2)	
I_{XX}	Moment of inertia in roll	Table 1)
I_{YY}	Moment of inertia in pitch	
I_{ZZ}	Moment of inertia in yaw	
I_{XZ}	Product of inertia	
l_p	Rolling moment due to rate of roll derivative (body axes)	
l_r	Rolling moment due to rate of yaw derivative (body axes)	
l_v	Rolling moment due to sideslip derivative (body axes)	
l_ξ	Rolling moment due to aileron derivative (body axes)	
l_ζ	Rolling moment due to rudder derivative (body axes)	
m	Mass of aircraft (*see* Table 1)	
m_Q	Pitching moment due to rate of pitch derivative	
$m_{\dot{\alpha}}$	Pitching moment due to rate of change of incidence derivative	
n_p	Yawing moment due to rate of roll derivative (body axes)	
n_r	Yawing moment due to rate of yaw derivative (body axes)	
n_v	Yawing moment due to sideslip derivative (body axes)	
n_ξ	Yawing moment due to aileron derivative (body axes)	
n_ζ	Yawing moment due to rudder derivative (body axes)	
p	Rate of rotation (roll) about the x-body axis	
q	Dynamic pressure (lb/ft^2)	
q_W	Rate of rotation (pitch) about the y-wind axis	
Q	Rate of rotation (pitch) about the y-body axis	
r	Rate of rotation (yaw) about the z-body axis	
r_W	Rate of rotation (yaw) about the z-wind axis	
S	Wing area (*see* Table 1)	

LIST OF SYMBOLS—*continued*

T_X	Component of thrust along the x-body axis
T_Z	Component of thrust along the z-body axis
V	True air speed (ft/sec)
y_p	Sideforce due to rate of roll derivative
y_v	Sideforce due to sideslip derivative
y_ξ	Sideforce due to aileron derivative
y_ζ	Sideforce due to rudder derivative
α	Angle of incidence
β	Angle of sideslip
γ	Flight path angle
ρ	Air density (0·000238 slug/ft^3)
ϕ	Angle of bank in wind axes
ϕ_B	Angle of bank in body axes
θ	Angle of pitch in body axes
ψ_B	Angle of yaw in body axes
ψ_W	Angle of yaw in wind axes
ξ	Aileron angle
ζ	Rudder angle

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APPENDIX

Equations of Motion used in Simulating the HP 115

The general purpose analogue computer was programmed to solve very complete aircraft equations of motion with six-degrees of freedom. The complete equations[9] are set out below, together with the approximations used in the simulation and the values used to programme the computer.

A.1. *Force Equations in Wind (Flight Path) Axes.*

The complete equations are:

$$m\,\dot{V} = (T_X \cos\alpha - q\,S\,C_D)\cos\beta + Y_S \sin\beta - mg\sin\gamma + T_Z \sin\alpha\cos\beta$$

$$m\,V\,r_W = -(T_X\cos\alpha - q\,S\,C_D)\sin\beta + Y_S\cos\beta + mg\cos\gamma\sin\phi - T_Z\sin\alpha\sin\beta$$

$$m\,V\,q_W = T_X\sin\alpha + q\,S\,C_{L_T} - mg\cos\gamma\cos\phi - T_Z\cos\alpha\,.$$

There were approximated by:

$$m\,\dot{V} = T_X\cos\alpha - q\,S\,C_D - mg\,\gamma$$

$$m\,V\,r_W = -(m\,\dot{V} + mg\,\gamma)\,\beta + mg\sin\phi + Y_S$$

$$m\,V\,q_W = T_X\sin\alpha - T_Z\cos\alpha + q\,S\,C_{L_T} - mg\,(1 - \tfrac{1}{2}\gamma^2)$$

where

$$Y_S = \rho\,V^2\,S\,(y_v\,\beta + y_\xi\,\xi + y_\zeta\,\zeta) + \tfrac{1}{2}\rho\,V\,S\,b\,y_p\,p\,.$$

The values used in the programme were:

$$\dot{V} = 6{\cdot}8 \times 10^{-3}\,T_N\cos\alpha - q\,S\,(0{\cdot}03 - 0{\cdot}30\alpha + 1{\cdot}95\alpha^2 + 0{\cdot}27\alpha\eta) \times 10^{-2} - 32{\cdot}2\gamma$$

$$r_W = -\frac{\beta}{V}(\dot{V} + 32{\cdot}2\gamma) + 32{\cdot}2\,\frac{\sin\phi}{V} + V\,(-109\beta + 0{\cdot}98\xi + 9{\cdot}4\zeta + 27{\cdot}9\alpha\zeta) \times 10^{-5}$$
$$+(-4{\cdot}05 + 30{\cdot}6\alpha)\,p \times 10^{-3}$$

$$V\,q_W = 6{\cdot}8 \times 10^{-3}\,T_N\sin\alpha + 3 \times 10^{-4}\,T_N\cos\alpha - 32{\cdot}2 + 16{\cdot}1\gamma^2$$
$$+q\,S\,(-0{\cdot}9 + 26\alpha + 5{\cdot}8\eta) \times 10^{-5}\,.$$

A.2. *Moment Equations in Body Datum Axes.*

The complete equations were used in the simulation, and are:

$$I_{XX}\,\dot{p} = (I_{YY} - I_{ZZ})\,Q\,.\,r + I_{XZ}\,(\dot{r} + p\,.\,Q) + q\,S\,b\,(l_v\,\beta + l_\xi\,\xi + l_\zeta\,\zeta) + \tfrac{1}{4}\rho\,V\,S\,b^2\,(l_p\,p + l_r\,r)$$

$$I_{YY}\,\dot{Q} = (I_{ZZ} - I_{XX})\,r\,.\,p + I_{XZ}\,(r^2 - p^2) + d\,.\,T_N + q\,S\,\bar{\bar{c}}\,C_m + \rho\,V\,S\,\bar{\bar{c}}^2\,(m_Q\,Q + m_{\dot{\alpha}}\,\dot{\alpha})$$

$$I_{ZZ}\,\dot{r} = (I_{XX} - I_{YY})\,p\,.\,Q + I_{XZ}\,(\dot{p} - Q\,.\,r) + q\,S\,b\,(n_v\,\beta + n_\xi\,\xi + n_\zeta\,\zeta) + \tfrac{1}{4}\rho\,V\,S\,b^2\,(n_p\,p + n_r\,r)\,.$$

The values used in the programme were:

$$\dot{p} = -0{\cdot}85\, Q\,.\,r + 0{\cdot}70\,(\dot{r} + p\,.\,Q) + q\,S\,(-0{\cdot}9\beta - 9{\cdot}23\alpha\beta - 1{\cdot}1\xi + 12{\cdot}7\zeta l_\zeta) \times 10^{-3}$$

$$+ V\,(-0{\cdot}57\,p - 3{\cdot}13\,\alpha p + 7{\cdot}62\,\alpha^2\,p + 6{\cdot}5\,r\,l_r) \times 10^{-2}$$

$$\dot{Q} = 0{\cdot}98\,p\,.\,r + 0{\cdot}068\,(r^2 - p^2) + 3{\cdot}95 \times 10^{-5}\,T_N$$

$$+ q\,S\,(0{\cdot}95 - 27{\cdot}45\alpha - 17{\cdot}8\eta - 57{\cdot}8\alpha\eta) \times 10^{-5}$$

$$- V\,(1{\cdot}049Q + 0{\cdot}514\,\dot{\alpha}) \times 10^{-2}$$

$$\dot{r} = -0{\cdot}83\,p\,.\,Q + 0{\cdot}063\,(\dot{p} - Q\,r)$$

$$+ q\,S\,(12\beta - 9{\cdot}45\xi + 41{\cdot}4\alpha\xi - 127\,a^2\,\xi - 4{\cdot}8\zeta) \times 10^{-5}$$

$$- V\,(-0{\cdot}51p + 3{\cdot}92\alpha p + 3{\cdot}71r - 27{\cdot}7\alpha r + 57{\cdot}9\alpha^2\,r) \times 10^{-3}$$

where

$$l_\zeta = 0{\cdot}0074\,, \qquad \alpha \leqslant 0{\cdot}244\,(14^\circ); -0{\cdot}00464 + 0{\cdot}0493\,\alpha\,, \qquad \alpha > 0{\cdot}244$$

$$l_r = 0{\cdot}074 + 0{\cdot}344\,\alpha\,, \qquad \alpha \leqslant 0{\cdot}244; -0{\cdot}141 + 1{\cdot}23\,\alpha\,, \qquad \alpha > 0{\cdot}244\,.$$

A.3. *Kinematic Equations.*

The complete equation,

$$\dot{\alpha}\cos\beta = -q_W + Q\cos\beta - \sin\beta\,(p\cos\alpha + r\sin\alpha)\,,$$

was approximated by,

$$\dot{\alpha} = -q_W + Q - \beta\,(p\cos\alpha + r\sin\alpha)\,.$$

The complete equation,

$$\dot{\beta} = r_W + p\sin\alpha - r\cos\alpha\,,$$

was used.

The Euler angle equations,

$$\dot{\psi}_W\cos\gamma = r_W\cos\phi + q_W\sin\phi$$

and

$$\dot{\phi}\cos\beta = p\cos\alpha + r\sin\alpha + q_W\sin\beta + \dot{\psi}_W\sin\gamma\cos\beta\,,$$

were approximated by,

$$\dot{\psi}_W = r_W\cos\phi + q_W\sin\phi$$

$$\dot{\phi} = p\cos\alpha + r\sin\alpha + \dot{\psi}_W\sin\gamma\,.$$

The remaining Euler angle equation,

$$\dot{\gamma} = q_W \cos \phi - r_W \sin \phi ,$$

was used in the complete form.

The transformations from wind to body Euler angles were simplified to:

$$\phi_B = \phi$$

$$\theta = \gamma + \alpha$$

$$\psi_B = \psi_W - \beta + \phi \,.\, \sin \alpha \,.$$

TABLE 1

Reference Dimensions and Inertia Data Pertinent to the HP 115 *Simulation.*

1 *Dimensions and weights*		
Wing area	S	432·5 ft^2
Wing span	b	20·0 ft
Aerodynamic mean chord	$\bar{\bar{c}}$	27·0 ft
Aircraft centre line chord	c_0	40·0 ft
Weight	W	4750 lb
Mass	m	147·5 slug
Cg position (aft of leading edge of centreline chord)		0·548 c_0
2 *Inertias* (*in body datum axes*)		
Moment of inertia in roll	I_{XX}	1609 slug ft^2
Moment of inertia in pitch	I_{YY}	17343 slug ft^2
Moment of inertia in yaw	I_{ZZ}	18754 slug ft^2
Product of inertia	I_{XZ}	1191 slug ft^2
Inclination of principal inertia axes to body datum axes		3·95° nose down

TABLE 2

Pilots Taking Part in the HP 115 *Simulation.*

Pilot	HP 115 experience up to 1 September 1964*	Experience in the simulated HP 115	
		Flight/simulator comparison	Comparison of motion and visual cues
	hr min	hr min	hr min
A	40 30	3 30	nil
B	48 30	2 20	3 25
C	18 30	3 30	2 50
D	6 30	0 45	2 00
E	1 05	1 20	2 05
F	nil	2 55	nil
Three others	—	2 50	—
		17 10	10 20
		27 hr 30 min total	

*Date of completion of the simulator exercise.

TABLE 3

Pilots Taking Part in the Comparison of Various Motion and Visual Cues.

Motion cues \ Visual cues	Contact analogue display (35°)	Skyscape display (horizontal angle subtended)		
		35°	95°	180°
No Motion	B, C	B, C, D, E	B, C, D, E	B, C, D, E
Pitch attitude, roll attitude	B, C	B, C, D, E	B, C, D, E	B, C, D, E
Pitch attitude, roll with washout	B, C	B, C, D, E	B, C, D, E	B, C, D, E
Pitch with 'normal *g*', roll attitude	B, C	B, C, D, E	B, C, D, E	B, C, D, E
Pitch with 'normal *g*', roll with washout	B, C	B, C, D, E	B, C, D, E	B, C, D, E
Pitch attitude, sideslip	B, C	B, C, D, E	B, C, D, E	B, C, D, E

B, C, D and E are the pilots of Table 2.

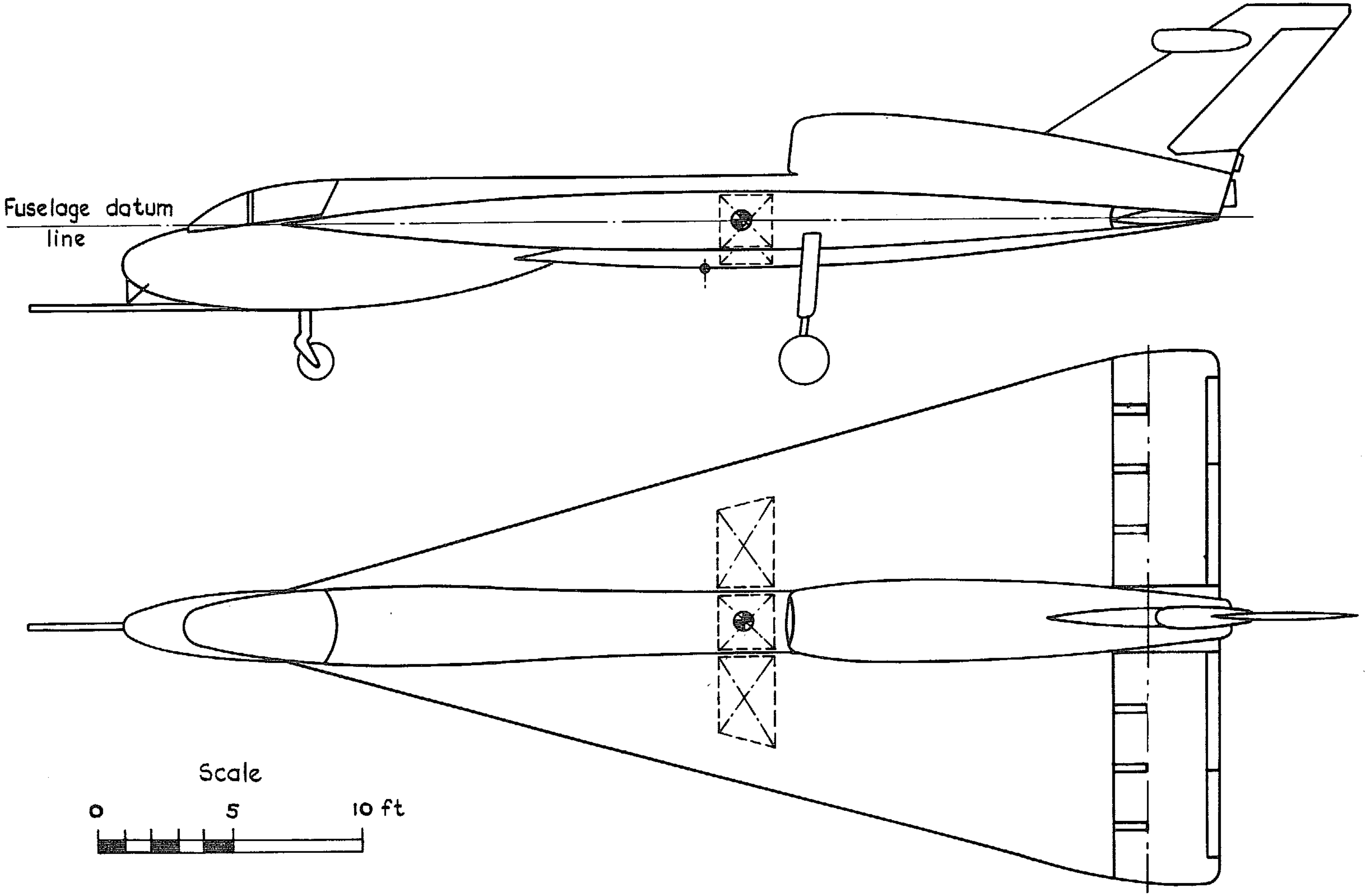


FIG. 1. General arrangement of Handley-Page HP 115.

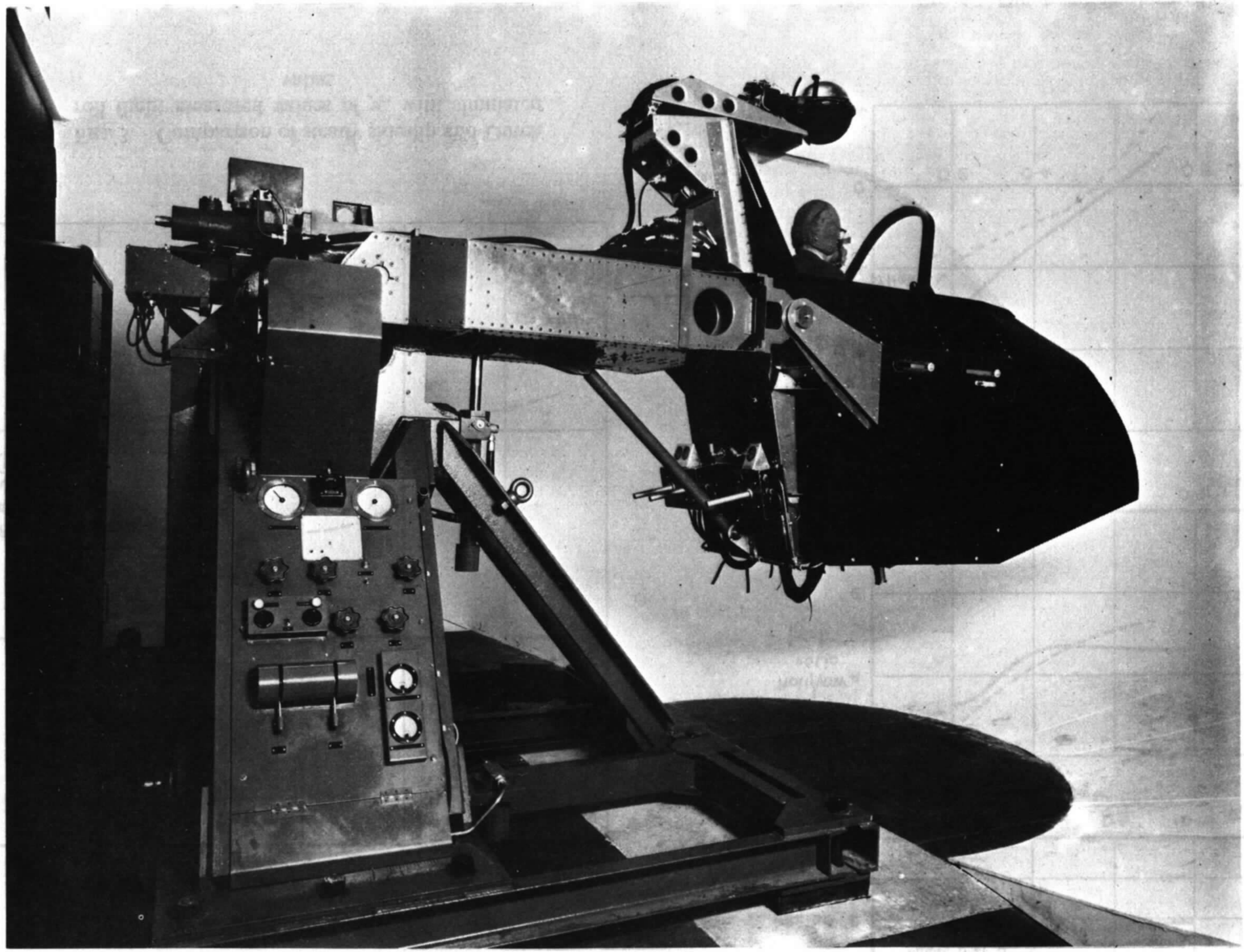


FIG. 2. General view of simulator cockpit and moving mechanism.

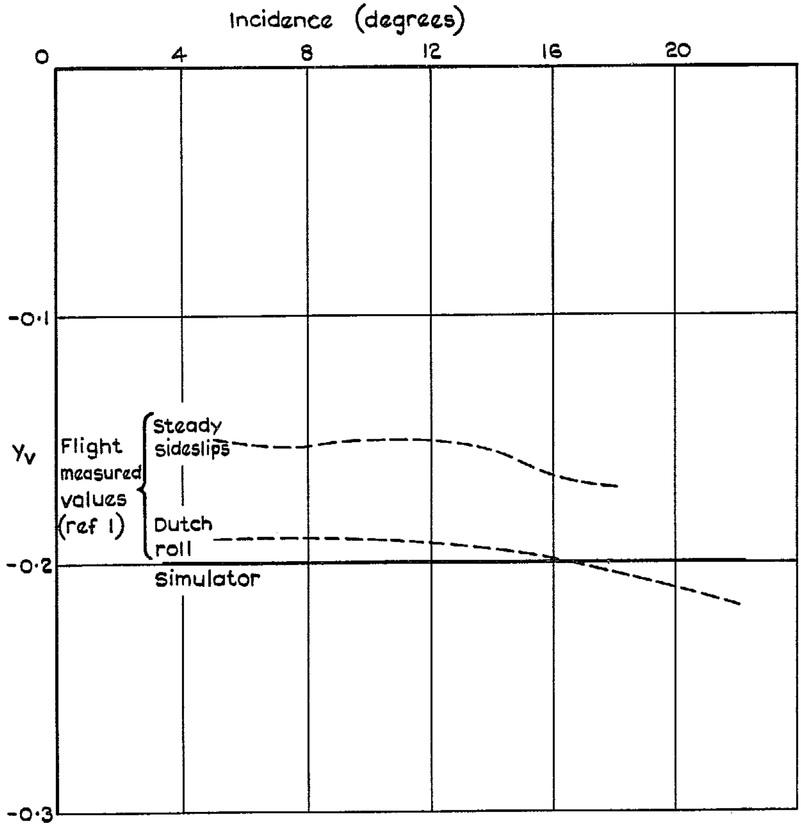


FIG. 3. Comparison of steady sideslip and Dutch roll flight measured values of y_v, with simulated value.

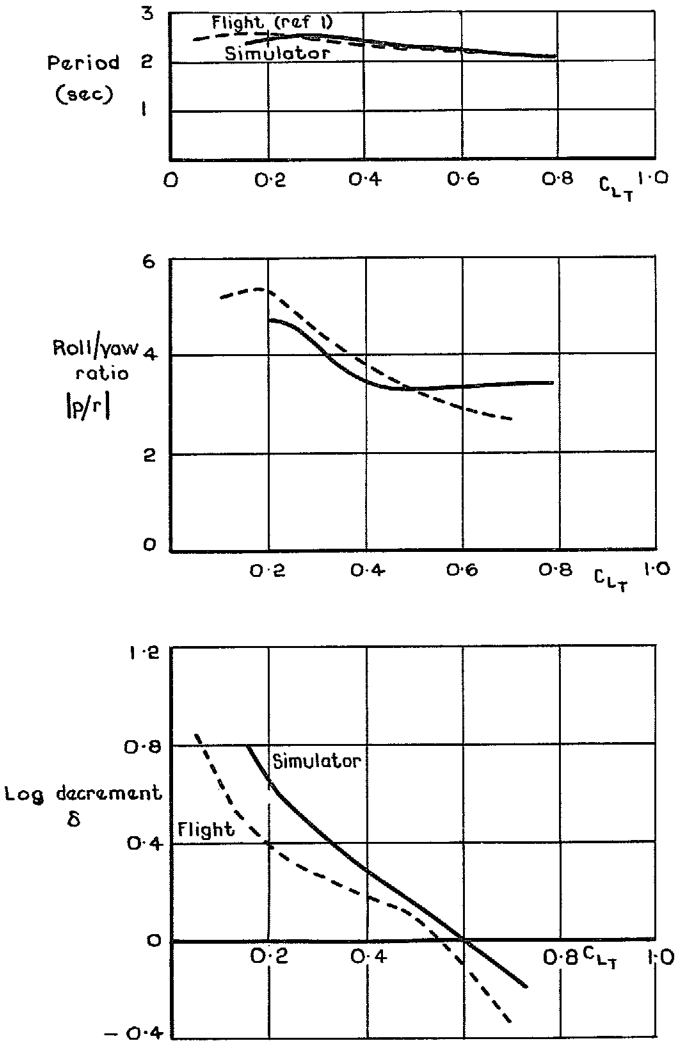
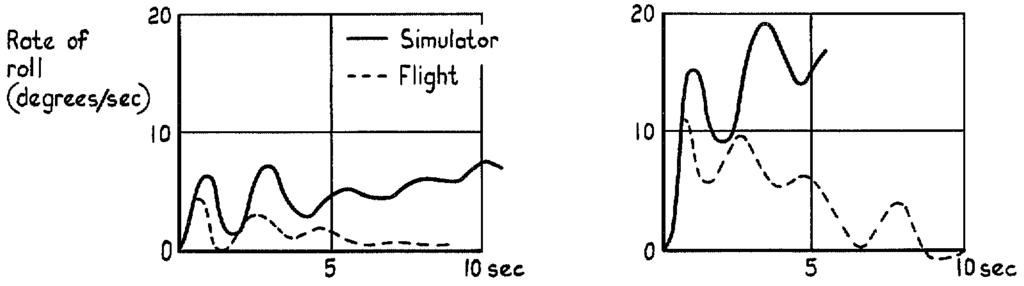
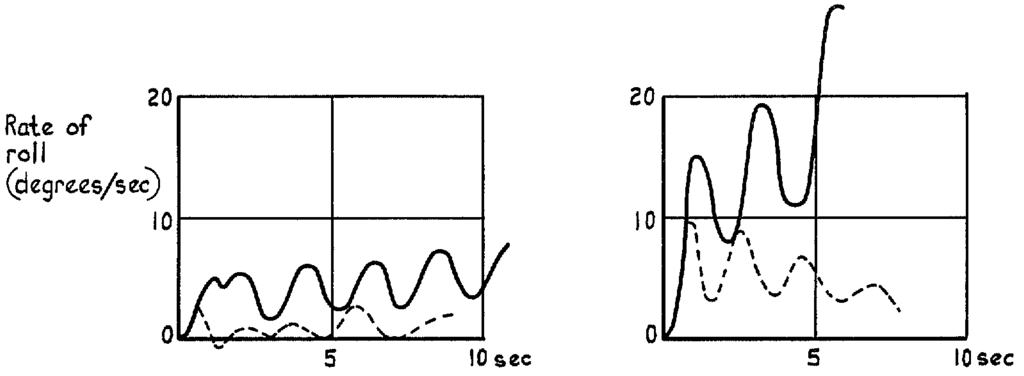


FIG. 4. Dutch-roll characteristics.



(a) 10% aileron step at 120 kt (b) 20% aileron step at 120 kt



(c) 10% aileron step at 80 kt (d) 20% aileron step at 80 kt

FIG. 5 a to d. Comparison of simulated and flight response to a step aileron input.

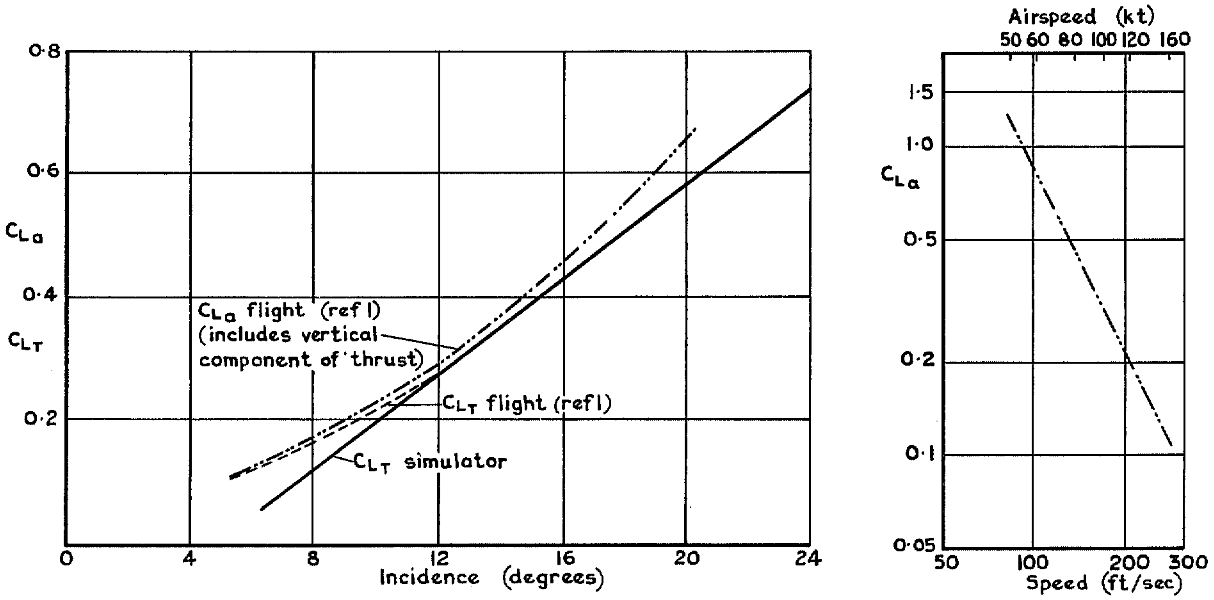


FIG. 6. Lift coefficient *versus* incidence and airspeed.

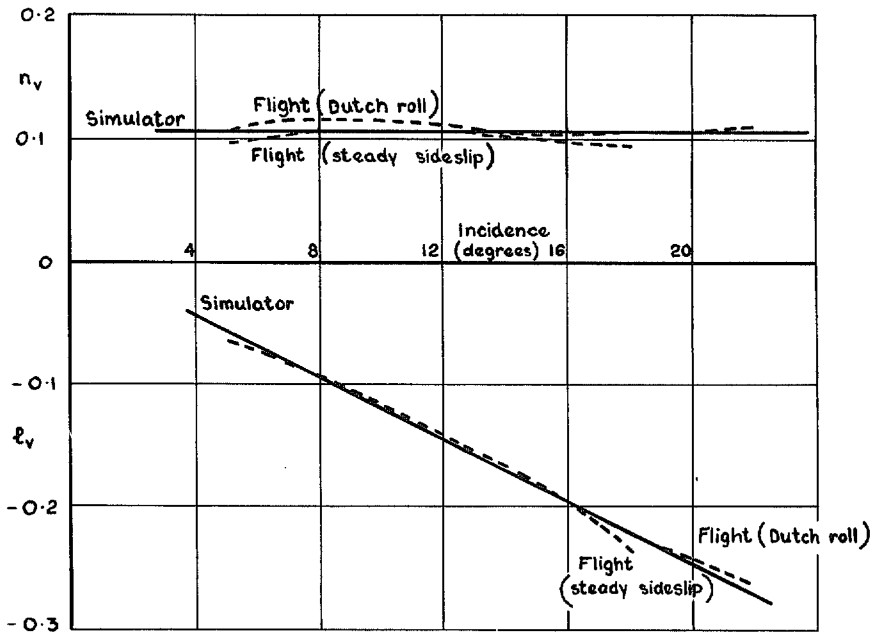


FIG. 7. Comparison of flight and simulator values of l_v and n_v in body axes.

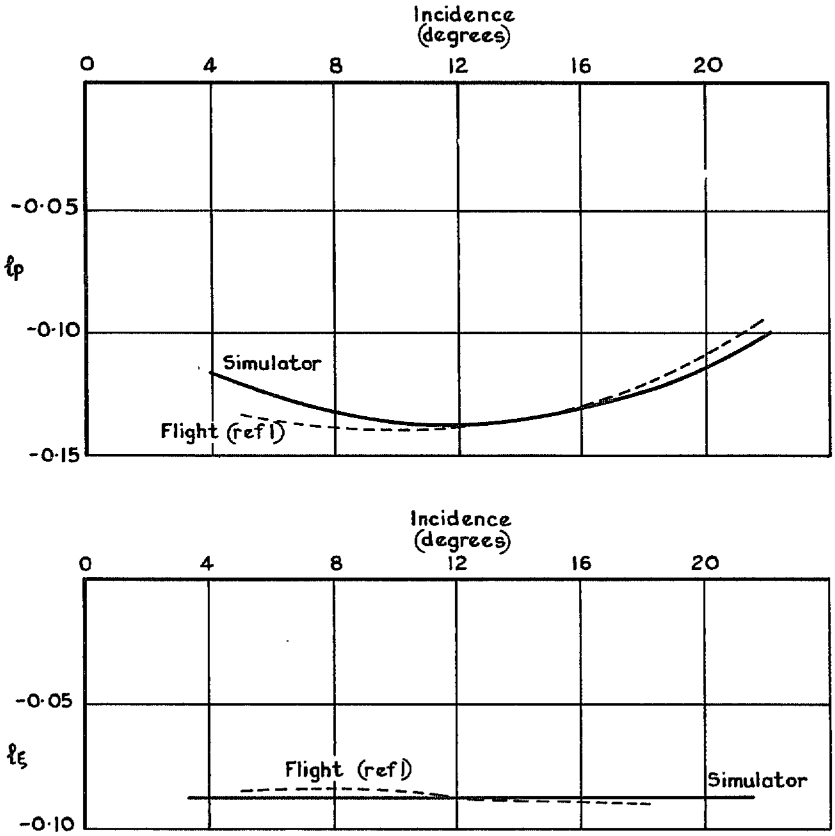


FIG. 8. Comparison of flight and simulator values of l_p and l_ξ in body axes.

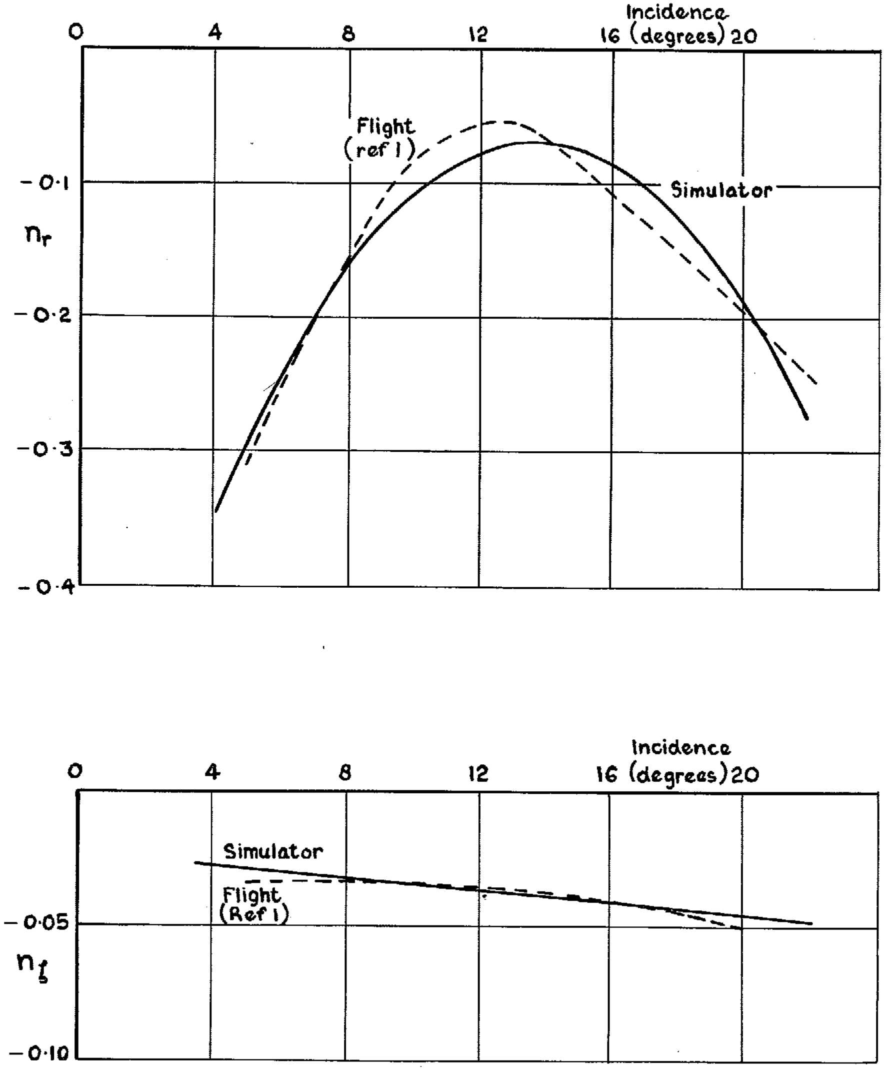


FIG. 9. Comparison of flight and simulator values of n_r and n_ζ in body axes.

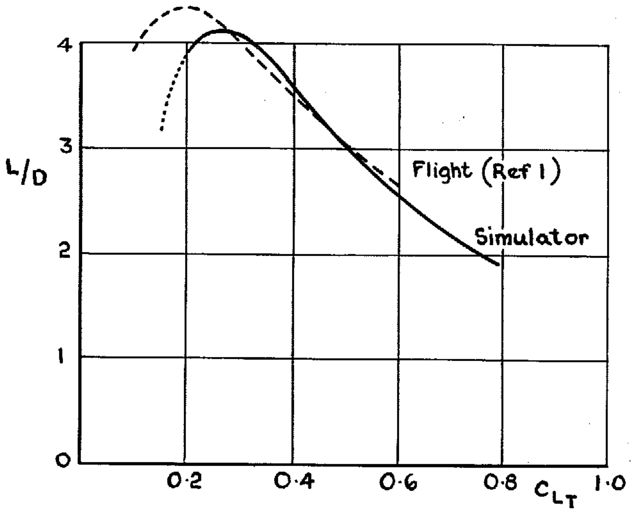


FIG. 10a. Comparison of flight and simulated values of lift/drag ratio.

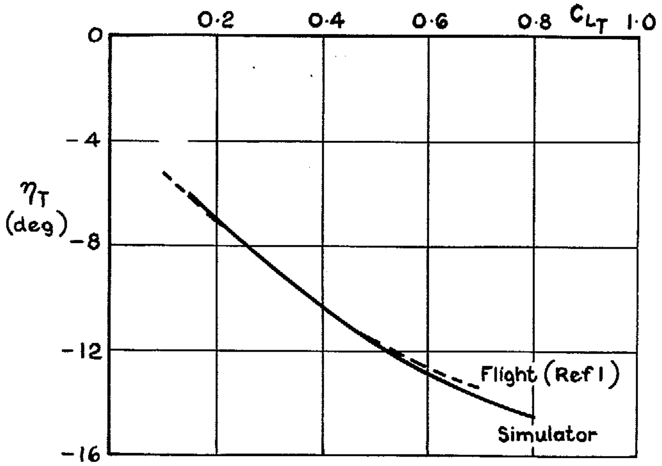
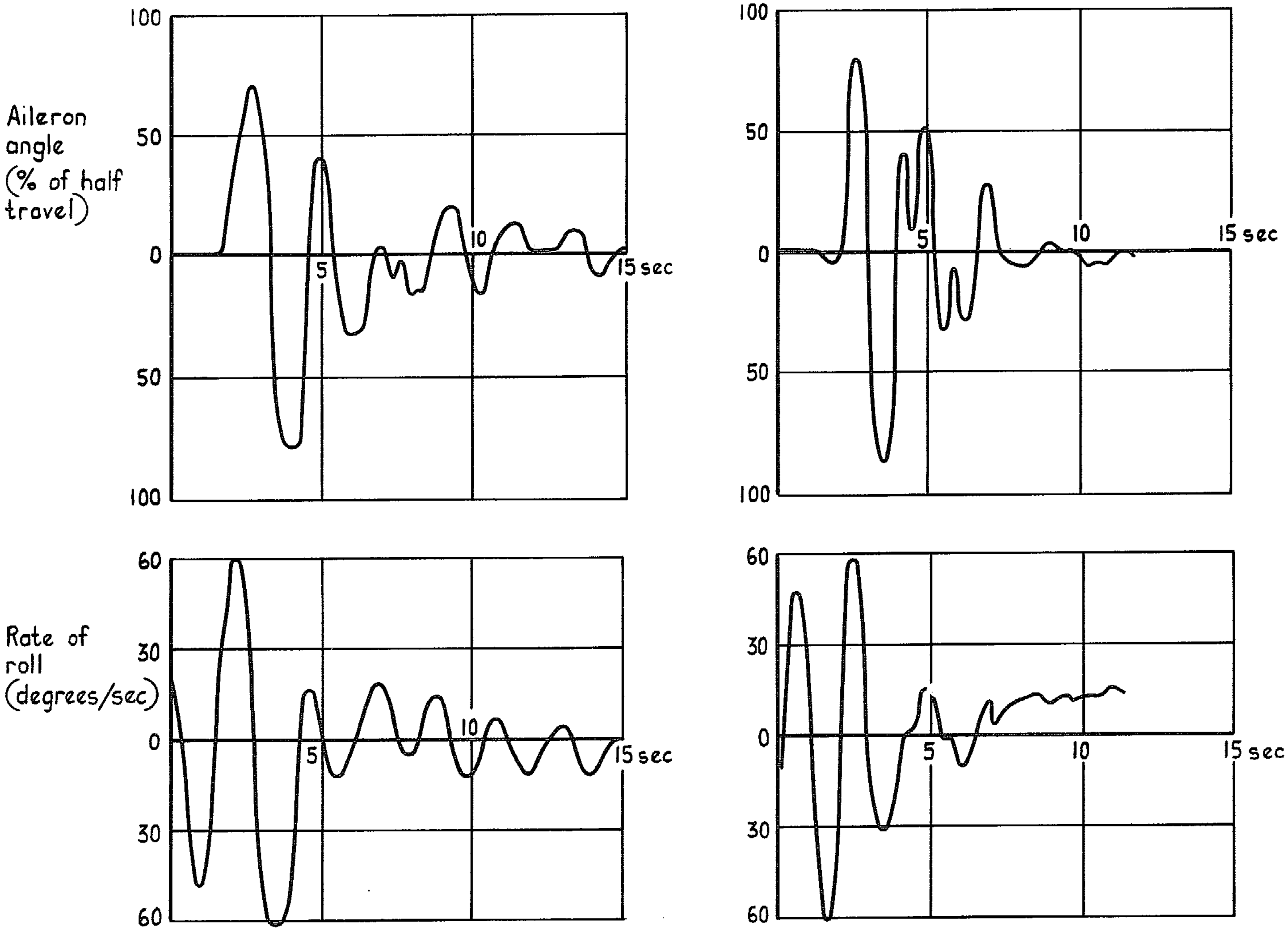
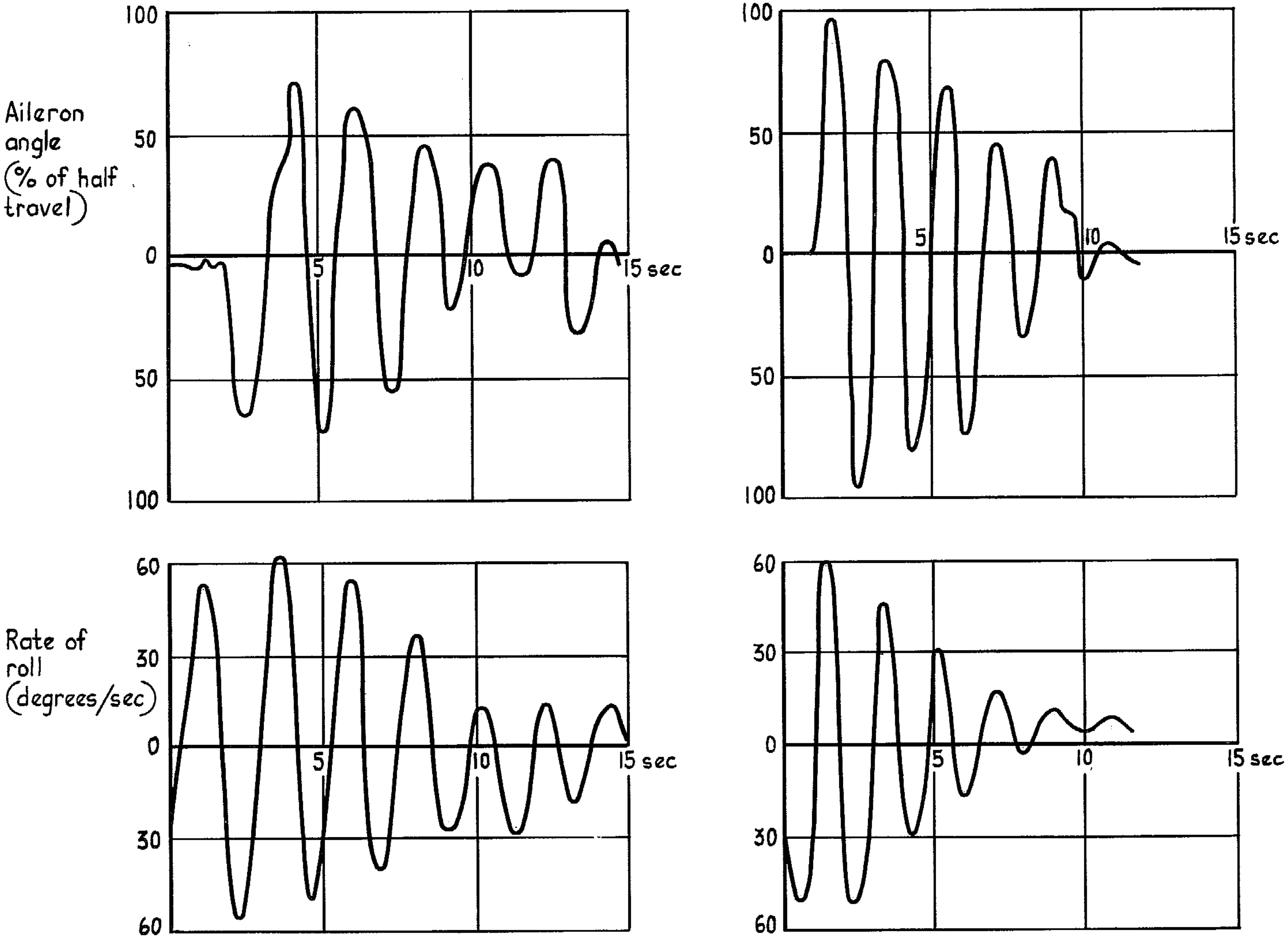


FIG. 10b. Comparison of flight and simulated values of elevator angle to trim.



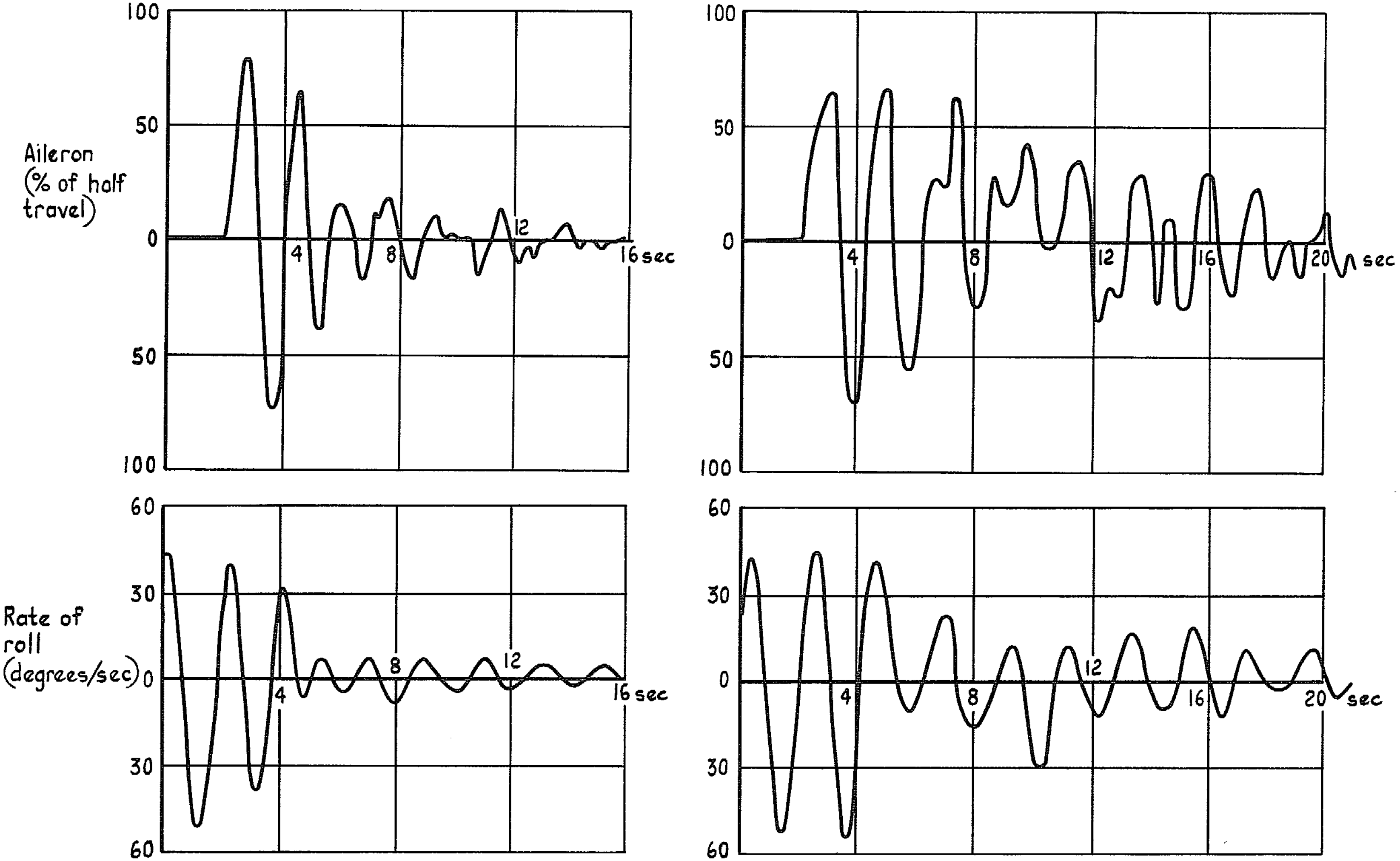
(a) Simulator **(b) Flight**

FIG. 11 a & b. Divergent Dutch roll controlled by pilot C using aileron.



(a) Simulator **(b) Flight**

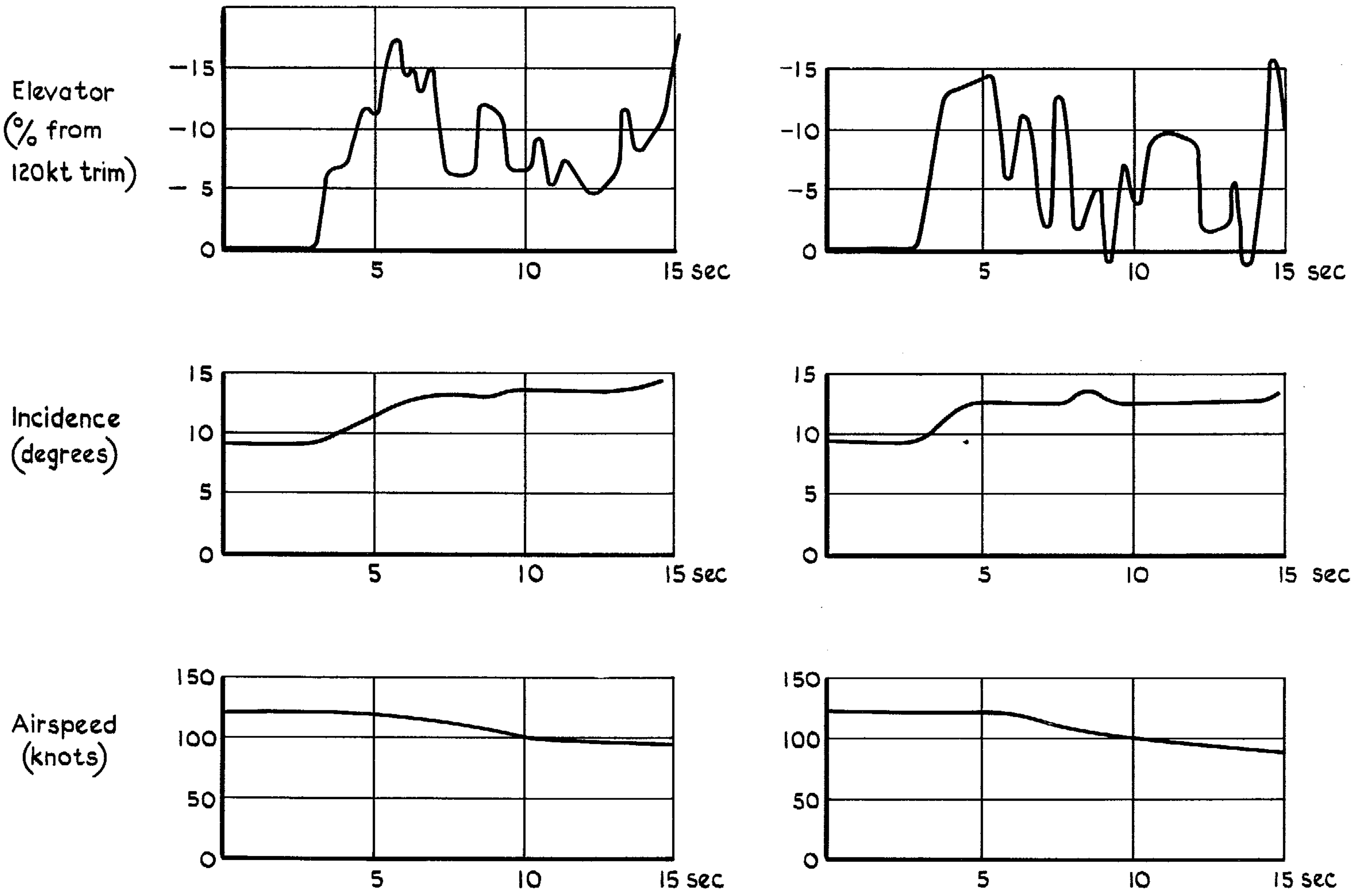
FIG. 12 a & b. Divergent Dutch roll controlled by pilot F using aileron.



(a) With contact analogue display and cockpit motion

(b) With cockpit motion but without external visual display

FIG. 13 a & b. Effect of visual cues on the control of the divergent Dutch roll by aileron.



(a) Simulator

(b) Flight

FIG. 14 a & b. Comparison of flight and simulator time histories during a speed reduction in level flight.

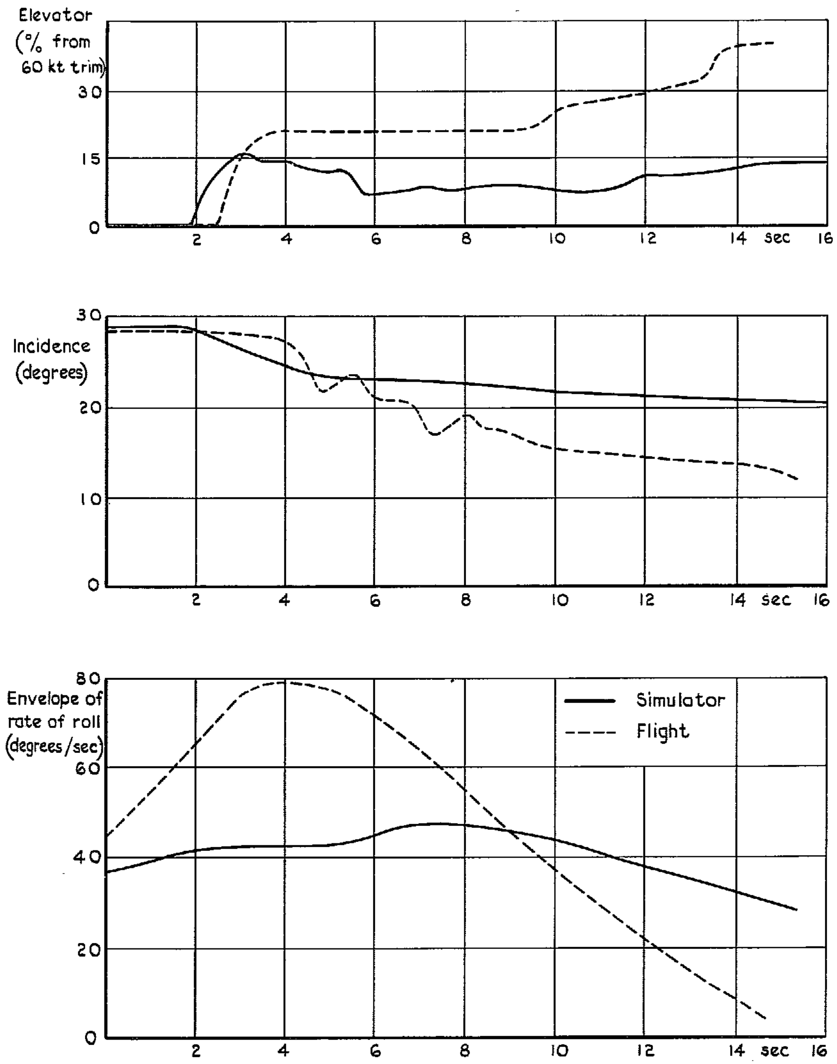


FIG. 15. Divergent Dutch roll controlled by pilot C by reducing incidence.

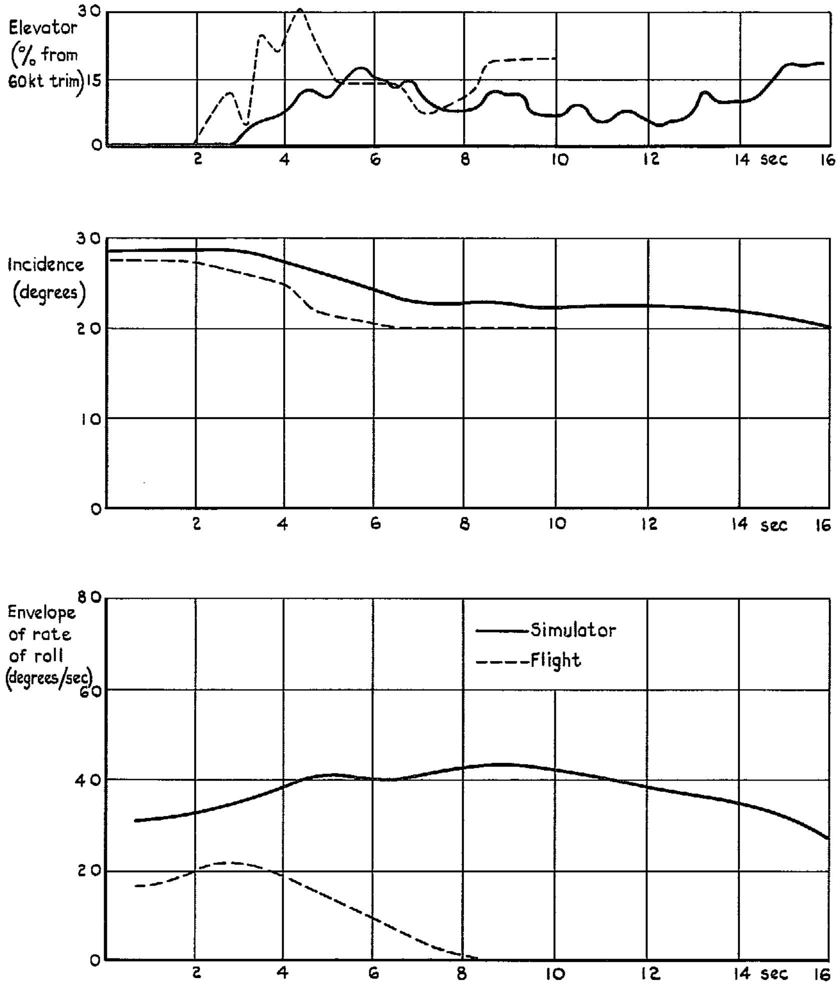


FIG. 16. Divergent Dutch roll controlled by pilot F by reducing incidence.

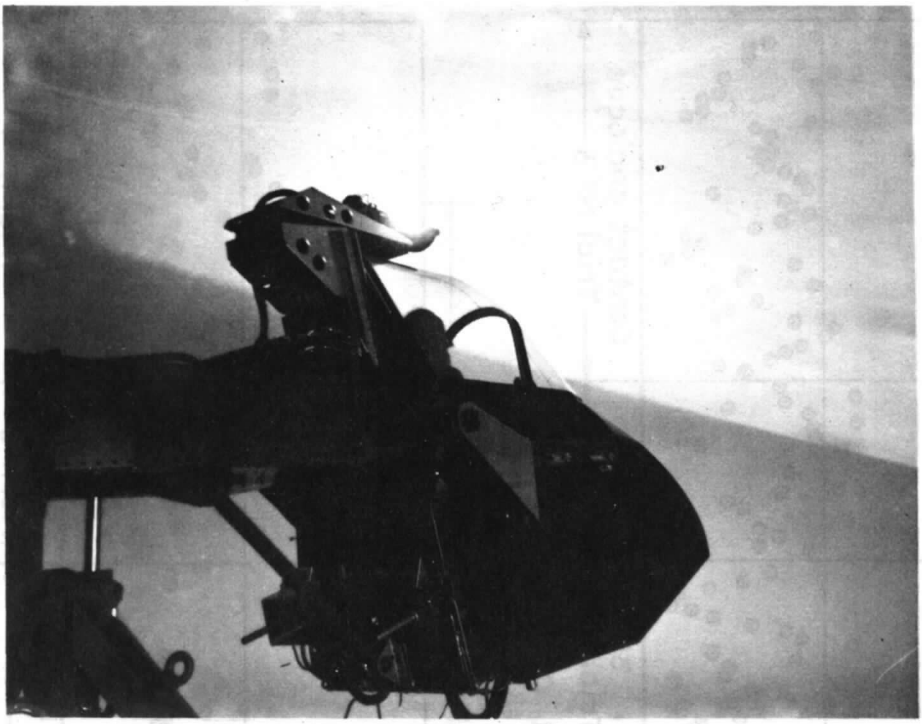


FIG. 17a. The skyscape external visual background.

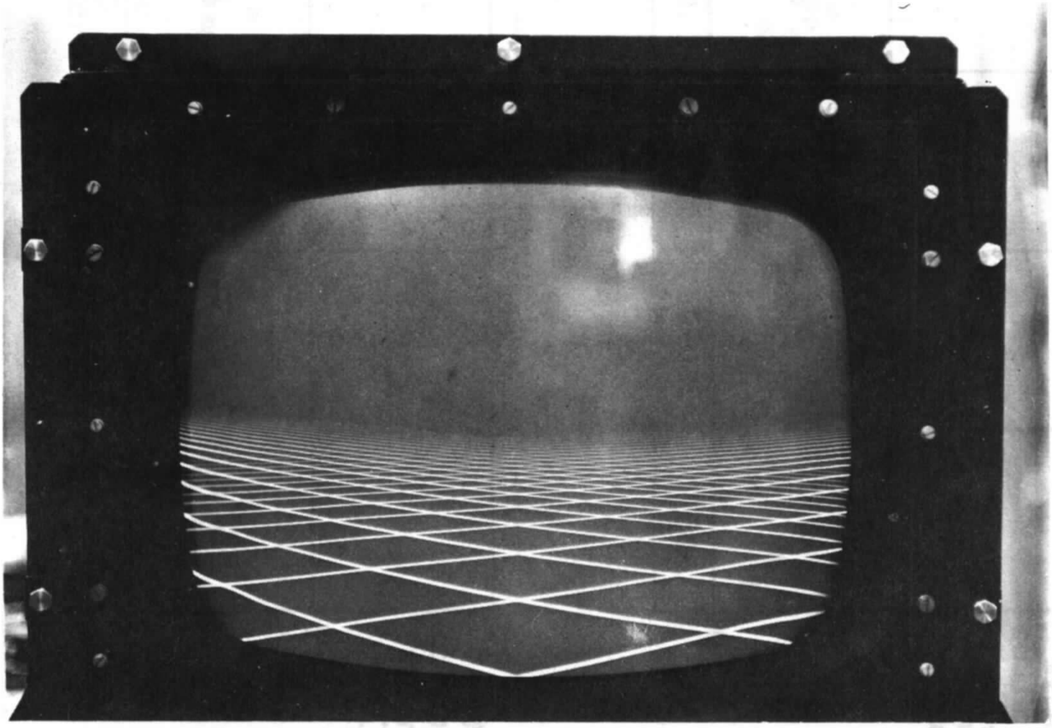


FIG. 17b. The contact analogue external visual background.

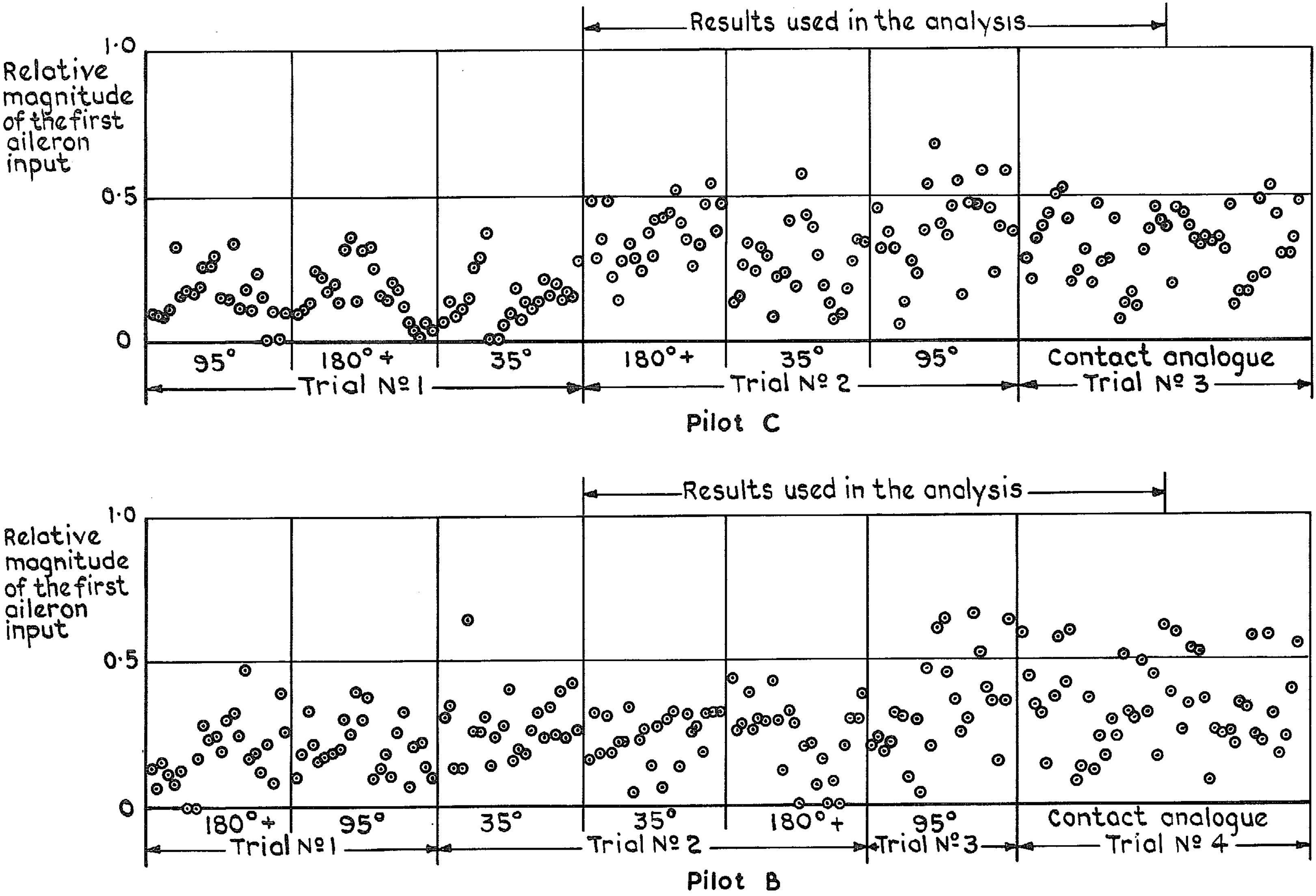
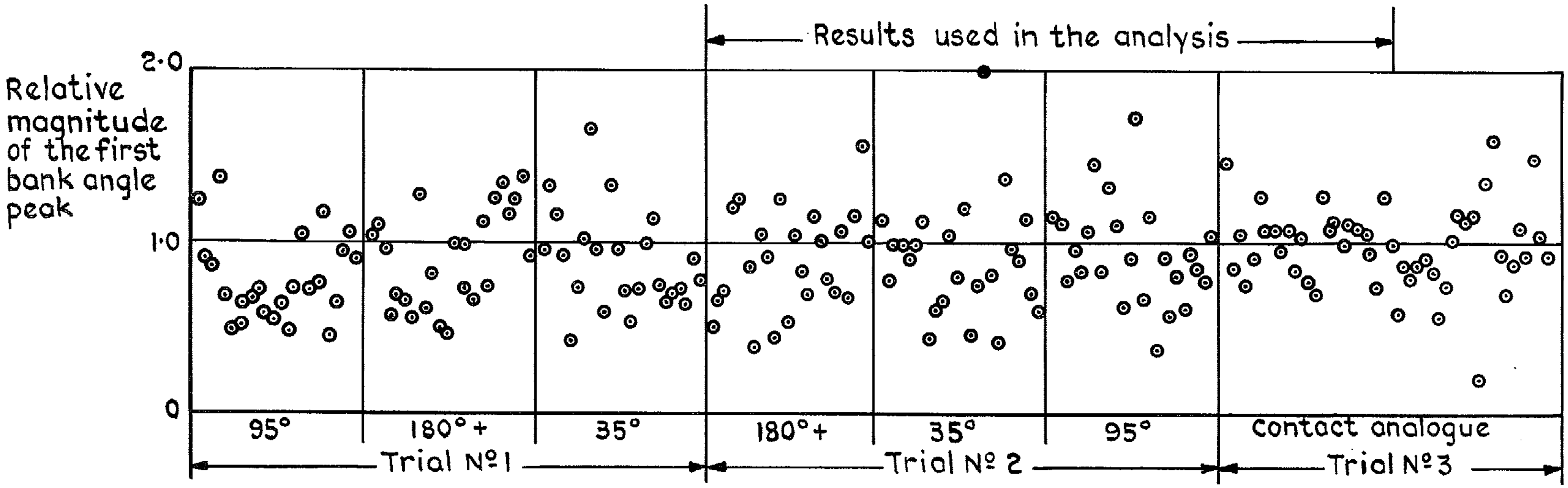
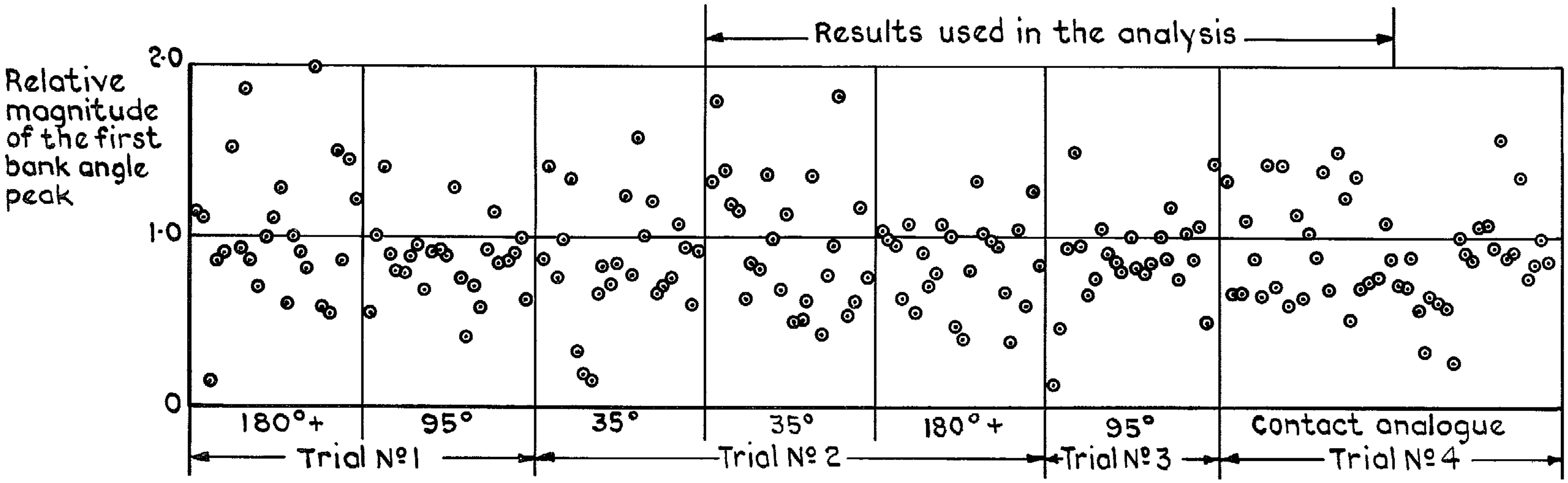


FIG. 18. Effect of learning on the relative magnitude of the first aileron input.



Pilot C



Pilot B

FIG. 19. Effect of learning on the relative magnitude of the first bank angle peak.

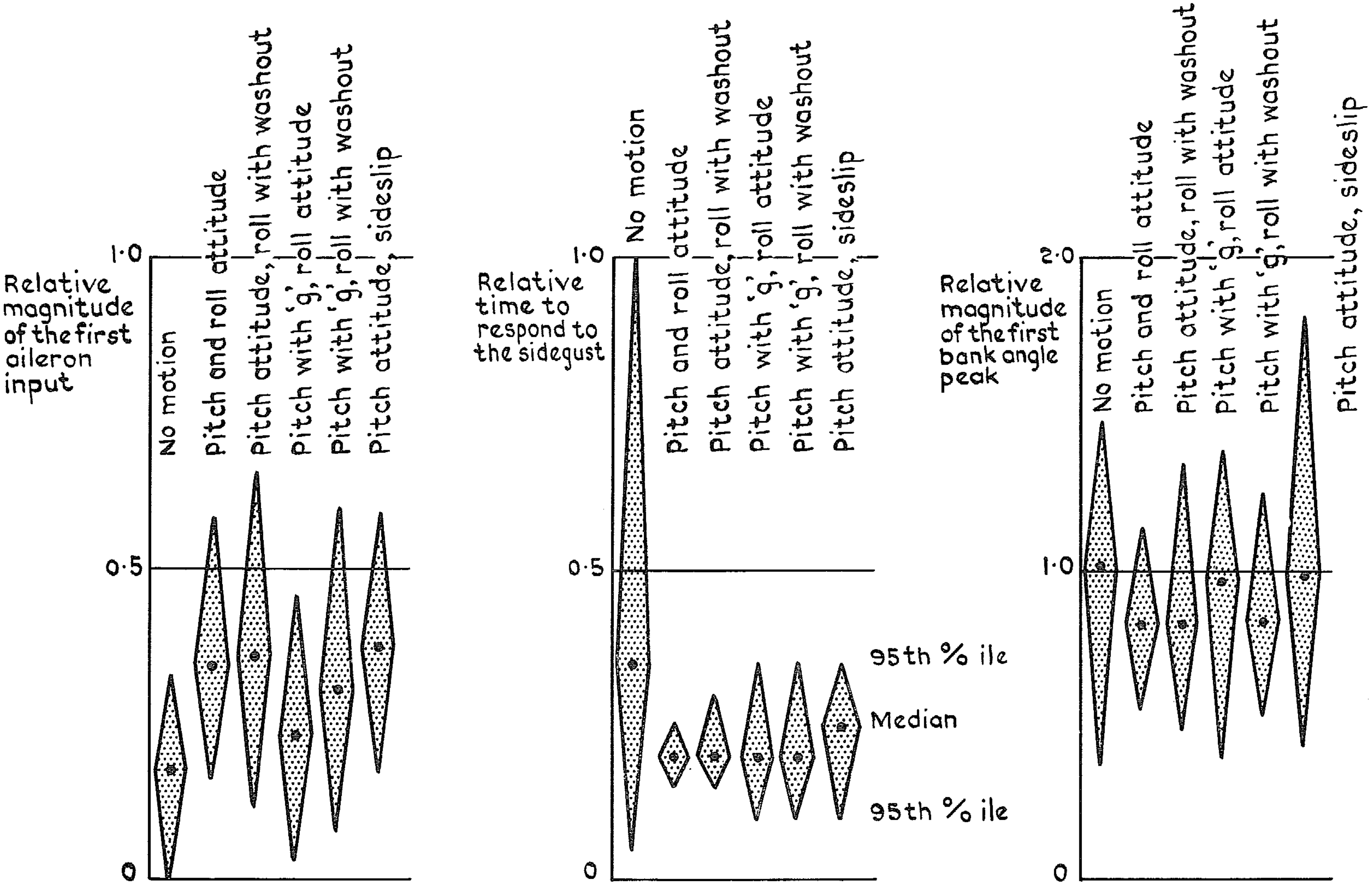


FIG. 20. Comparison of six motion cues.

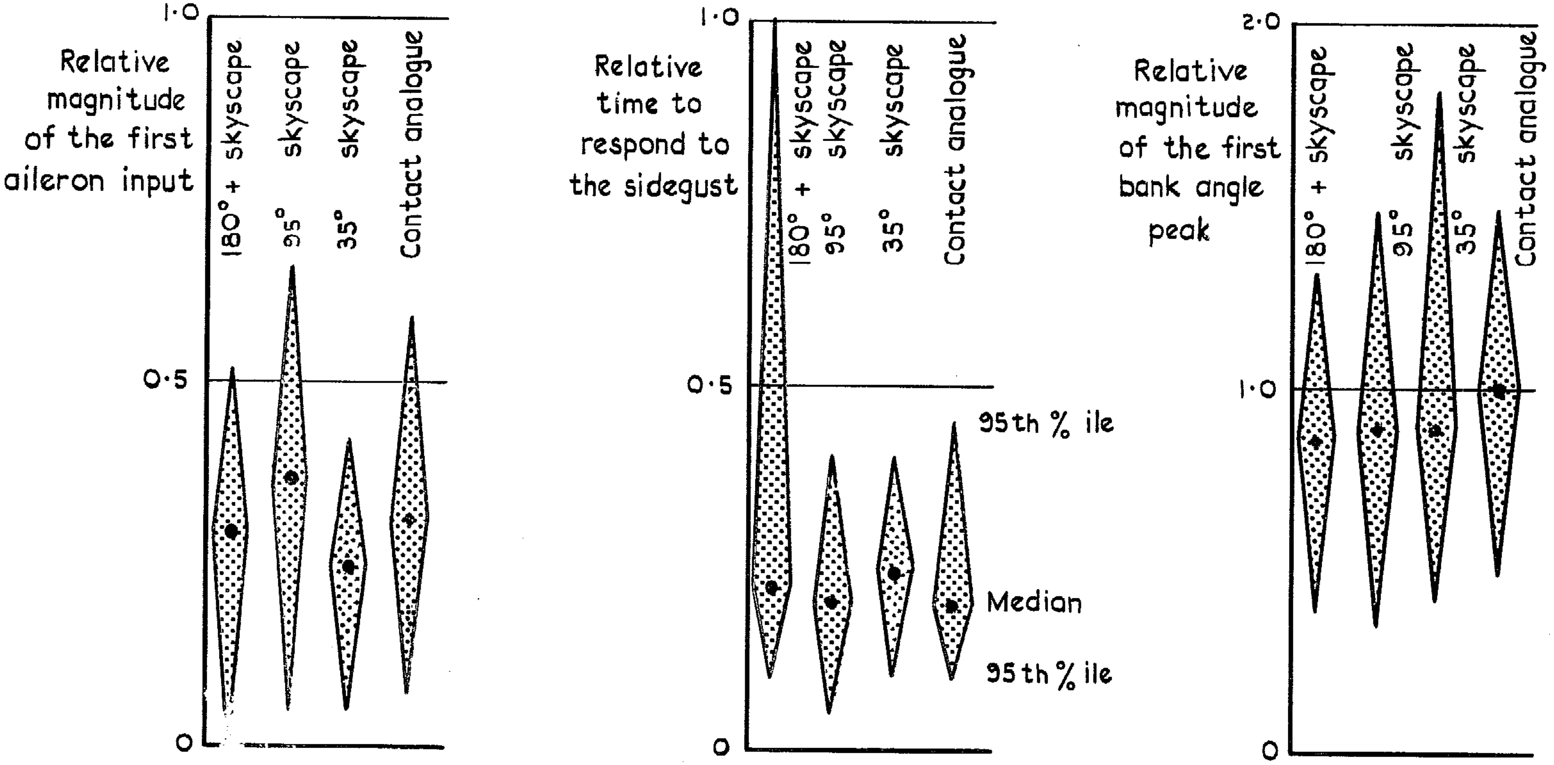


FIG. 21. Comparison of four visual cues.

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