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A Piloted Simulator Study of a Jet VTOL Aircraft in Partially Jet-Borne Flight

By K. P. King and A. McPherson
Aerodynamics Dept., R.A.E., Bedford

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A Piloted Simulator Study of a Jet VTOL Aircraft in Partially Jet-Borne Flight

By K. P. King and A. McPherson
Aerodynamics Dept., R.A.E., Bedford

Reports and Memoranda No. 3647*
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Summary.

A simulation of a small jet VTOL aircraft has been used to examine the principles of controlling such aircraft in the partly jet-borne regime. An investigation of three alternative techniques for control at constant speed was made, from which the pilots were able to select a single control technique that was effective from the lowest speed simulated (40 kt) to the highest (150 kt). The preferred technique was to use thrust to control flight path and thrust vector angle to control airspeed while using attitude (controlled by the elevator) to make fine adjustments to both flight path and airspeed.

A preliminary study of techniques for performing the transition between wing-borne and jet-borne flight was then made. Although computation limitations precluded transitions to speeds below 40 kt, some valuable information was gained. In particular, a number of transitions were performed successfully, and without great difficulty, while following an I.L.S. beam. As a result of these tests, it is believed that jet VTOL aircraft with adequate stability may have a greater potential than had been anticipated for operating in poor weather, without the complicated flight-director systems and automatic controls that have generally been thought to be necessary.

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1. *Introduction.*

Despite the amount of flying that has been done to date with jet-lift VTOL aircraft, the principles of controlling them in partly jet-borne flight have been as yet imperfectly understood. The transition between wing-borne and jet-borne flight has been considered as essentially a dynamic manoeuvre, and for the relatively unexacting task of operating from a conventional airfield little difficulty has been experienced in performing it adequately. However, the operational possibilities of flying partly jet-borne either for take off or landing at overload weight (STOL), or as part of a poor-weather approach procedure, and the need for terminating a decelerating transition accurately and economically if the aircraft is to operate into small sites, make it important that the methods of control in this phase of flight should be fully understood.

A study of stabilised flight at intermediate speeds in the transition range would provide a useful guide to the problem, but the high fuel consumption and rapid ageing of current jet-lift engines allow little time for investigating this regime in real flight. It was, therefore, felt that a flight simulation would be invaluable for a preliminary study which, it was hoped, would significantly reduce the time spent in actual flight trials.

For this study at R.A.E. Bedford a generalised light jet VTOL aircraft was represented on a ground-based, piloted flight simulator with cockpit motion and a simple external visual display. The latter, however, gave only attitude information so that the pilot had to rely mainly on instruments. Although cockpit motion in both pitch and roll was used, and indeed the simulated aircraft could be controlled about all three axes, all deliberate manoeuvres were made in the longitudinal plane since it was in only that plane that there was a redundancy of controls and a choice of techniques available.

The experiment was conducted in two stages. The first was an examination of the various possible techniques for controlling the aircraft at constant speeds in partly jet-borne flight; the second was a preliminary exploration of the problems of the transition. At the time this work was being done, the SC 1 and P 1127 aircraft were both flying at Bedford and pilots were able to make direct comparisons between actual and simulated jet VTOL flying.

In Sections 2 and 3 the simulator and cockpit arrangements are described. The first part of the experiment, which dealt with flight at constant speed, is described in Section 4, while the second part, which dealt with transitions, is discussed in Section 5.

2. *Description of the Simulator.*

The Aero Flight simulator used comprises a single-seat cockpit free to move in pitch and roll, a general purpose analogue computer to solve the six-degree-of-freedom equations of motion and ancillary equipment including visual displays and trace recorders. The simulator is described in detail in Ref. 1, and the cockpit, showing the moving mechanism and the external visual display used during this exercise, is illustrated in Fig. 1. Views of the interior of the cockpit showing the instrument panel and principal controls are shown in Figs. 2 and 3. The cockpit is moved by hydraulic jacks and can be rotated about the roll and pitch axes, the ranges of movement being ±15° in roll and −10° to +20° in pitch. Cockpit movement represented aircraft pitch and roll directly as this representation has been shown, in previous simulations[1], to provide a satisfactory degree of realism. Fig. 1 shows the external visual display which consists of a horizon and cloud scene, but no ground detail. It is therefore somewhat similar to the view from the cockpit of an aircraft flying at altitude in rather hazy conditions. The projector[1] comprises a small filament lamp which casts the shadow of a horizon ring, driven in roll, pitch and yaw from the computer, onto a hemispherical dome surrounding the cockpit.

The general-purpose analogue computer was programmed to solve the six-degree-of-freedom equations of motion in a combination of flight path (wind) and principal inertia (body) axes. The axis systems are illustrated in Fig. 4. The moment equations were solved in principal inertia axes, in which the product of inertia term is zero, and the inertia cross-coupling terms were omitted, since the product of two rates of rotation was assumed to be negligible. The force equations were solved in flight path axes since this affords a simple representation of the equations of motion, at least down to 40 kt, the lowest speed simulated. 40 kt was chosen as the lowest speed since experience in flight has shown that at speeds below about

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40–50 kt a jet VTOL aircraft is very much a hovering vehicle (although aerodynamics may affect the short-term stability) and some changes in the simulation representation would have been required for lower speeds. As the purpose of the simulation was to explore the partly jet-borne, partly wing-borne regime, it was felt that the exclusion of speeds below 40 kt would in no way invalidate the results. Turbulence was not simulated for any of the tests.

2.1. *The Simulated Aircraft.*

The simulated aircraft was not a model of any specific type but was intended to be representative of the class of small jet VTOL aircraft of which the P 1127 and SC 1 are examples. Provision was made for simulating both a single fully vectored engine and separate lift and propulsion engines and, as on both the aircraft mentioned, reaction controls about all three axes were included to supplement the aerodynamic surfaces at low speed. The moments produced by the reaction controls were proportional to engine thrust (lift engine thrust in the case of separate engines) as well as to stick movement. A simple autostabilizer providing rate damping about all three axes was also included. The coefficients used were initially chosen from those that were found in a previous simulation[2] to give satisfactory handling and were later confirmed by the experienced VTOL pilots as making the handling of the simulated aircraft resemble that of the SC 1 and P 1127.

Since the simulation was intended as a preliminary study of techniques of control in partly jet-borne flight the equations of motion and the derivatives were kept as simple as possible. The values of derivatives and other parameters used in the simulation are shown in Table 1 and the equations of motion are given in Appendix A. Fig. 5 shows a trim curve of the simulated aircraft in the form of a plot of thrust vector angle against speed for several (trim) values of incidence and thrust/weight ratio. That thrust axis inclination is an advantage[3], even in conventional flight, can be seen from the fact that the minimum thrust/weight ratio to trim in level flight, in the speed range simulated, occurred with the thrust axis inclined several degrees. Fig. 6 shows the elevator angle to trim and, like Fig. 5 is for the simulated aircraft with a single fully vectored engine. For the separate lift and propulsion engine configuration no such simple picture could be drawn for there was then an endless number of combinations of propulsion engine thrust, lift engine thrust and lift engine angle, which produced the required thrust vector for any given incidence and airspeed. The elevator angle to trim was different with each combination for, although the resultant thrust vector was the same in each case, it was only the lift engine component which affected the balance of pitching moments.

The trim changes arising from changes in the vectored thrust were the result of two effects, which were computed separately. The first, intake momentum, has, in previous simulations of conventional aircraft, been included only as a modification of gross thrust. With a vectored thrust engine the angular relationship between intake momentum and the thrust vector varies with nozzle angle setting as well as incidence. Thus intake momentum effects were considered independently and the intake momentum drag and gross thrust terms appear separately in the force equations. As shown in Fig. 7, intake momentum drag is an important component of total drag at all the speeds simulated and at the angle of incidence most commonly used. The simulated aircraft was assumed to have air intakes for the vectored engine above the centre of gravity so that its intake momentum drag gave rise to a nose-up pitching moment as shown in equation (13) in Appendix A.

The second effect is specific to jet VTOL aircraft and arises from the interference of the vectored jet efflux with the free air flow about the wing. This results in a loss of lift and a nose-up pitching moment[4]. Loss of lift was not included in the equations since a sufficiently high maximum thrust/weight ratio (1.23) was provided to avoid any limitation from that cause. The pitching moment, however, was included but, since the relationship between this and the thrust vector angle, thrust and airspeed, indicated in Ref. 4, is an extremely complicated one, a simplified form was used after the experienced VTOL pilots confirmed that it produced realistic trim changes.

Further characteristics of the simulated aircraft are illustrated in Figs. 8 and 9 which show, respectively, the proportions of weight supported by the wing and the jet over the speed range simulated and the normal and longitudinal accelerations produced by changes in the three main controls, elevator, thrust

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vector angle control and vectored thrust throttle. The propulsion engine throttle was not included since it was found to be of little use except in conventional flight (Section 4.1.1).

The engine controls (Fig. 3) and the combinations that were most frequently used are described in detail in Section 3. The instrument pnale consisted of standard conventional aircraft instruments except for an incidence gauge and a thrust vector angle indicator. Referring to Fig. 2, the latter two, together with a fuel-remaining counter made up the top row of instruments. The thrust vector angle indicator was labelled 'nozzle angle' by analogy with the P 1127 aircraft in which the angle of the vectored thrust is controlled by rotating exhaust nozzles. The middle row of instruments comprised a turn-and-slip indicator, an airspeed indicator, an artificial horizon (similar in appearance to a director horizon but indicating only pitch and roll attitude), a vertical speed indicator and a rev/min gauge for each engine. The bottom row comprised an altimeter, a gyro compass and an I.L.S. instrument. The radio altimeter, zero-reader and flap position indicator shown in Fig. 2 were not used in this simulation.

2.2. *Validation of the Simulation.*

Most of the trials, including all the systematic tests described in the following sections, were conducted using the cockpit motion and visual background described above, since previous simulation experience[1] strongly supported the belief that cockpit motion and visual cues improve the validity of the simulation. However, three trials were conducted to establish the value to the pilot, of the kinaesthetic and visual cues for this particular simulated aircraft. Pilots were asked to fly manoeuvres at a series of partly jet-borne speeds with four different combinations of cues. The results of these tests are discussed in detail in Appendix B, where it is shown that the simulated aircraft could be controlled more confidently and easily, though not necessarily more precisely, with motion and visual cues than with either one or the other alone, and that with neither cockpit motion nor external visual background the ease and precision of control deteriorated markedly.

Although the simulated aircraft was representative of the class of light VTOL aircraft in general, rather than of any particular aircraft, it was felt that greater confidence could be placed in the results of the exercise if a satisfactory flight/simulator comparison could be made. A comparison of time histories of manoeuvres at constant partly jet-borne speeds in flight using the P 1127 and on the simulator showed good agreement, and encouraged confidence in the validity of the simulation. A comparison of time histories of transition manoeuvres also showed satisfactory agreement. The flight/simulator comparison is discussed in detail in Appendix B.

3. *Layout of the Engine Controls.*

A subsidiary objective of this simulation was an attempt to establish the relative merits of different cockpit layouts of the engine controls. The throttle and thrust vector angle controls available are shown in Fig. 3. A fixed propulsive engine (T_p) and a vectored thrust engine (T_L) were simulated. The vector angle (θ_j) was adjustable by means of a lever controlling nozzle position or by buttons giving a rate of change of nozzle angle. Several arrangements of the controls were possible and they included those appropriate to both the SC 1 (partly vectored power plant with separate propulsion engine) and the P 1127 (one fully vectored power plant) engine configurations. The simulated aircraft was representative of the class of light jet VTOL aircraft and a change from SC 1 to P 1127 control layouts involved no change in either the dynamics of the simulated aircraft or in the view and visual and motion cues. The following table describes the principle functions of the controls available and should be read in conjunction with Fig. 3.

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Control	Position in the cockpit	Remarks
Propulsive engine throttle (T_p)	Conventional throttle on port bulkhead. OR Twist grip on collective lever	'Collective' was used (by analogy with a control with similar freedom in helicopters) as a convenient way of describing the control which was free to move in the up-down sense with an independent rotation of the twist grip.
Vectored thrust throttle (T_L)	Up-down sense of collective lever. OR Conventional throttle on port bulkhead.	
Thrust vector angle control (θ_j)		
(a) position control	Lever alongside the conventional throttle.	The track of this lever was 'gated' at the angle with which the simulated aircraft would hover in zero wind with a 9° nose-up attitude.
(b) rate control	Button on the front of the control column. OR Button on the end of the collective twist grip.	These buttons moved the nozzles at a fixed rate of 5°/sec.

The change-over between the configurations could be effected in a few seconds by the simulator operator, so that successive trials could be made using different control layouts but with the same dynamic response.

During most of the exercise two alternative configurations were used, closely resembling the control layouts of the SC 1 and P 1127 aircraft. The two configurations are described below:

(A) *One fully vectored power plant* (P 1127 engine configuration)

Vectored thrust: This was controlled by the conventional throttle on the port bulkhead.

Vector angle: The main control was the lever alongside the conventional throttle but in about a quarter of the trials in which this configuration was used an alternative control was provided by means of a three-position slider on the front of the stick grip. This worked in such a sense that when pushed upwards it changed the vector angle to accelerate the simulated aircraft along the flight path.

(B) *Partly vectored power plant with separate propulsion engine* (SC 1 engine configuration)

Vectored thrust: This was controlled by the collective lever operating in the up-down sense.

Propulsion thrust: This was controlled by either the conventional throttle or the collective twist grip, the change over between the two being effected by the simulator operator between trials. The direction of this thrust was fixed along the body x-axis.

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Vector angle: The main control was again the lever alongside the conventional throttle while the button on the front of the stick grip provided an alternative. A second alternative in this configuration was a similar button mounted on the end of the collective twist grip.

The angular range of the vectored thrust in the two configurations described was made approximately the same as that in the appropriate aircraft. The ranges were from 0° to +120° for the single fully vectored engine and from +67° to +100°* for the separate lift engine configuration. The travel of the lever which formed the main control of the vector angle was made approximately the same as that in the P 1127 and hence its sensitivity in the separate lift engine configuration was only about $\frac{1}{4}$ as great as in the fully vectored engine configuration. To make the sensitivities the same and still leave the choice of configuration with the simulator operator would have meant modifying the cockpit hardware quite considerably and this was not thought worthwhile since the pilots found the different sensitivities perfectly acceptable.

There were other features of the thrust vector angle control, however, which drew adverse comment. In particular the gate in the control run in the fully vectored thrust configuration significantly debased the handling when the trim vector angle was close to the position of the gate. Pilots were then frequently obliged to negotiate it when controlling speed by varying thrust vector angle. In addition the proximity and similarity of the thrust vector angle lever and the conventional throttle sometimes led to their being confused. This was particularly troublesome when the conventional throttle controlled the vectored thrust. Pilots then preferred to control the vector angle by the button on the stick.

No other systematic differences between the configurations were found and since the separate lift and propulsion engine layout had no particular merit from the handling point of view most of the trials were conducted using the fully vectored thrust configuration. However the discussion of handling which follows applies equally well to both configurations except where something specific to one of them is mentioned, e.g. propulsion engine throttle, or where thrust vector angles of less than 67° or greater than 100° are used.

4. *Handling at Constant Partly Jet-Borne Speeds.*

These tests were carried out to assess the effectiveness of controls and combinations of controls at constant, partly jet-borne speeds. The intermediate conditions between conventional and hovering flight have been difficult to study in current research jet-VTOL aircraft for a number of reasons, including high fuel consumption, reduced engine life and pitch-up or wing-dropping tendencies. Thus, even those pilots (A, B, C of Table 2) experienced in flying jet VTOL aircraft have had little opportunity to become familiar with handling in the partly jet-borne regime. This simulation allowed the pilots to explore handling qualities in partly jet-borne conditions, without the limitations of real flight. The understanding and confidence gained by the pilots during the simulator exercise have already proved of the greatest value in flight.

For this investigation, pilots were asked to make small excursions from trimmed level flight at about 8–10° incidence at each of the speeds 150, 120, 100, 80, 60 and 40 kt. The proportion of the weight supported by the jet reaction and by the wing is shown in Fig. 8 for a range of speeds at a representative incidence (8°). Six test pilots, with varying degrees of experience of jet VTOL aircraft (*see* Table 2), took part. They were briefed to spend as much time as required to make an assessment of the effectiveness of the individual controls (i.e. throttle, thrust vector angle and elevator), and of the combination of controls. The pilots were told the limitations of the simulator (e.g. incidence had to be kept within −10° to +20°) and asked to maintain their excursions within reasonable limits (±10 kt from trim speed, ±500 ft/m from level flight, and ±20° of bank were suggested) but were otherwise left to explore the configurations on their own initiative, and to develop their own techniques of assessment. The simulator operator did, however, ensure that all possible combinations of controls were investigated at each speed.

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*The angle (tilt) of the SC 1's lift engines is normally defined relative to a datum perpendicular to the fuselage datum and is called +ve when the engines are tilted so as to produce an accelerating component of thrust. Hence the range of movement is usually described as from +23° to −12°. (2° more than the simulation.)

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Pilots were encouraged to comment on each configuration both while it was being tested and immediately afterwards, and on completion of the exercise they completed a *pro-forma*, an example of which is shown as Fig. 10. These comments, together with time histories of relevant parameters, formed the basis for the interpretation of the results reported in the remainder of this section. Pilots' comments on techniques of handling at constant partly jet-borne speeds, extracted from the general comments on the *pro-forma*, appear in Appendix C. The assessments lasted, on average, 40 min at each speed for five pilots, and an average of 20 min at each speed for the sixth (*see* Table 2).

During the early tests pilots discovered many aspects of operating in the partly jet-borne regime which had been obscured in flight tests by the limitations referred to earlier. While these discoveries were exciting, and the several false trails followed provided a useful insight into the piloting of research aircraft, an historical account in the body of this Report would be tedious and perhaps confusing for the reader. In essence, the pilots came to appreciate the effectiveness of the individual controls, and the remainder of this section consequently deals first with individual control effectiveness (Section 4.1) and then discusses the way in which this understanding was used in developing a technique for controlling the simulated aircraft (Section 4.2).

4.1. *Individual Control Effectiveness.*

In the longitudinal plane the pilot is mainly concerned with the control of speed and flight path, and this control is achieved, in conventional aircraft, by use of the throttle and the elevator. Further, in conventional flight, only two of the parameters speed, flight path and incidence are independent, the third being dependent on the others. In the case of a jet VTOL aircraft in partly jet-supported flight, the situation is by no means so simple. For the control of speed and flight path there are now three controls available to the pilot (four when a separate propulsion engine is fitted) and incidence has become an effectively independent variable since, at any speed, the proportions of wing and jet lift can be varied. Before investigating methods of controlling speed and height pilots spent some time establishing the effects of each of the three (or four) cockpit controls.

The pilots controls can be thought of as having a short term and a long term (trim) effect. This can be illustrated by the response of a longitudinally stable conventional aircraft to a step input of elevator. Here the short-term response is dominated by the short-period mode and is mainly evident to the pilot as changes in pitch attitude and normal acceleration leading to a change in height. In the short term there is little or no speed change. However, provided that the speed is greater than the minimum-drag speed, in the long term the aircraft will reach a new stable trimmed condition at a slightly different speed *via* the phugoid mode. Thus, in conventional flight, the elevator can be thought of as a short-term control of flight path and a long-term control of speed.

The tests described in this section were concerned with small changes from a trimmed condition, so that the short term effectiveness of the controls in partly jet-borne flight was assessed. These short-term effects are illustrated in Fig. 9 and the long-term (trim) effects are shown in Figs. 5 and 6. The accelerations shown in Fig. 9 were due to the short-term effects of changes in the controls of 5 per cent of the full travel from the trim settings. The change in each control was made in such a sense as to produce an acceleration in the direction of flight or an acceleration upwards. In the ensuing discussion, each control is discussed in terms first of its effect on flight path and speed, which had to be accurately controlled and second of its effect on incidence and attitude which were only maintained within reasonable limits.

4.1.1. *Propulsion engine throttle.* At all partly jet-borne speeds the function of the propulsion engine throttle can be replaced by another—and often a more effective—control. A particular disadvantage of controlling speed by varying propulsion thrust was that throughout most of the partly jet-borne regime if the propulsion engine thrust was set high enough to produce a noticeable deceleration on closing the throttle it had to be opposed by vectored thrust. This would result in an uneconomical use of fuel and obviously could not be contemplated in practice. For these reasons the pilots disliked using the propulsion engine throttle, except at 150 kt when the simulated aircraft could be completely wing-supported, and most of the trials were conducted using the single fully vectored engine configuration.

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4.1.2. *Vectored thrust throttle.* The vectored thrust throttle provided a good control of flight path when the jet lift supported about half or more of the weight of the simulated aircraft. When supporting about 60 per cent or more of the weight (i.e. below 100 kt) changes in the jet lift provided the only practical method of controlling the flight path and it was an easy method to use since the interaction with speed was negligible. However, it was never thought to be as effective a short-term control over flight path as the elevator is in conventional flight. When the proportion of the weight supported by jet reaction was less than 50 per cent, (i.e. speeds above 120 kt) the throttle could still be used as an effective height control but interaction with speed began to be troublesome and in general the elevator was preferred.

In the conditions represented in this exercise the throttle never provided good speed control, and it had hardly any effect at all on speed when the simulated aircraft was largely jet-supported.

It is easy to understand how these results arise if the orientation of the jet efflux is considered. At low airspeed the jet must be almost normal to the flight path ($\theta_j \simeq 80°$ for flight at 10° nose-up attitude) so that changes in thrust level will have an immediate effect on the flight path but a very small effect on speed. Even at 150 kt a thrust vector angle of 45° is required at 8° incidence (Fig. 5) so that the angle of the thrust line relative to the flight path is 53° and changes in thrust still have more effect on flight path than on speed.

The proportions of jet and wing contribution to the total lift force at constant speed can be varied by, for example, increasing the vectored thrust and decreasing the wing incidence. Thus, to some extent, incidence and thrust can be considered interchangeable. This interchange could be of considerable importance for a pilot wishing to set optimum conditions for (say) a slow approach. Whatever the aircraft weight or the atmospheric conditions he could choose an approach speed and then adjust the throttle until the incidence was at a value which gave the maximum safe wing lift leaving an adequate margin for manoeuvre or external disturbance.

In the simulated aircraft throttle changes gave rise to a small change in trim but did not otherwise affect the attitude.

The pilots considered that the vectored thrust throttle provided the only practical short-term control of flight path when 60 per cent or more of the weight of the simulated aircraft was jet supported (100 kt and lower speeds in Fig. 9) and that the elevator was the best immediate control of flight path when 50 per cent or less was supported by jet lift.

4.1.3. *Elevator control* (including pitch reaction control) (Fig. 9). The elevator gave good short-term control of flight path at 150 kt, but the effectiveness reduced with speed until, at 40 kt, it had practically no effect on the flight path. The elevator remained the best control of flight path down to about 100 kt and could still be used for fine adjustments down to 60 kt.

The elevator, by changing pitch attitude and hence thrust vector angle relative to the flight path, could be used to control speed in the short term at all the speeds simulated, but at high speed the interaction with flight path control made it unacceptable and it was clearly inefficient when thrust vector angle could be changed without altering attitude. At low speed, interference with flight-path control was not a problem but the large changes in attitude necessary to control speed made the use of elevator less practical than use of thrust vector angle.

Elevator was always the best short-term control of incidence but care had to be taken to avoid exceeding the incidence limits. Generally speaking the lower the speed the easier it was to exceed the incidence limits, particularly if the elevator was being used to control flight path or speed. However below about 80 kt, because of the low proportion of wing lift the penalties that might be incurred in the real flight case, such as the stall, would not be very severe.

The elevator always gave direct control of attitude.

4.1.4. *Thrust vector angle control.* Thrust vector angle was an effective control of speed in all the conditions simulated, the effectiveness increasing as the thrust vector approached the vertical and the thrust was increased. When the thrust vector was close to the vertical, changes in its angle made practically no short-term difference to the flight path, and even when it was within 45° of the horizontal thrust vector angle was considered an impractical control of flight path because of the large interaction with airspeed.

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The short-term effect of thrust vector angle on incidence was negligible but the trim changes resulting from changes in thrust vector angle interfered with control of attitude.

4.2. *A Technique for the Control of the Simulated Aircraft.*

The understanding of individual control effectiveness throughout the speed range was a necessary first step which led on to the development of a technique for the complete control of the simulated aircraft. In early trials three control techniques were examined and the titles applied to them 'thrust vector angle constant', 'throttle constant' and 'attitude—sensibly—constant' are largely self-explanatory. These represented interim suggestions on methods of control to be used while the pilots explored the handling of the simulated aircraft and before they had formed their own judgements of the best control technique. It is worthwhile recording that the pilots who had no previous VTOL experience were completely unable to set up a given trimmed condition until they tried one of these techniques. The results of the study of these techniques are described in Table 3 and Appendix C.

The attitude—sensibly—constant technique, in a slightly developed form, proved to provide the most successful method of controlling the simulated aircraft. However, before going on to discuss this, a brief account will be given of the other two techniques and the reasons for discarding them.

4.2.1. *The discarded techniques.* For the 'thrust vector angle constant' technique, pilots were asked to trim the simulated aircraft in level flight at 150, 120, 100, 80, 60 or 40 kt at about 8° incidence, and then to leave the thrust vector angle control fixed while making small excursions in flight path and speed. This was a practical method of control at all the six test speeds, but it was not without disadvantages as can be gathered from the replies by pilots to a questionnaire (Fig. 10) which have been collected in Table 3b and Appendix C Section C.2. At the lowest speeds simulated this technique worked well since the throttle controlled the flight path without interfering with speed control, while the elevator, by changing the aircraft attitude and hence the direction of the thrust vector, controlled the speed. However, it is clearly inefficient to change the orientation of the thrust vector by tilting the whole aircraft when the thrust vector angle control could be used. As speed increases the elevator becomes an increasingly effective flight path control and some confusion arose regarding which of throttle and elevator should be used for this function, as can be deduced from Table 3b. In any case, whichever controller was used to initiate, for example, a speed change, the other had to be adjusted to maintain the chosen flight path.

An attempt was made to extract data from the time histories for statistical analysis, but differences between pilots disguised any possible variations in the effectiveness of the technique at different speeds. This result would not be particularly surprising in any circumstances, since it is known that pilots differ greatly in their performance even of rigorously controlled tasks. In the present exercise, where the task was left largely to the initiative of the individual pilot, differences in performance sufficient to hide any differences between speeds, were to be expected. Nonetheless, it was felt to be worth extracting the frequency with which the rate of climb exceeded ±10 ft/sec and the speed was more than 10 kt from the trim value, since the pilots had been briefed that these figures represented reasonable limits to gentle manoeuvring. The actual number of crossings of the limits and the time spent in assessing the configurations varied considerably. (From two ±10 kt and three ±10 ft/sec crossings in 93 sec by pilot D at 80 kt, to seven ±10 kt and seventeen ±10 ft/sec crossings in 886 sec by pilot A at 100 kt.) Fig. 11 shows the frequency of the errors for the six speeds simulated. The broadest part of the diamond is at the mean frequency, while the top and bottom represent respectively the highest and lowest frequencies attained. A general trend towards better control of speed and poorer control of flight path as speed increases is apparent although the pilots made no specific comments to this effect.

For the 'throttle constant' technique pilots were again asked to trim the simulated aircraft in level flight at 150, 120, 100, 80, 60 and 40 kt at about 8° incidence and then to leave the vectored thrust throttle fixed while making small flight path and speed excursions. This method was of practical use at the higher test speeds but at the lower speeds, where the wing lift was low, changes in incidence arising from elevator movements made little change in the lift and so were ineffective in adjusting the flight path. Pilots' comments on this technique have been collected in Table 3c and Appendix C Section C.3. Fig. 12 shows the frequency with which the rate of climb exceeded ±10 ft/sec and the speed was more than ±10 kt from

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the trim value. The actual number of crossings of the limits and the time spent in assessing the configurations varied from two ±10 kt and three ±10 ft/sec crossings in 90 sec by Pilot C at 100 kt, to five ±10 kt and six ±10 ft/sec crossings in 877 sec by Pilot F at 60 kt. The same trend as in Fig. 11 is apparent and since the pliots' comments on this technique are quite different, it appears that the trend is not the result of the particular control technique used but is probably a feature of the simulation.

4.2.2. *The preferred control technique.* The preferred control technique was called 'attitude—sensibly—constant' since the pilots were asked to use the vectored thrust throttle and the thrust vector angle control as primary controllers of flight path and speed, while maintaining roughly constant attitude by use of the elevator control. At first the injunction to maintain constant attitude was interpreted by the pilots as implying that the elevator should be used to reduce the effects of trim changes caused by moving the throttle or the thrust vector angle control. However, as their experience of and confidence in handling in partly jet-borne flight increased, the pilots began to use the elevator positively as a fine control of speed or flight path. Some evidence of the early more rigid control of attitude can be found in the attitude traces of Figs. 13a and 14a, while the later more liberal interpretation can be seen in Figs. 13c and 14c.

In the conditions flown (approximately 8° incidence) the effectiveness of the controls for the purpose for which they were used increased as speed was reduced, i.e. as the jet efflux came closer to the vertical and as more of the weight was jet supported. The frequency of errors exceeding ±10 ft/sec and ±10 kt (Fig. 15) was not significantly different from that with the other techniques but the pilots' comments indicate that this was a more effective technique throughout the speed range. Table 3a shows that there was some disagreement amongst the pilots as to the highest speed at which this technique would be used. Although four of the pilots felt that about 100 kt was the highest speed at which they would use this method of control, with one exception their reasons for rejecting it at higher speeds were on the grounds of inefficiency (Table 3a). Pilot C rejected the technique at speeds above about 100 kt on the grounds that the effects of throttle and thrust vector angle became confused, but, nonetheless, he wrote in his general comments (Appendix C Section C.1) 'This method is probably the most promising single method of control'. The importance in the change of interpretation of the use of the elevator control lies in the attitude of mind of the pilots. This change came about when the pilots started thinking of the jet efflux as a single entity. Some pilots thought of the jet as a force vector, others as a supporting pillar but, whatever their conception, the idea of a single physical medium enabled them to make economical and co-ordinated use of the cockpit controls to achieve a sure command of the simulated aircraft. This conception of the jet is the most important result of this part of the simulation exercise. In particular it allowed the experienced VTOL pilots, who between them had flown partly jet-borne many times, to fly the actual aircraft with a new confidence and understanding. It is hardly surprising that this result had not been achieved in flight when one remembers that the pressures on the pilot in an actual aircraft combine with the low fuel state to reduce the time available for calm consideration. Like many important results, once the discovery has been made it is both obvious and logical.

One further aspect of this technique should be emphasised. When using the P 1127 control configuration with the thrust vector angle controlled by a lever adjacent to the throttle (*see* Fig. 3), pilots sometimes confused the two levers. More important, this configuration demanded that the primary control of both speed and flight path was by the left hand. When the aircraft was substantially jet supported, many of the pilots were reluctant to leave the throttle and would have been even more loth to do so in a real flight situation. (One pilot overcame this difficulty by using his left hand to move the throttle and his right to change the nozzle angle while attempting to maintain constant attitude by gripping the stick between his knees!)

5. *Investigation of Transition Techniques.*

Having settled on a preferred technique for control in the partly jet-borne regime the pilots were in a good position to make a preliminary study of transition techniques. The term 'transition' is here used to describe the process of changing from conventional wing-borne flight to hovering or low speed jet-borne flight or *vice-versa.* The former is referred to as a decelerating transition and the latter as an accelerating

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transition. In practice decelerating transitions are more difficult to perform for two main reasons. One is that in a decelerating transition aerodynamic lift is decreasing and the pilot must devote a great deal of his attention to compensating for this with jet lift if he is to avoid hitting the ground, whereas in an accelerating transition height control does not demand so much attention for the total lift normally increases. The other is that in a decelerating transition the pilot will normally be aiming to arrive at a chosen point and the flight path must be controlled much more closely than when accelerating away from a point.

Attention was therefore confined to decelerating transitions and, although complete transitions to the hover could not be performed, owing to the low speed limitation of the simulation, it was considered that decelerations down to 50 kt covered the region of interest. At this speed the simulated aircraft was almost fully jet-borne, as can be seen from Fig. 8, and it certainly handled like a hovering vehicle. This view was confirmed by the experienced VTOL pilots who took part in the tests. Even if there had been no speed limitation, hovering would not really have been feasible for the visual display did not provide plan position information. A visual display providing both range and plan position information was planned for a later experiment but it was considered that a useful preliminary study of transition techniques could be made without this.

The transitions performed fall into three main categories:

(1) Transitions with constant flight path or rate of descent (Section 5.1).

(2) The 'stepped approach technique' consisting of a deceleration in level flight to an intermediate speed, a constant speed descent, and a final level decelerating transition (Section 5.2).

(3) Transitions performed on an I.L.S. approach (Section 5.3).

The investigation was qualitative in nature being mainly confined to examining the problem of controlling the aircraft while decelerating at different rates. Two different deceleration techniques were employed and their relative merits were assessed from the point of view of ease of control. Because the pilot was not presented with range information it was not strictly meaningful to assess the influence of technique on task performance, i.e. on the ability to terminate the transition at a chosen point. Nevertheless, the distance covered during the transition was recorded to see whether any of the techniques would produce consistency despite the lack of range information.

As in the study of control at constant speed the pilots were encouraged to comment both during and after each sortie and these comments form a valuable part of the results. In addition a questionnaire was completed by four of the pilots at the end of the exercise and this, together with a brief summary of their replies, is shown in Table 4. Their individual replies are given in more detail in Appendix D.

5.1. *Transitions with Constant Flight Path or Rate of Descent.*

Transitions were first performed in level flight and the relative merits of two different methods of decelerating were examined. In the first, called the 'constant thrust vector angle deceleration technique', the pilot selected a predetermined thrust vector angle, using the lever control, and did not then alter it until he reached 50 kt. The thrust vector angles used were 120°, 90° and 81° (the hover gate). In the second, called the 'controlled deceleration technique', the pilot aimed to decelerate from 150 kt to 50 kt in 100 sec (i.e. a mean deceleration of 1 kt/sec), varying the thrust vector angle as necessary to produce the required deceleration. This rather slow deceleration was chosen to ensure that the pilot used the thrust vector angle control progressively and hence to bring out the essential difference between the techniques, which was not the time taken but the number of controls that the pilot had to operate during the deceleration.

Descending transitions were then performed maintaining a constant rate of descent and using the controlled deceleration technique, although in a few cases instead of completing the deceleration in 100 sec the pilot aimed to complete it in 1000 ft height change. Some descending transitions were also performed in which the pilot attempted to maintain a constant glide path angle although he had no defined glide

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path to follow. An I.L.S. instrument was available and was indeed used later on in the transition investigations (Section 5.3) but it was not desired at this stage to simulate anything as specialised as an I.L.S. approach. The external view was provided to make the simulated environment more like visual flight than instrument flight, but unfortunately it was not possible to simulate the kind of external visual aid that is used to define a glide path, e.g. VASI, HILO etc. Therefore glide path angle was determined through attitude and incidence. To simplify this a rate of descent was established at 150 kt such that the glide path angle was 6° and then the attitude was adjusted to make the incidence 6°. The pilot then aimed to maintain the glide path angle by keeping the attitude and incidence constant using the instruments and the external projected horizon.

In all the transitions the pilots were asked to keep the incidence reasonably constant, i.e. within 2° or 3° of it's initial value. The reason for this was that it was considered important to see how well incidence could be controlled during the transitions because most jet VTOL aircraft are incidence-sensitive in at least part of their flight envelope. In most of the level transitions an incidence of about 8° was maintained but some were performed to investigate a technique which it was thought might be useful for avoiding incidence problems. In this the incidence was first reduced to zero, increasing thrust to maintain the flight path and maintaining 150 kt with the thrust vector angle control. Then when properly trimmed at 150 kt and 0° incidence the deceleration was performed and the incidence was kept at zero throughout.

5.1.1. *Method of decelerating.* The constant thrust vector angle technique was found fairly easy and straightforward, since the flying task reduced to a two control problem, but the pilots did not like having simply to accept whatever deceleration resulted. Some commented that they felt as though they were trying to control a ballistic missile and the technique became dubbed the ballistic type of deceleration as a result of this. In general they considered that the technique was not very realistic since in flight the pilot will always have to adjust the deceleration to stop at the chosen point. Although it may sometimes be possible to make the necessary adjustments by altering aircraft attitude, thrust vector angle would normally be used as it is a much more powerful control and is practically interaction-free. It cannot even be claimed that the technique produced consistent results in terms of distance travelled. The best results were obtained with the transitions performed with $\theta_j = 90°$ and an incidence of 8°. In these the variation was from 3800 ft to 4800 ft in 14 runs. Clearly this is not consistent enough to be of any practical value and it is unlikely that more consistent results would be obtained in flight where turbulence is normally present.

Examples of transitions performed using this technique are shown in Figs. 16, 17 and 18, the thrust vector angles used being 120°, 81° and 90° respectively. The forward movement of the stick as speed decreased was the result of the nose-up pitching moment which arose from the increased thrust. Selecting $\theta j = 120°$ produced a much more rapid deceleration than is available on any current VTOL aircraft but it is significant that no control problems were encountered. The pilots said that the transition was over so quickly that provided the starting conditions were set up correctly there was simply not time for any large errors to develop. Selecting $\theta_j = 81°$ produced a more realistic deceleration although in some instances (such as the example in Fig. 17) it was prolonged by a small nose-down attitude drift which caused the deceleration to stop before 50 kt. The pilot then had to pull the nose up to continue the deceleration.

The controlled deceleration technique was found more difficult but was preferred by all the pilots simply because it was controlled. Although the suggested target of 100 sec resulted in a slower deceleration than was normally achieved with the constant thrust vector angle technique, it should be emphasised that this was not one of the reasons for the pilots preference. In fact some of the pilots commented that they would have preferred a faster deceleration and, as one of the pilots pointed out, under favourable circumstances this technique may permit faster decelerations than the constant thrust vector angle technique.

When aiming to complete the deceleration in 100 sec the actual time achieved varied from 64 sec to 147 sec but in the majority of runs it was between 80 sec and 100 sec. Fig. 19 shows an example of one of these transitions and it can be seen that although the deceleration is not very uniform the mean value is almost exactly the required rate. Fig. 20 shows an example of one of the transitions in which the pilot aimed to complete the deceleration in 1000 ft height change. This was an even more difficult task because

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both the A.S.I. and altimeter had to be monitored continuously to judge whether the deceleration was correct. Despite the high workload however the pilots still preferred this to the constant thrust vector angle deceleration technique.

5.1.2. *Control of flight path.* Rather surprisingly the deceleration technique that was employed made no noticeable difference to the standard of flight path control, which in all cases was not as good as is normally achieved in flight. In the level flight transitions small rates of climb and descent were frequently developed sometimes reaching 400 ft/min before being corrected, while in the constant rate of descent transitions, deviations from the chosen rate of descent were on average slightly larger. This somewhat poor standard is thought to be attributable to a deficiency in the instrumentation, rather than to any basic difficulty in controlling the flight path while decelerating, for all the pilots complained that the V.S.I. was sluggish. In point of fact it was not, thought it differed in type from those that the pilots were used to and its sensitivity was only half as great. This deficiency may partly explain why flight path control was not as good in the constant rate descents as in level flight where the altimeter yielded additional error information, but what is probably a more important reason is that maintaining a constant rate of descent while decelerating meant following a curved flight path. Since incidence was being kept constant a continuous change of attitude in the nose-down sense was necessary and this was contrary to the pilots instinctive actions when decelerating. The result was that incidence generally increased instead of attitude decreasing during most of the transition, as can be seen from the example in Fig. 20. Only towards the end did the pilot manage to keep the incidence roughly constant by reducing the attitude.

Maintaining a constant glide path angle by keeping attitude and incidence constant was found quite difficult and was not considered by any of the pilots to be a practical method in flight. Nevertheless the variations in glide path angle did not normally exceed ±2° and in some runs, e.g. Fig. 21, were only ±1°. The most notable feature was that the variations in glide path angle were no greater during the transitions than during the preceding descents at constant speed.

5.1.3. *Control of incidence.* As with control of flight path, the deceleration technique employed made no noticeable difference to the standard of incidence control achieved. In all the types of transition the incidence was kept within the suggested limits of ±3° in the majority of runs and in some it was kept within much closer limits. In the transition illustrated in Fig. 19 for example the variations are no more than ±1·5° throughout. On the other hand there were a number of instances in which, although the incidence was controlled fairly closely during the early part of the transition, it steadily increased below about 80 kt and sometimes reached 15° with little or no attempt made to reduce it. Fig. 22 shows an example of such a case. It is interesting to note that although this occurred on only three runs made by pilots with no previous VTOL experience it happened fairly frequently during the runs made by pilots who had flown VTOL aircraft. This is believed to be because these pilots had learned from experience in flight that incidence was not important below a certain speed, (generally that at which the elevator ceased to be effective as a height control) and this experience caused them to make a more liberal interpretation of the briefing on incidence control.

The technique of performing the deceleration at zero incidence was found to be particularly simple and straightforward (although the task of maintaining 0° incidence was no different from keeping it constant at any other value) because the flight path control task was greatly simplified. Fig. 23 shows a typical example of one of these transitions and it can be seen that no throttle movements were made throughout the deceleration since there was practically no change in the balance of vertical forces. An additional benefit of the constant thrust, which added to the simplicity of the technique, was that there were no power-induced trim changes throughout the deceleration so that the pilots performed the more familiar action of pulling the stick back as the speed reduced. It should be noted however that although the task of reducing the incidence to zero at constant speed was found straightforward in the simulator it has not been so with either the P 1127 or the SC 1 in flight. This is partly because of a reduction in pitch stability when these aircraft become jet-borne at a conventional flying speed but mainly because using a high level of lift thrust while maintaining a forward speed of more than about 60 kt causes severe buffeting that has been variously described as 'like riding over cobblestones' and 'like floating on the

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surface of vigorously boiling water'. This effect makes the aircraft difficult to handle and makes the setting up and holding of steady conditions almost impossible. The technique also results in a high fuel consumption and the pilots did not think it would have any practical value unless these shortcomings could be overcome.

5.2. *The Stepped Approach Technique.*

This is a theoretical technique for making an approach and landing at a small site in low cloud or poor visibility. Descending below a low cloud base at conventional flight speeds is rather hazardous particularly over unfamiliar ground and if the descent can be made at a lower speed several advantages are apparent. Less height is required to pull out, less space is required for any other manoeuvres that may be necessary, and the pilot has more time to assess his position and look for the landing site. The proposed technique therefore takes advantage of the ability of VTOL aircraft to fly at speeds much below conventional flying speeds. It is illustrated in Fig. 24 and consists of three distinct stages as follows:

(1) A deceleration at the approach altitude to some predetermined partly jet-borne speed.

(2) A descent at that speed until visual ground contact is made.

(3) A final level deceleration and landing when the landing site is seen.

A detailed description and theoretical assessment of the technique is given in Ref. 5. However the technique simulated was somewhat simplified since it was not possible to simulate an approach to a fixed point. The procedure adopted was first to decelerate from 150 kt to 90 kt maintaining constant height, then descend 1000 ft at 1000 ft/min and finally level out and decelerate to 50 kt.

The first thing that became apparent was that it was possible to 'cut the corners', to use the pilots' expression, so that the three stages were not entirely separate but overlapped each other slightly. Fig. 25 shows a run in which this was done deliberately. The descent started before the first deceleration was complete because thrust was not increased sufficiently to compensate for the loss of lift as the speed fell. Then the second deceleration started during the flare because the thrust vector angle was not changed sufficiently as the flight path levelled out. For comparison, Fig. 26 shows the technique being performed as intended, i.e. each stage being properly completed before starting the next.

Allowing the stages of the technique to overlap, as in Fig. 25, could be hazardous in flight for it was found that, if the simulated aircraft was not properly trimmed at 90 kt before the descent was initiated, there was a danger of suddenly finding the incidence was very high when the descent was established. Provided that the three stages were kept separate, however, no particular difficulty was encountered and after their short simulator experience of the technique the pilots felt that they would be quite happy to try it out in flight.

5.3. *Transitions Performed on an I.L.S. Approach.*

Having obtained a reasonable degree of success with the transition techniques described in the previous sections the next stage was aimed at studying the possibilities of performing a transition while following an I.L.S. beam. The I.L.S. instrument, which can be seen in Fig. 2, was a normal aircraft type and defined a 4° glide path, but because of lack of computer capacity its sensitivity to height and lateral displacement errors did not vary with distance in the normal way but was fixed at a value equal to that of a normal I.L.S. system at a range of about $1\frac{1}{2}$ miles. The signals to the I.L.S. instrument could be switched on and off as required at the control console.

The procedure adopted was to trim the simulated aircraft at 135 kt and about 8° incidence and fly level at 1500 ft. The controller then switched on the localiser and as soon as the pilot was following this the glide path signal was switched on. The pilot then followed the glide path and localiser maintaining 135 kt and 8° incidence until at 800 ft the transition was initiated. The aim in this case was to decelerate to 50 kt by the time 300 ft was reached, maintaining about 8° incidence.

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The results of these tests were very encouraging. Two pilots participated and neither complained of any difficulty either in following the glide path at a steady speed or in performing a decelerating transition while following it. Incidence was not controlled quite as well as in the other descending decelerating transitions but it never exceeded the suggested limits until the speed had fallen to the region where aerodynamic effects are small. This can be seen in Fig. 27 which shows a typical example of one of these transitions.

The accuracy of following the glide path was comparable with the accuracy achieved in flight with conventional aircraft on raw I.L.S. approaches[6]. Fig. 28 shows the time histories of speed, height, glide path error and localiser error for five runs and illustrates not only the accuracy but the consistency that was achieved.

6. *Conclusions.*

Handling a jet VTOL aircraft in the partly jet-borne regime can be difficult, primarily because of the redundancy of controls available to the pilot to control flight path and airspeed. This was true for both the configurations tested here, i.e. a single fully vectored engine and separate lift and propulsion engines. The difficulties can be resolved quite readily, however, if the pilot can spend some time calmly examining the effectiveness of each control throughout the speed range. Operational limitations normally prohibit such an approach in flight, but the simulator is not subject to these limitations and, in the tests reported here, it provided the participating pilots with some extremely valuable experience which could not have been obtained by other means. Those pilots who had no previous experience in VTOL aircraft found the redundancy of controls so confusing that at first they were completely unable to set up a given trimmed condition. However after assessing the controls and coming to an appreciation of their individual effectiveness they were able to settle on a control technique using all three controls with complete confidence. Even the pilots who had considerable experience in jet VTOL aircraft (i.e. the P 1127 and the SC 1) found that they still had something to learn about techniques for control in the partly jet-borne regime and were able to fly the aircraft with a new confidence and understanding after their simulator experience.

The control technique which was found by all the pilots to be the most useful throughout the speed range simulated (40 kt to 150 kt) was termed the attitude-sensibly-constant technique. This name arose because in the early trials using this technique the pilots used the stick to maintain roughly constant attitude while controlling flight path with vectored thrust and airspeed with thrust vector angle. As they gained confidence in using three controls, however, they began to use attitude as a fine control of both flight path and airspeed. The reason for this being the most effective single technique throughout the speed range simulated is easy to understand when one considers that the thrust vector of the simulated aircraft flying at 8° incidence was never inclined at less than 53° to the flight path. This situation is similar to that which exists with both the P 1127 and the SC 1, but it may not be representative of other jet VTOL aircraft and the preferred control technique of this exercise may not always be the best. Nevertheless this simulation has been extremely valuable in clearly demonstrating the necessity of fully understanding individual control effectiveness before deciding on the best control technique for the partly jet-borne regime.

It has also demonstrated the importance of giving careful consideration to the layout of the engine controls. Having the main controls of vectored thrust and thrust vector angle by similar levers next to one another was found to be most unsatisfactory. Further, it was generally considered that any combination of two separate controls for these quantities operated by the same hand would be unsatisfactory.

The transition investigations were of a preliminary nature only and the results obtained do not prove anything conclusively but rather indicate that a more detailed investigation would be extremely valuable. Despite the simple nature of the experiment however a number of points worth noting did emerge. Regarding transition techniques, that of becoming entirely jet-borne before decelerating was found in the simulator to be a particularly simple one from the control point of view. There are, however, considerable problems (notably high fuel consumption and severe buffeting) in becoming jet-borne at conventional flight speeds in current jet VTOL aircraft, but if these are less severe in future generation aircraft there may be a case for an investigation of this technique in flight. In addition the 'stepped

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approach technique', which is as yet only a theoretical proposal, was found to be fairly straightforward in the simulator and there was no apparent reason why it should not be so in flight. Constant rate of descent transitions, on the other hand, may not be quite as straightforward as they appear at first sight. Although the pilots did not mention any particular difficulty it was noticed that normally the incidence steadily increased, apparently due to the pilots instinctive reluctance to change the attitude nose down while decelerating. This is a point worth bearing in mind when planning flight investigations of transition techniques, particularly with aircraft that are sensitive to incidence.

Regarding the method of decelerating, it is significant that all the pilots preferred the controlled deceleration technique, even though it imposed a higher workload than the constant thrust vector angle technique, because they preferred to retain complete control of the situation at all times. Although it was thought that the constant thrust vector angle technique might have the advantage of greater consistency in the distance covered during the transition this was found to be not so. The distance is affected by so many factors, e.g. start conditions, how well incidence and flight path are controlled, etc. that consistency should not be expected.

Perhaps the most important result of these tests is that some very useful information was gained about pilots' ability to perform decelerating transitions with little or no outside information. In particular the successful performance of decelerating transitions while following a constant sensitivity I.L.S. beam does suggest that VTOL operations in weather minima considerably less than the current limits for such aircraft may be possible, even without the flight director systems or partly auto-coupled approaches that have been thought to be essential provided that the aircraft has adequate stability. However it would be unwise to place undue emphasis on this deduction which is, after all, based on only a preliminary investigation of the problem. There is clearly a need for further simulation to make a more detailed study of transitions.

7. *Future Work.*

Experience gained from this experiment suggests several requirements for future VTOL simulation and these are as follows:

(1) The full speed range from zero to about 150 kt should be available.

(2) Some form of visual display (e.g. shadowgraph or television) should be available in order to simulate visual decelerating transitions terminating at a chosen point.

(3) It should be possible to simulate emerging from cloud after a blind approach.

(4) It should be possible to simulate various kinds of blind approach aid (e.g. BABS, TACAN etc.) with a view to assessing their usefulness for VTOL operations in instrument flight.

(5) Improvements and innovations in the field of blind flying instruments for VTOL aircraft should be assessed.

In addition to the above, attention should be paid to making the simulation more realistic. In particular the thrust/weight ratio and stability should be more representative of existing aircraft and other possible improvements, such as the addition of turbulence and perhaps a stall, should be examined.

A further VTOL simulation incorporating these suggestions would go a long way towards answering some of the questions relating to the operational use of VTOL aircraft and, it is believed, would make a valuable contribution to the state of the VTOL art.

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LIST OF SYMBOLS

a_1	Roll reaction control sensitivity	
a_2	Pitch reaction control sensitivity	
a_3	Yaw reaction control sensitivity	
b	Aircraft span	
b_1	Autostabiliser roll damping constant	
b_2	Autostabiliser pitch damping constant	
b_3	Autostabiliser yaw damping constant	
$\bar{c}$	Mean chord	
c_2	Height of vectored engine intake above *cg*	
C_D	Aerodynamic drag coefficient	
C_L	Aerodynamic lift coefficient	
d_2	Empirical constant	
e_2	Empirical constant	
g	Acceleration due to gravity	
h	Height of simulated aircraft	
I_{xx}	Moment of inertia about the x-body axis	
I_{yy}	Moment of inertia about the y-body axis	
I_{zz}	Moment of inertia about the z-body axis	
I_{xz}	Product of inertia	
l_v	coefficients of rolling moment due to	sideslip
l_ξ		aileron
l_p		rate of roll
l_r		rate of yaw
m	Mass of the simulated aircraft	
m_0	Air mass flow of vectored engine	
m_α	Coefficients of pitching moment due to	incidence
$m_{\dot{\alpha}}$		rate of change of incidence
m_η		elevator
m_q		rate of pitch
n_v	Coefficients of yawing moment due to	Sideslip
n_ζ		rudder
n_r		rate of yaw
p	Rate of roll	

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q	Rate of pitch about y-body axis	
q_w	Rate of pitch about y-wind axis	
r	Rate of yaw about z-body axis	
r_w	Rate of yaw about z-wind axis	
S	Wing area	
T_L	Gross thrust of the vectored engine	
T_p	Net thrust of the propulsion engine	
V	Airspeed	
W	Aircraft weight	
y_v	Coefficients of sideforce due to	sideslip
y_ξ		aileron
y_ζ		rudder
α	Angle of incidence	
β	Angle of sideslip	
γ	Flight path angle	
δ_L	Thrust vector angle measured from z-body axis	
θ_j	Thrust vector angle measured from x-body axis	
ξ	Aileron angle	
η	Elevator angle	
ζ	Rudder angle	
ϕ	Angle of bank	
θ	Angle of pitch	
ψ_B	Angle of yaw w.r.t. body axes	
ψ_w	Angle of yaw w.r.t. wind axes	
ρ	Air density	

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APPENDIX A

Equations of Motion used in the Simulation.

The lowest speed simulated was 40 kt and this permitted the use of small angle approximations to the trigonometric functions of the angles of incidence and sideslip. The equations of motion are expressed in a combined system of flight path (wind) and principal inertia (body) axes, as shown in Fig. 4. For convenience the angle of the vectored thrust has here been defined relative to the z body axis and is called δ_L. From Fig. 4 it can be seen that $\delta_L = \theta_j - 90°$.

A.1. *Force Equations with Respect to Flight Path Axes.*

(i) Force along the x flight path axis

$$m\dot{V} = T_p \cos\alpha \cos\beta - T_L \sin(\alpha+\delta_L)\cos\beta - \frac{1}{2}\rho V^2 S\, C_D - V\dot{m}_0 - mg\sin\gamma. \qquad \text{(A.1)}$$

This was approximated by

$$m\dot{V} = T_p - T_L \sin(\alpha+\delta_L) - \frac{1}{2}\rho V^2 S\, C_D - V\dot{m}_0 - mg\,\gamma. \qquad \text{(A.2)}$$

Substituting the values of parameters used in the simulation

$$\dot{V} = 2{\cdot}5 \times 10^{-3}\, T_P - 2{\cdot}5 \times 10^{-3}\, T_L \sin(\alpha+\delta_L) - 9{\cdot}66 \times 10^{-3}\left(\frac{1}{2}\rho V^2\right)$$

$$-4{\cdot}5 \times 10^{-4}\left(\frac{1}{2}\rho V^2\right)\alpha^2 - 1{\cdot}125 \times 10^{-2}\, V - 0{\cdot}78 \times 10^{-6}\, V\, T_L - 0{\cdot}56\,\gamma. \qquad \text{(A.3)}$$

(ii) Force along the y flight path axis

$$mV r_w = -T_p \cos\alpha \sin\beta + T_L \sin(\alpha+\delta_L)\sin\beta$$

$$+\rho V^2 S\,(y_v\,\beta + y_\xi\,\xi + y_\zeta\,\zeta) + mg\cos\gamma\sin\phi. \qquad \text{(A.4)}$$

This was approximated by

$$mV r_w = -T_p\,\beta + T_L \sin(\alpha+\delta_L)\,\beta + \rho V^2 S\, y_v\,\beta + mg\,\phi. \qquad \text{(A.5)}$$

Substituting the values of parameters used in the simulation

$$V r_w = -1{\cdot}5 \times 10^{-3}\, T_p\,\beta + 1{\cdot}5 \times 10^{-3}\, T_L\,\beta \sin(\alpha+\delta_L)$$

$$-2{\cdot}3 \times 10^{-1}\left(\frac{1}{2}\rho V^2\right)\beta + 19{\cdot}0\,\phi. \qquad \text{(A.6)}$$

(iii) Force along the z flight path axis

$$mV q_w = T_p \sin\alpha + T_L \cos(\alpha+\delta_L) + \frac{1}{2}\rho V^2 S\, C_L - mg\cos\gamma\cos\phi. \qquad \text{(A.7)}$$

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This was approximated by

$$mV\,q_w = T_p\,\alpha + T_L\cos(\alpha+\delta_L) + \frac{1}{2}\rho V^2\,S\,C_L - mg\left(1-\frac{1}{2}\left(\frac{\gamma}{57{\cdot}3}\right)^2\right). \qquad \text{(A.8)}$$

Substituting the values of parameters used in the simulation

$$V\,q_w = 1{\cdot}5\times10^{-3}\,T_p\,\alpha + 8{\cdot}4\times10^{-2}\,T_L\cos(\alpha+\delta_L) + 1{\cdot}5\left(\frac{1}{2}\rho V^2\right)\alpha$$

$$-1092+0{\cdot}17\,\gamma^2. \qquad \text{(A.9)}$$

A.2. *Moment Equations with Respect to Principal Inertia Axes.*
(i) Moment about the x principal inertia axis

$$I_{xx}\,\dot{p} = (I_{yy}-I_{zz})\,q\,r + L + (a_1\,\xi + b_1\,p)\,T_L\,. \qquad \text{(A.10)}$$

This was approximated by

$$I_{xx}\,\dot{p} = L + (a_1\,\xi + b_1\,p)\,T_L$$

$$= \left(\frac{1}{2}\rho V^2\right)S\,b\,(l_v\,\beta + l_\xi\,\xi) + \frac{1}{4}\rho V\,S\,b^2\,(l_p\,p + l_r\,r)$$

$$+(a_1\,\xi + b_1\,p)\,T_L. \qquad \text{(A.11)}$$

Substituting the values of parameters used in the simulation

$$\dot{p} = -1{\cdot}0\times10^{-2}\left(\frac{1}{2}\rho\,V^2\right)\alpha\,\beta - 0{\cdot}13\left(\frac{1}{2}\rho\,V^2\right)\xi - 4{\cdot}14\times10^{-3}\,V\,p$$

$$+1{\cdot}8\times10^{-3}\,Vr - 5{\cdot}2\times10^{-4}\,T_L\,\xi - 2{\cdot}9\times10^{-4}\,T_L\,p. \qquad \text{(A.12)}$$

(ii) Moment about the y principal inertia axis

$$I_{yy}\,\dot{q} = (I_{zz}-I_{xx})\,r\,p + M + (a_2\,\eta + b_2\,q)\,T_L + c_2\,m_0\,V$$

$$+d_2\,V^2\,T_L + e_2\,V^2\,\delta_L. \qquad \text{(A.13)}$$

This is approximated by

$$I_{yy}\,\dot{q} = (I_{zz}-I_{xx})\,r\,p + M + (a_2\,\eta + b_2\,q)\,T_L + c_2\,m_0\,V$$

$$= \left(\frac{1}{2}\rho V^2\right)S\,\bar{c}\,(m_\alpha\,\alpha + m_\eta\,\eta) + \frac{1}{2}\rho\,S\,V\,\bar{c}^2\,(m_q\,q + m_{\dot{\alpha}}\,\dot{\alpha})$$

$$+(a_2\,\eta + b_2\,q)\,T_L + c_2\,m_0\,V + d_2\,V^2\,T_L + e_2\,V^2\,\delta_L. \qquad \text{(A.14)}$$

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APPENDIX A

Substituting values of parameters used in the simulation

$$\begin{aligned}\dot{q} = {} & -2{\cdot}5 \times 10^{-2}\left(\frac{1}{2}\rho V^2\right)\alpha - 2{\cdot}5 \times 10^{-2}\left(\frac{1}{2}\rho V^2\right)\eta - 1{\cdot}7 \times 10^{-3}\, V q \\ & -1{\cdot}7 \times 10^{-3}\, V\dot{\alpha} - 1{\cdot}8\; 10^{-4}\, T_L \eta - 2{\cdot}5 \times 10^{-4}\, T_L q \\ & +3{\cdot}99 \times 10^{-2}\, V + 2{\cdot}76 \times 10^{-6}\, V\, T_L + 7{\cdot}3 \times 10^{-6}\left(\frac{1}{2}\rho V^2\right) T_L \\ & -1{\cdot}76 \times 10^{-3}\left(\frac{1}{2}\rho V^2\right)\delta_L . \end{aligned} \tag{A.15}$$

(iii) Moment about the z principal inertia axis

$$I_{zz}\,\dot{r} = (I_{xx} - I_{yy})\, p\, q + N + (a_3\,\zeta + b_3\, r)\, T_L . \tag{A.16}$$

This was approximated by

$$\begin{aligned} I_{zz}\,\dot{r} &= N + (a_3\,\zeta + b_3\, r)\, T_L \\ &= \frac{1}{2}\rho V^2\, S\, b\,(n_v\,\beta + n_\zeta\,\zeta) + \frac{1}{4}\rho V\, S\, b^2\, n_r\, r + (a_3\,\zeta + b_3\, r)\, T_L . \end{aligned} \tag{A.17}$$

Substituting the values of parameters used in the simulation

$$\begin{aligned}\dot{r} = {} & 1{\cdot}6 \times 10^{-2}\left(\frac{1}{2}\rho V^2\right)\beta - 2{\cdot}4 \times 10^{-2}\left(\frac{1}{2}\rho V^2\right)\zeta - 0{\cdot}95 \times 10^{-3}\, V r \\ & -9{\cdot}3 \times 10^{-5}\, T_L\,\zeta - 1{\cdot}56 \times 10^{-4}\, T_L\, r . \end{aligned} \tag{A.18}$$

A.3. *Kinematic Relationships.*

$$\dot{\alpha}\cos\beta = -q_w + q\cos\beta - \sin\beta\,(p\cos\alpha + r\sin\alpha). \tag{A.19}$$

This was approximated by

$$\dot{\alpha} = q_w + q \tag{A.20}$$

$$\dot{\beta} = r_w + p\sin\alpha - r\cos\alpha . \tag{A.21}$$

This was approximated by

$$\dot{\beta} = r_w - r . \tag{A.22}$$

The Euler angle equations

$$\dot{\psi}_w \cos\gamma = r_w \cos\phi + q_w \sin\phi \tag{A.23}$$

and

$$\dot{\phi}\cos\beta = p\cos\alpha + r\sin\alpha + q_w\sin\beta + \dot{\psi}_w \sin\gamma\cos\beta \tag{A.24}$$

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were approximated by

$$\dot{\psi}_w = r_w \cos \phi + q_w \sin \phi \tag{A.25}$$

and $$\dot{\phi} = p + \dot{\psi}_w \sin \gamma \qquad \text{respectively.} \tag{A.26}$$

The remaining Euler angle equation

$$\dot{\gamma} = q_w \cos \phi - r_w \sin \phi \quad \text{was used in the complete form.} \tag{A.27}$$

The transformations from wind to body Euler angles were simplified to

$$\phi_B = \phi \tag{A.28}$$

$$\theta = \gamma + \alpha \tag{A.29}$$

$$\psi_B = \psi_w - \beta + \alpha \phi . \tag{A.30}$$

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APPENDIX B

Comparison of the Simulated Aircraft with Actual Aircraft and the Effect of Varying Visual and Motion Cues.

The results of a simulation must be treated with some caution until it can be shown that the simulator provides a valid representation of the actual aircraft. In this experiment the simulated aircraft was intended to represent a class of aircraft rather than one particular machine, so that it was difficult to prepare *a priori* standards for comparison. The choice of aerodynamic and other data used in programming the simulator (*see* Table 1) ensured that the static and dynamic behaviour of the simulated aircraft was representative. Since, however, the results described in this Report were based on pilot opinion and measured time histories, it was thought important to compare flight and simulator time histories and to canvas pilot opinion. These comparisons are discussed in Section B.1.

Section B.2 describes the outcome of a short experiment in which the motion and visual cues available to the pilot in the simulated aircraft were varied. In previous simulations of aircraft with widely varying characteristics it had been found[1] that the pilot 'flew' the simulated aircraft in a way much more like the real thing when cockpit motion and an external visual background were provided than when one or both of these were not available. As there was no reason to believe that a simulated aircraft in partly jet-borne flight would fail to conform to this general pattern, motion and visual cues were used from the outset. However, before the end of the simulation, this assumption was checked and the results are reported in this Appendix.

B.1. *Comparison of the Simulated Aircraft with an Actual Aircraft.*

A number of runs were made in level flight at around 8° incidence in the P 1127 aircraft at constant, partly jet-borne, speeds and these were compared with simulated runs in the same conditions by the same pilot. The pilot was briefed to fly at 1000 ft so that the external visual cues would be similar to those in the simulator (at lower heights it was thought likely that ground detail would provide additional information). Despite these precautions to obtain a valid comparison, two differences should be noted:

(1) The flight was made in very hazy conditions and the horizon provided an even poorer attitude reference than the external horizon simulated. In addition because the aircraft was not designed to be flown on instruments the artificial horizon is a small instrument which could not be used as an accurate pitch attitude reference. As a result the pilot did not attempt to fly the attitude—sensibly—constant technique.

(2) For a number of reasons the time available in flight for each condition was severely limited. In the first place the fuel consumption at the lower, partly jet-borne speeds was high so that the pilot could not spend much time with high power settings. In the second place there was a limit of about 5 minutes on the time that the nozzles could be deflected so that the pilot had to fly conventionally between each recorded run.

Some of the time histories measured in flight and on the simulator are compared in Figs. 29 to 31. The traces of the controlled parameters, speed, pitch attitude and incidence show reasonable agreement but the control movements, except for the throttle, which was moved in only one of the runs anyway, are somewhat different as is often the case when comparing flight and simulator results. An interesting feature of the thrust vector angle control traces in Figs. 30 and 31 is that the ranges of movement are very similar but while the flight trace indicates frequent small movements of the control, the simulator traces show infrequent, fairly gross movements. A possible explanation of this difference is that, in flight, the pilot feels accelerations along the flight path so that he would be immediately aware of the effect of thrust vector angle changes. In the simulator, on the other hand, the effect of a change in thrust vector angle would not be appreciated except by reference to the airspeed indicator.

Commenting on the flight, the pilot said, 'a number of unavoidable mechanical differences in the controls and flight instruments make the simulator and aircraft appear different, but in fact their basic handling is remarkably similar'. In general all the pilots with VTOL experience felt that though there were differences between the simulated and the actual aircraft they were not such as to invalidate the

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conclusions drawn from the simulation. In a flight report, Pilot B said:

'Simulator practice enabled each system of control to be used without mental confusion. Before practice this would have been difficult. No variances from simulator practice noted, just that the ability to control speed by attitude changes was more limited than expected. The procedure was exactly as practised regularly on the simulator, but was easier in flight (due to g cues?). Before simulator practice this procedure was difficult, now it's easy.'

B.2. *Variation of Visual and Motion Cues.*

Three trials were conducted to establish the value of kinaesthetic and visual cues to the pilot. Pilots were asked to manoeuvre the simulated aircraft at a series of partly jet-borne speeds with the following combinations of cues:

(i) cockpit motion and the external visual background,

(ii) cockpit motion but no external visual background,

(iii) fixed cockpit with the external visual background, and

(iv) fixed cockpit and no external visual background.

The relative merits of the four combinations were assessed by comparing recorded time histories and from subjective opinions of the pilots.

Time histories of handling at speeds around 90 kt using the attitude—sensibly—constant technique, with the four combinations of cues, by an experienced VTOL pilot (Pilot B of Table 2), and an inexperienced VTOL pilot (Pilot F) are shown in Figs. 32 and 33 respectively. The records give very little indication of differences in the value of the cues, but the two traces at the top of Fig. 33, showing roll and pitch attitude merit closer consideration. The bank angle traces in Fig. 33b and d are similar to each other but rather different in range and frequency from the bank angle traces in Fig. 33a and c. These latter figures show a tighter control of bank angle which could be a consequence of the strong visual indication of roll attitude from the external visual display. A comparison of the pitch attitude traces of Fig. 33a and b with those of Fig. 33c and d could, by similar reasoning, indicate that cockpit motion enabled the pilot to keep a tighter control over pitch attitude. On the evidence of Figs. 32 and 33 alone, however, it would be difficult to draw positive conclusions.

Pilot subjective opinion, because it is based on only three trials, may not be conclusive but it throws some interesting light onto the subject of satisfactory cues.

(i) *Cockpit motion and the external visual background.* With these cues the simulator was felt to be representative of flight in visual conditions, so that pilots were not afraid to use large control inputs. Attitude changes were immediately obvious and the pilots were prepared to fly 'hands off'.

(ii) *Cockpit motion but no visual background.* Pitch attitude control was good and trim changes with power or thrust vector angle were immediately obvious. Roll attitude was not appreciated so well as pitch attitude which is the reverse of the real flight situation. The differences between this cue and no motion and no visual background were less obvious when using the constant attitude technique.

(iii) *Fixed cockpit with the external visual background.* First impression was that the lack of motion in roll made turning manoeuvres more realistic, but to see the bank angle without feeling associated movement was disorientating. After a few minutes with this combination of cues pilots complained of nausea. One pilot felt that without motion he was less likely to overcontrol in bank.

(iv) *Fixed cockpit and no visual background.* The three pilots who 'flew' the simulated aircraft with this combination of cues had somewhat different reactions:

(a) Pilot B (an experienced VTOL pilot—*see* Table 2) felt that he could learn to control the simulated aircraft on instruments alone but that it would always be difficult and would take many hours of practice. Much more concentration was required and pitch attitude control was particularly difficult so that the

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attitude—sensibly—constant technique was very much more difficult (Fig. 32d) than with any other combination of cues. It was difficult to include the incidence gauge in the scan of the instrument panel.

(b) Pilot F (an inexperienced VTOL pilot) found it difficult to judge control movements. He had a feeling of detachment and found it difficult to relate the instrument readings to an aircraft situation. He felt that 'things can happen without you realizing it, it is like sitting at a desk with lots of black boxes in front of you. In an aircraft you are aware of attitude changes without looking at the instruments but with only instruments to tell you what is happening its rather like learning a trick'.

(c) The third pilot (listed amongst the 'Others' in Table 2) was an experienced VTOL pilot but had 'flown' the simulated aircraft for only one hour before this trial. He lost control within a few seconds of the simulation being freed and he felt sure that the stability of the simulated aircraft had been reduced about all axes.

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APPENDIX C

Pilot Comments on Constant Speed Control Techniques.

The six pilots (A to F in Table 2) who took part in the study of handling at constant, partly jet-borne speeds were asked to complete the proforma illustrated in Fig. 10. The three control techniques studied were called 'attitude—sensibly—constant', 'thrust vector angle constant' and 'throttle constant' for convenience, and the general comments of the pilots on these techniques are reported below. As in Table 3, which gives a brief summary of the comments presented here, the term 'nozzle angle' is used instead of thrust vector angle.

C.1. *Attitude—Sensibly—Constant Technique.*

Pilot A: It is very much easier to hold attitude steady in instrument flight rather than use it as a primary control. It is useful that in this technique each control has a simple *unique* effect and this control may not be the most efficient but is mentally the least demanding.

Pilot B: Continuous control of nozzle angle, and lift power, cause trim changes which complicate the task of holding attitude constant. In practice it is just as easy to allow variations in attitude to occur to follow flight path changes as it is to hold attitude constant. But attention to three controls is continuously necessary.

Pilot C: Nozzle and throttle controls must be co-ordinated. Power is a left hand function and nozzle angle is so tied up with incidence and speed that it seems more natural to include this with the right hand function of attitude control, i.e. throttle controlled by left hand and nozzle controlled by a button on the stick would be ideal for this method of control. This method is probably the most promising single method of control.

Pilot D: Very good control of height and speed, but descending causes large incidence variation. As tried in the simulator, it would be very useful to have nozzle control on the stick.

Pilot E: This appears to be the most easily controlled mode at 80, 60, 40 kt. It may require a little more time at each speed to optimise thrust and nozzle but permits the use of these two as the most immediate and precise controls of height and speed respectively.

Pilot F: Whereas attitude was constant in steady flight at the various speeds, attitude change was used as a smoothing control over speed and height when these were controlled with nozzle and throttle respectively. This 'smoothing' was easy and natural, and increased the accuracy, whilst reducing the work load. It is important that this technique was used to set up all the trim configurations at 100 kt and below.

C.2. *Nozzle Angle Constant Technique.*

Pilot A: At high airspeed it is easy to over-incidence if trying to slow down, i.e. pull stick back to slow down, therefore climb, therefore reduce thrust—thrust is slow to stop the climb (that is, with a sluggish V.S.I. it takes a long time to see the effect), therefore easy to grossly over-reduce thrust and thus very easy to over incidence off quite small attitude changes. As a thrust reduction may well also reduce intake momentum drag, airspeed may not reduce therefore no other warning of over-incidencing except incidence itself. The converse is possible if an acceleration is required and it is consequently easy to generate negative lift and this requires full thrust and yet the aircraft neither climbs nor accelerates! This is particularly bad at decelerating nozzle angle settings. At low airspeed incidence/attitude changes generate little change of lift, therefore cross effects are much reduced and are insignificant below 60 kt.

Pilot B: Only acceptable below 60 kt. A cumbersome method. A change of mental attitude is necessary in the course of a transition as one converts to this method of control.

Pilot C: Not such a powerful control of airspeed as nozzle angle movements since attitude changes are normally more limited due to incidence side effects. View *can* deteriorate seriously with deceleration.

Pilot D: Near lower limit need very large attitude changes and yet only get slack speed control.

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Pilot E: It is not possible to use one fixed angle to cover the whole speed band, but for each band of about 20 kt a new nozzle angle will be necessary, i.e. manoeuvres involving large speed changes cannot use this technique as defined.

Pilot F: At high helicopter speed (120 kt or so) it would be easy to control on the stick and, bearing in mind the difficulty in operating the collective, one would probably tend to do this. The method of controlling an aircraft of any sort is never as well defined as that of a low speed VTOL machine, and can be much affected by some extraneous thing—such as difficulty in operating the collective, the fact that one is at maximum continuous power and wishes to leave the throttle alone, flying immediately beneath cloud, or for any other reason. In this series of tests the nozzle was unattractive because of difficulty in operating around the hover-stop, and I see that some people have tended to disregard this difficulty, which is only local.

C.3. *Throttle Constant Technique.*

Pilot A: As airspeed is reduced, although attitude response remains good, it is increasingly easy to over-incidence. Flight path response to changes of incidence reduces (significantly so below about 100 kt) and thus, in effect, as well as a low speed limit to this technique there would in practice be a *height* limit, i.e. stick would be all right for glide path control but may be unacceptable, even at 120 kt, for rapid obstacle avoidance.

Pilot B: Very easily learnt since it is similar to conventional flight. Use of this technique may be extended to lower speeds by programming power increases from incidence increases. Very poor acceleration from low speed corners of the envelope.

Pilot C: Proved in flight in P 1127 to be easiest technique over speed range 150–90 kt. Throttle fixed concept allows known margin of reserve power for flare/overshoot/emergency to be always available.

Pilot D: The simulator confirmed my general thinking and previous flying techniques in conventional flight. The lower speed limit (about 100–120 kt) may be rather high but below that limit variations of thrust and nozzle are required as well as stick movements.

Pilot E: The description 'conventional' can be used reasonably to embrace vertical maneouvre by attitude and longitudinal manoeuvre by nozzle angle (or by a separate propulsion engine, if one is available).

Pilot F: There are situations in which any pilot undoubtedly controls speed with throttle, and others where speed is definitely controlled with stick. Away from these definite cases are the others where some confusion may exist and differences of opinion may arise. I think I am definitely a stick-for-speed man, any added complications like the few mentioned under 'nozzle constant' technique can reverse a particular situation immediately. On further thought, perhaps in most situations it is necessary to devote oneself to one parameter and one uses all available means to control that parameter. Therefore, in these special cases that some people produce—such as action required when slow and low on glide path—the answer will always be the same, since height in that particular case is paramount.

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APPENDIX D

The Pilots Replies to the Questionnaire on Transitions.

At the end of the study of transitions the four pilots who performed most of the sorties completed a questionnaire which was inspired by observations noted and comments made during the experiment. Since the pilots always used the term 'nozzle angle' instead of thrust vector angle, as a result of their association with the P 1127 aircraft, this term was used in the questions.

Question 1. *Do you prefer the ballistic type of deceleration (i.e. selecting a given nozzle angle) or a slower one in which you continuously vary nozzle angle to control the deceleration and why?*

Pilot A: Slower varying nozzle preferred for following reasons: (1) Using the ballistic method small errors in the start conditions, i.e. speed, incidence, attitude, flight path and time of start, can have a marked effect on where the deceleration finishes; (2) The ballistic type of deceleration is uneven making range judgement difficult: (3) In practice corrections will always be necessary and by varying the nozzle angle (though not necessarily continuously) the pilot can maintain an acceptable level of deceleration throughout.

Pilot B: Due to range judgement problems it will always be necessary to alter the deceleration to arrive at the hover. By all means use a constant nozzle angle, but only till an error becomes obvious—then alter it.

Pilot C: I prefer to be able to control the nozzle angle continuously for then if conditions are changing more rapidly than I like or can cope with the deceleration can be halted at will. It is a mistake to think that continuous control will always give slower transitions. The very fact that control is retained may allow faster decelerations under favourable conditions. It retains full flexibility of one of the most powerful primary controls on the aircraft.

Pilot F: I prefer a controlled deceleration because it is controlled and hence can be varied.

Question 2. *If asked to do the former and you found you were undershooting or overshooting (in visual flight) would you alter attitude or nozzle angle and why?*

Pilot A: Nozzle angle would always be used unless only a lever control was available. Attitude control would then predominate at times when it was not expedient to remove the hand from the thrust control. Reasons for preferring nozzle angle are: (i) it is a very powerful speed control; (ii) constant attitude flying is relatively simple and ensures that gross changes in incidence do not occur; (iii) the landing attitude can be maintained throughout and thus the view remains unimpaired.

Pilot B: Nozzle angle first—it is most powerful and introduces fewest side effects. If nozzle is not enough then use attitude as well below about 60 kt when aerodynamics are unimportant.

Pilot C: Nozzle angle if enough is available. It can be used more coarsely (i.e. quick changes of 30° are quite acceptable) than aircraft attitude which always causes view changes and may produce a big aerodynamic interaction depending on airspeed.

Pilot F: I would alter nozzle angle because it would be simpler, requiring only one action.

Question 3. *Do you prefer a lever or a button on the stick for nozzle angle control and would this choice be the same for either type of transition described above?*

Pilot A: For either type of deceleration and most modes of flight a button is preferable. However for STOs a lever is probably better. Much research into the form and position of this control is needed.

Pilot B: A lever is better for direct control of nozzles. However the 1127 set up is not acceptable due to the confusion between throttle and nozzle angle lever.

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Pilot C: Overall I prefer a button on the stick. A lever has some advantages. Its position gives nozzle angle information and nozzle response can be almost as quick as you care to make it but for manoeuvres where control of lift thrust and nozzle angle is needed simultaneously it has impossible disadvantages.

Pilot F: I have very little experience of a button but what I had I did not like because nozzle rate could not be changed and I found the workload higher because of this.

Question 4. *Would you use aerodynamic lift for flight path control as long as possible or change to using lift thrust at the moment of starting the deceleration?*

Pilot A: Preferably lift thrust for flight path control right from the start, but the technique should not be so critical as to demand this for it is difficult to make an instantaneous mental switch from one control mode to another.

Pilot B: As long as possible use aerodynamic lift progressively 'boosting' this with power as it becomes ineffective.

Pilot C: In general it is preferable to use one method of control from the beginning to the end of a VSTOL manoeuvre which tends to make the answer 'lift thrust all the way'. However so much depends on aircraft characteristics and the particular manoeuvre that I do not think it is reasonable to ask this question in a completely general way.

Pilot F: I would go over to jet-lift immediately whilst still using aerodynamic lift as a back-up initially.

Question 5. *Do you think that starting the deceleration fully jet-borne is a technique worth considering?*

Pilot A: It may have theoretical advantages but would seem to have little practical value by reason of (i) high fuel consumption (ii) possible aerodynamic interference effects.

Pilot B: Possibly—only at maximum rates of deceleration though.

Pilot C: The method has serious basic disadvantages—notably fuel consumption and engine life. So in general the answer is no. However it is always dangerous to exclude an idea completely. If nothing else this method does represent one end of the scale of possibilities and, goodness knows, there are few times when even the end of the scale is known!

Pilot F: I think that such a technique would be prohibitively expensive in engine life and fuel consumption.

Question 6. *If using wing lift do you think it is worth making maximum use of it, i.e. letting incidence approach as near as practical to its limit as speed falls, or would you keep the incidence to its value at the start of the transition (assuming this is some way below the limit)?*

Pilot A: Keeping the incidence roughly constant (as in the constant attitude technique) and leaving a wide margin greatly reduces pilot workload. With a low thrust/weight ratio however, e.g. STOL approaches, it will be necessary to use as much wing lift as practical but it is certainly not advisable to try and squeeze the last drop of lift out of the wings.

Pilot B: In slow decelerations use the incidence (you have time to do so) leaving a margin dependent on aircraft stability and handling, turbulence and experience. In fast decelerations do not bother—it is short and does not matter. Big safety margins make it easy to fly.

Pilot C: I think to make maximum use of wing lift for other than STOL approaches or take offs is just adding another critical factor unnecessarily.

Pilot F: I would use the maximum incidence possible bearing in mind aircraft limitations, turbulence etc.

Question 7. *Do you think that holding a glide path by keeping attitude constant and holding a given incidence would be a practical technique?*

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Pilot A: I have not tried it but with present methods of presenting incidence information I would say it was impractical. It would depend on how steady attitude could be held and may have some application to aircraft with attitude stabilisation.

Pilot B: No. No feedback of displacement error—too easy to err on setting attitudes.

Pilot C: No. You would be no better off than looking at a good V.S.I. and in addition attitude would have to be kept really steady as opposed to 'sensibly constant'.

Pilot F: I think that it would be hard work and inaccurate.

Question 8. *Can you suggest any improvements to the standard flight instruments that would be likely to make instrument transitions easier?*

Pilot A: The presentation of incidence needs improving. A strip indicator or coloured light system may well be better. The method of measuring as well as presenting sideslip needs investigation. The A.S.I. should read to zero or less if possible. The V.S.I. must be instantaneous. The artificial horizon should be such that precise pitch attitudes can be set.

Pilot B: Only the same improvements one would ask of a conventional aircraft except that incidence indication and sensitive sideslip indication are now necessary. Flight path indication on the attitude indicator might possibly offer a big advance in incidence presentation.

Pilot C: The A.S.I. should read to zero. The attitude indicator should give accurate roll and pitch information. If incidence is critical this information might be O.K. included in the attitude display. Sideslip indication might be O.K. incorporated in the middle of the heading display. The turn and slip indicator would be better replaced by a second attitude indicator as a standby. The V.S.I. is important and may need optimising for the aircraft in question. The Kestrel type, called 'instantaneous or inertial' is supposed to be very good indeed.

Pilot F: On the attitude indicator an adjustable reference would ease attitude holding. A phase advance system on the A.S.I. would ease controlled decelerations.

Question 9. *Would you prefer to keep the tasks of descending and decelerating separate if (a) the only additional information you have is range and some azimuth guide (e.g. BABS); (b) you have range and I.L.S. or similar information?*

Pilot A: In either case I would rather be at low speed when breaking out of a 200 ft overcast in poor visibility. Under I.F. conditions I would prefer a level deceleration at altitude followed by a constant low speed descent but if fuel consumption precludes this I would first settle down onto a steady glide path (in conventional flight) and then decelerate to a suitable speed maintaining either a straight glide path or a steady rate of descent depending on the aids available.

Pilot B: Height control is always necessary. The altimeter provides the necessary information for level flight—the same workload is involved in a descent if some instrument indicates height error relative to a glide path so that fundamentally there is no difference between flying level and down 3°. It's just that current instrumentation is better geared to flying level when outside information is not available. I.L.S. gives some outside information but its change of gearing is confusing.

Pilot C: (a) Yes. (b) Probably O.K. to do both together.

Pilot F: (a) Yes. Doing both together would impose too high a workload. (b) No. Would be prepared to descend and decelerate at the same time.

Question 10. *In what ways do you think the simulated transitions were unrepresentative of real flight?*

Pilot A: You are unlikely to kill yourself in the simulator! In the air time/fuel is vital. In comparison with current jet VTOL aircraft the simulator was more stable, did not experience any violent aerodynamic

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interference effects, incidence was not limiting and the thrust/weight ratio available was too large. Also transitions could not be finished. Often in real flight small errors only manifest themselves in the final phase of an exercise.

Pilot B: The simulation was stable, aerodynamically unrestricted (incidence, sideslip and nozzle angle at high speed plus high power) and lacked normal and longitudinal acceleration cues. There was no realistic range task and the thrust/weight ratio was too high.

Pilot C: The simulator had a huge thrust/weight ratio, zero fuel consumption and no normal and longitudinal accelerations. In the simulator there was no apprehension which in real life can go up markedly with workload and results in over control, tunnelling of vision, wrong decisions etc.

Pilot F: The simulator was unrepresentative because in real life outside information of range, bearing and glide path will be essential. In addition it was easier to fly as there were no outside disturbances and there was no anxiety about safety.

Question 11. *Which of these differences do you think would make the real thing more difficult and which would make it easier?*

Pilot A: Things which make it more difficult are lower stability, lower thrust/weight ratio, aerodynamic interference effects, fuel problems and the knowledge that you just have to get it right. Motion cues generally make it easier and visual cues, if available, obviously do.

Pilot B: The lower stability, aerodynamic limitations and lower thrust/weight ratio make the aircraft more difficult. The lack of acceleration cues makes the simulator more difficult. The range task may work either way—it's a question that needs answering.

Pilot C: Apprehension, fuel consumption and lower thrust/weight ratio make the aircraft more difficult. Acceleration cues make it easier.

Pilot F: Outside disturbances and anxiety about safety make the real aircraft more difficult. The outside information available in real flight would ease the task.

Question 12. *Do you think that the simulator exercises were representative enough to be of assistance when attempting instrument transitions in an aircraft?*

Pilot A: Yes. However this applies largely to developing techniques assuming the handling characteristics are at least satisfactory.

Pilot B: Very much of assistance. Further improvements would be made by limiting thrust/weight ratio, destabilising simulation a little and providing a more realistic form of range/deceleration task.

Pilot C: Yes. They were absolutely invaluable. I think that we should have a permanent VTOL simulation in which everything could be done *ad nauseam* both before and after each flight trial. This could lead to a very much more effective use of flight time.

Pilot F: Undoubtedly.

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TABLE 1

Dimensional and Derivative Data used in the Simulation.

Weights and dimensions.		
Aircraft mass	m	400 slug
Wing loading	mg/S	50 lb/ft^2
Thrust/weight ratio (main engine)	T_L/mg	1·23
Thrust/weight ratio (propulsion engine)	T_p/mg	0·31
Engine mass flow	m_0	$(4{\cdot}5+0{\cdot}0003125\ T_L)$ slug/sec
Relative density parameters	μ_1	50·2
	μ_2	65·24
Control surface movements: aileron		$\pm 10°$
elevator		$\pm 25°$
rudder		$\pm 15°$
Derivatives and coefficients.		
Lift coefficient	C_L	$0{\cdot}07\ \alpha°$
Drag coefficient	C_D	$0{\cdot}015+0{\cdot}0007\ (\alpha°)^2$
Rolling moment due to rate of roll	l_p/i_A	$-3{\cdot}5$ radian^{-1}
Rolling moment due to rate of yaw	l_r/i_A	$+1{\cdot}5$ radian^{-1}
Rolling moment due to sideslip	l_v/i_A	$-0{\cdot}1333\ \alpha°$
Rolling moment due to aileron	l_ξ/i_A	$-1{\cdot}6$ radian^{-1}
Pitching moment due to incidence	m_w/i_B	$-0{\cdot}3$
Pitching moment due to elevator	m_η/i_B	$-0{\cdot}3$ radian^{-1}
Pitching moment due to rate of pitch	m_q/i_B	$-2{\cdot}25$ radian^{-1}
Pitching moment due to rate of change of incidence	$m_{\dot{w}}/i_B$	$-2{\cdot}25$
Yawing moment due to rate of yaw	n_r/i_C	$-0{\cdot}8$ radian^{-1}
Yawing moment due to sideslip	n_v/i_C	$+0{\cdot}25$
Yawing moment due to rudder	n_ζ/i_C	$-0{\cdot}3$ radian^{-1}
Sideforce due to sideslip	y_v	$-0{\cdot}3$
Further: $n_p = y_p = y_r = l_\zeta = y_\zeta = n_\xi = y_\xi = 0$		
Autostabilizer roll damping/inertia ratio	b_1/I_{xx}	$-2{\cdot}90 \times 10^{-4}$ lbf^{-1} sec^{-1}
Autostabilizer pitch damping/inertia ratio	b_2/I_{yy}	$-2{\cdot}50 \times 10^{-4}$ lbf^{-1} sec^{-1}
Autostabilizer yaw damping/inertia ratio	b_3/I_{zz}	$-1{\cdot}56 \times 10^{-4}$ lbf^{-1} sec^{-1}

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TABLE 2

Pilot Jet VTOL Experience.

Pilot	Flying experience in jet VTOL aircraft prior to this simulation	Pilot experience in this simulation				
		Total experience in this simulation	Familiarisation in the simulator	Simulation of constant, partly jet-borne speed	Simulation of transition from wing to jet-borne flight	Variation of visual and motion cues and general
	hr min	hr min	hr min	hr min	hr min	hr min
A	19 00	10 20	1 50	4 05	4 25	nil
B	10 00	10 05	1 05	2 15	4 55	1 50
C	17 40	9 25	1 40	4 10	3 35	nil
D	4 25*	6 00	1 00	3 55	1 05	nil
E	4 55*	8 05	1 55	4 05	2 05	nil
F	nil	11 35	1 50	4 55	3 35	1 15
15 Others	—	19 55	12 00	3 25	2 00	2 30

*These pilots converted to jet VTOL aircraft during the period of this simulation.

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TABLE 3

*Replies by Pilots to Questionnaire on Constant Speed Techniques.**

(a) *Attitude—sensibly—constant technique.*

Question	Answer (Pilot indicated by the letter in brackets—*see* Table 2)
Flight path controlled by . . .	Vectored thrust throttle (A), (B), (C), (D), (E), (F).
Speed controlled by . . .	Nozzle angle (A), (B), (C), (D), (E), (F).
Upper speed limit.	150 kt or more (B), (D). About 100 kt (A—though quite usable up to 150 kt), (C), (E), (F).
Reason for this limit.	Powerful elevator control should be used at higher speed (A), (E), (F). Nozzle response poor at low thrust (i.e. high speed) (A), (F). Interference between thrust and nozzle angle increases (C). None (B), (D).
Lower speed limit.	40 kt or less (A), (B), (C), (D), (E), (F).
Reason for this limit.	None (A), (B), (C), (D), (E), (F).
Comments on incidence.	Large incidence changes with changes of power and nozzle (i.e. flight path and speed) at constant attitude (A), (B), (D), (E), (F). Largest variations at low speed (C).
Comments on attitude.	Easier to hold attitude constant than to use it for control in I.F. (A), (F). Should be changed when flight path is altered to keep incidence within reasonable limits (A), (B). Problems may arise if there are large trim changes with power or nozzle angle (C), (D). Can be used as a fine control of flight path and speed (E).

General comments on this technique appear in Appendix C.

N.B. The pilots always called thrust vector angle 'nozzle angle' which is the term used to describe the position of the exhaust nozzles of the P 1127 aircraft.

*A completed *pro-forma* showing the layout of the questions is shown in Fig. 10.

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TABLE 3—*continued*

(b) *Thrust vector angle constant technique.*

Question	Answer (Pilot indicated by the letter in brackets—*see* Table 2)
Flight path controlled by . . .	Either vectored thrust throttle or elevator depending on speed (A), (E). Vectored thrust throttle (B), (C), (D), (F).
Speed controlled by . . .	Either elevator or vectored thrust throttle depending on speed (E). Elevator (A), (B), (C), (D), (F).
Upper speed limit.	150 kt or more (A—best below 80 kt), (B—acceptable below 60 kt), (F). About 100 kt (C), (D), (E).
Reason for this limit.	Interference between the functions of the controls (A), (B), (C), (D). High fuel consumption (B), (E). Limited control of speed (B). None (F).
Lower speed limit.	40 kt or less (A), (B), (C), (D), (E), (F).
Reason for this limit.	None (A), (B), (C), (D), (E), (F).
Comments on incidence.	Easy to over-incidence at high speed (A), (B), (C), (E), (F). Provides a limit on available attitude changes (B), (D).
Comments on attitude.	Not very effective as a speed control (B), (C), (D). Only small changes needed (F).

General comments on this technique appear in Appendix C.

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TABLE 3—*continued*

(c) *Throttle constant technique.*

Question	Answer (Pilot indicated by the letter in brackets—*see* Table 2)
Flight path controlled by . . .	Elevator (A), (B), (C), (D—Primarily), (E). Elevator above about 120 kt, nozzle angle below (F).
Speed controlled by . . .	Nozzle angle (A), (B), (C), (D—Primarily), (E). Nozzle angle above 120 kt, elevator below (F).
Upper speed limit.	150 kt or more (A), (B), (C), (D), (E), (F).
Reason for this limit.	None (A), (B), (C), (D), (E), (F—complicated method with $\delta_L \simeq 45°$).
Lower speed limit.	About 100 kt (A), (D). About 80 kt (B), (C), (E). 40 kt or less (F).
Reason for this limit.	Flight path response becomes too slow unless gross changes of incidence are made (A), (B), (C), (D), (E). None (F).
Comments on incidence.	Easy to set up trim incidence regardless of weight, etc. (C), (E). Easy to keep incidence within limits (D), (F).
Comments on attitude.	Related to flight path as in conventional flight (B), (E). Small variations only (C), (D). Large changes required (F).

General comments on this technique appear in Appendix C.

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TABLE 4

A Summary of the Pilots' Replies to the Questionnaire on Transitions.

Question	Brief summary of pilots' replies
Do you prefer the ballistic type of deceleration (i.e. selecting a given nozzle angle) or a slower one in which you continuously vary nozzle angle to control the deceleration and why?	All preferred to vary nozzle angle as required. This does not necessarily involve continuous variations nor is the deceleration necessarily slower.
If asked to do the former and you found you were undershooting or overshooting (in visual flight) would you alter attitude or nozzle angle and why?	All would alter nozzle angle as large changes can be made with little or no interaction with height or glide path control.
Do you prefer a lever or a button on the stick for nozzle angle control and would this choice be the same for either type of transition described above?	Pilots A and C prefer a button while pilots B and F generally prefer a lever but in all cases the choice would depend on the flying task and a number of other factors.
Would you use aerodynamic lift for flight path control as long as possible or change to using lift thrust at the moment of starting the deceleration?	All except Pilot B would normally use lift thrust from the start but much depends on the aircraft characteristics and the particular circumstances.
Do you think that starting the deceleration fully jet-borne is a technique worth considering?	If the major problems (i.e. high fuel consumption and rapid ageing of current engines) can be overcome it may be a useful technique.
If using wing lift do you think that it is worth making maximum use of it, i.e. letting the incidence approach as near as practical to its limit as speed falls, or would you keep the incidence to its value at the start of the transition (assuming this is some way below the limit)?	Pilot F would normally make maximum use of incidence but Pilot C would not. Pilots A and B say that it would depend on the conditions.
Do you think that holding a glide path by keeping attitude constant and holding a given incidence would be a practical technique?	All agree that this is not a practical technique but Pilot A thinks that attitude stabilisation and improved presentation of incidence might alter the picture.
Can you suggest any improvements to the standard flight instruments that would be likely to make instrument transitions easier?	A.S.I. should read accurately to zero. V.S.I. should be instantaneous. Artificial horizon should give more precise pitch attitude information. Presentation of sideslip and incidence (standard to VTOL aircraft) needs improvement.
Would you prefer to keep the tasks of descending and decelerating separate if (a) the only additional information you have is range and some azimuth guide (e.g. BABS); (b) you have range and I.L.S. or similar information?	Pilots C and F said yes for (a) and no for (b). Pilot A said that the prevailing conditions are more important than the instruments available while Pilot B was not sure that there was any merit in keeping the tasks separate at all.
In what ways do you think that the simulated transitions were unrepresentative of real flight?	The thrust/weight ratio was too high; the simulator was stable at all speeds; there were no normal and longitudinal acceleration cues; no outside disturbances, no range information, no apprehension and no fuel consumption.
Which of these differences do you think would make the real thing more difficult and which would make it easier?	The lower thrust weight ratio, lower stability, outside disturbances, fuel consumption and apprehension would make the real thing more difficult while acceleration cues should make it easier. The addition of visual range information might work either way.
Do you think that the simulator exercises were representative enough to be of assistance when attempting instrument transitions in an aircraft?	Yes. All agreed that the simulator experience had already been of great assistance.

The individual pilots replies to each question are given in Appendix D.

N.B. The pilots always called thrust vector angle 'nozzle angle' which is the term used to describe the position of the exhaust nozzles of the P 1127.

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FIG. 1. Visual display produced by skyscape projector to represent flight at altitude.

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FIG. 2. Instrument panel layout.

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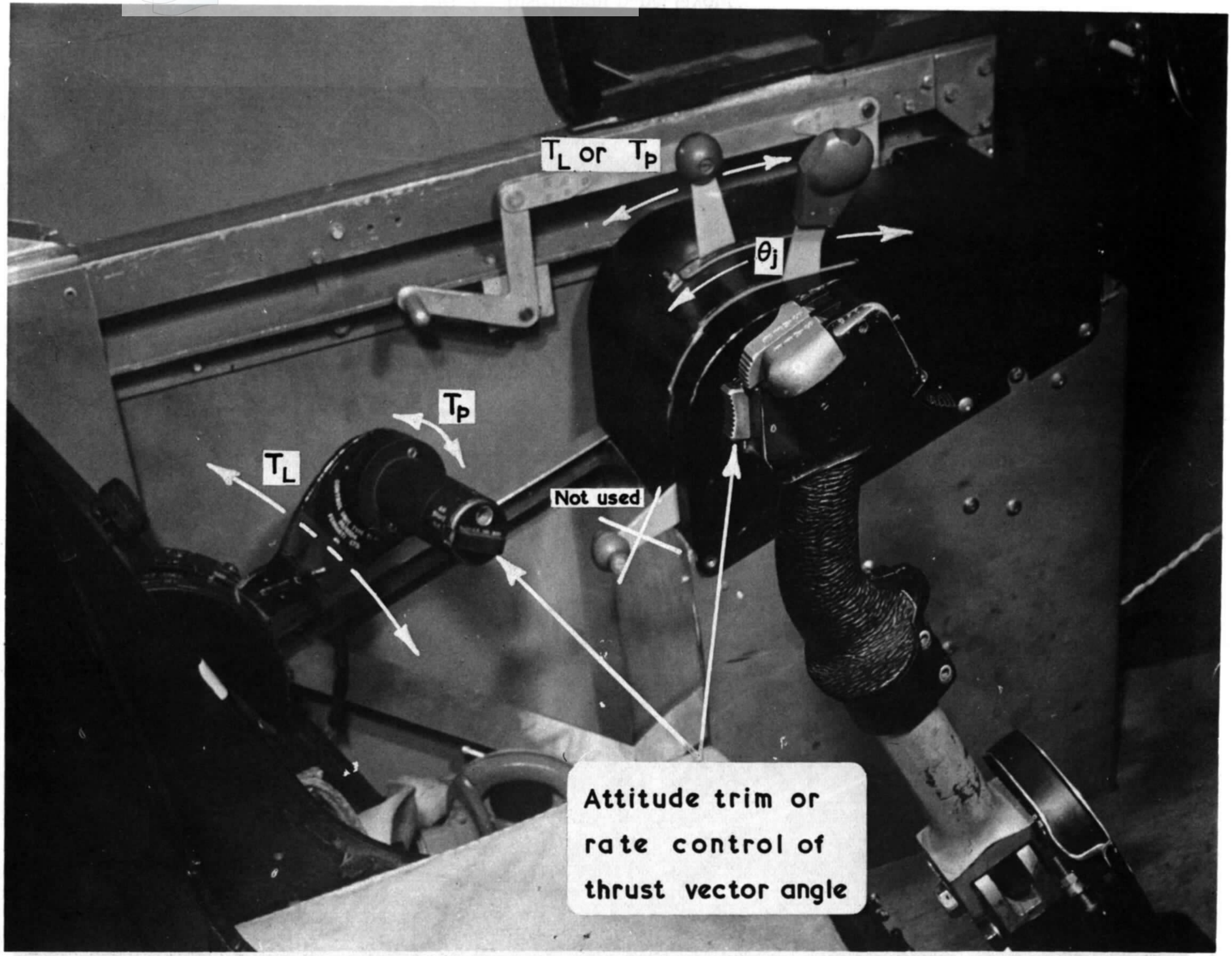

FIG. 3. Layout of throttle and thrust vector angle controls.

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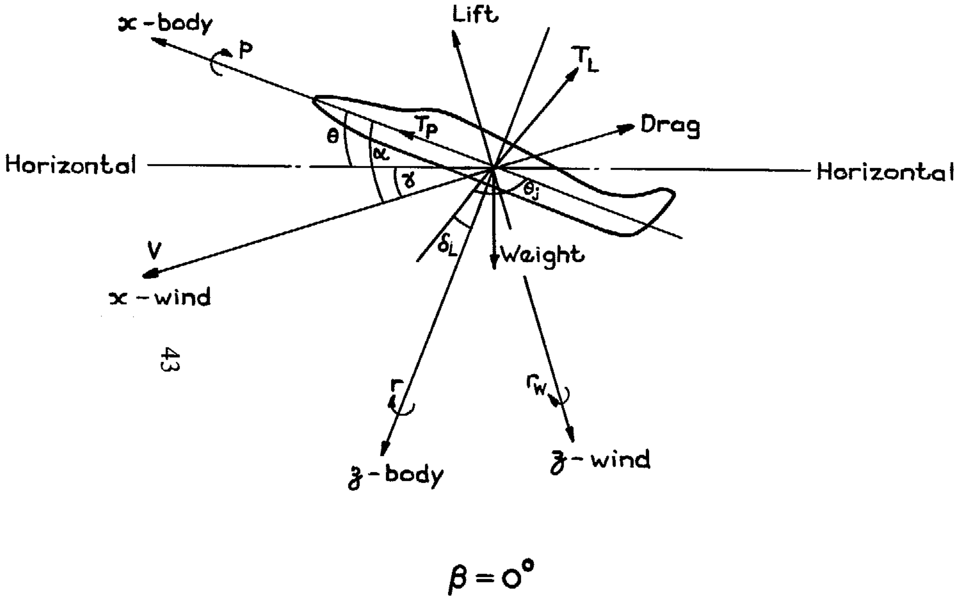

FIG. 4. Axis systems used in the simulation showing the forces acting on the aircraft.

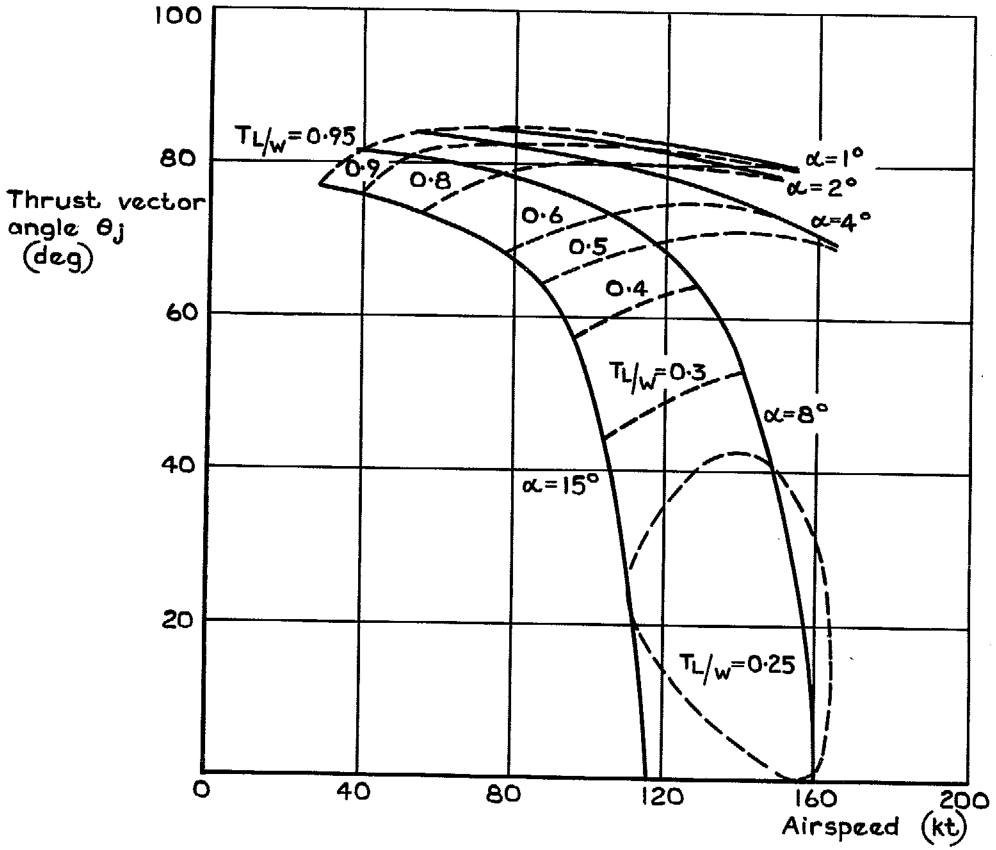

FIG. 5. Values of thrust vector angle, thrust and incidence to trim at a range of partly jet-borne speeds.

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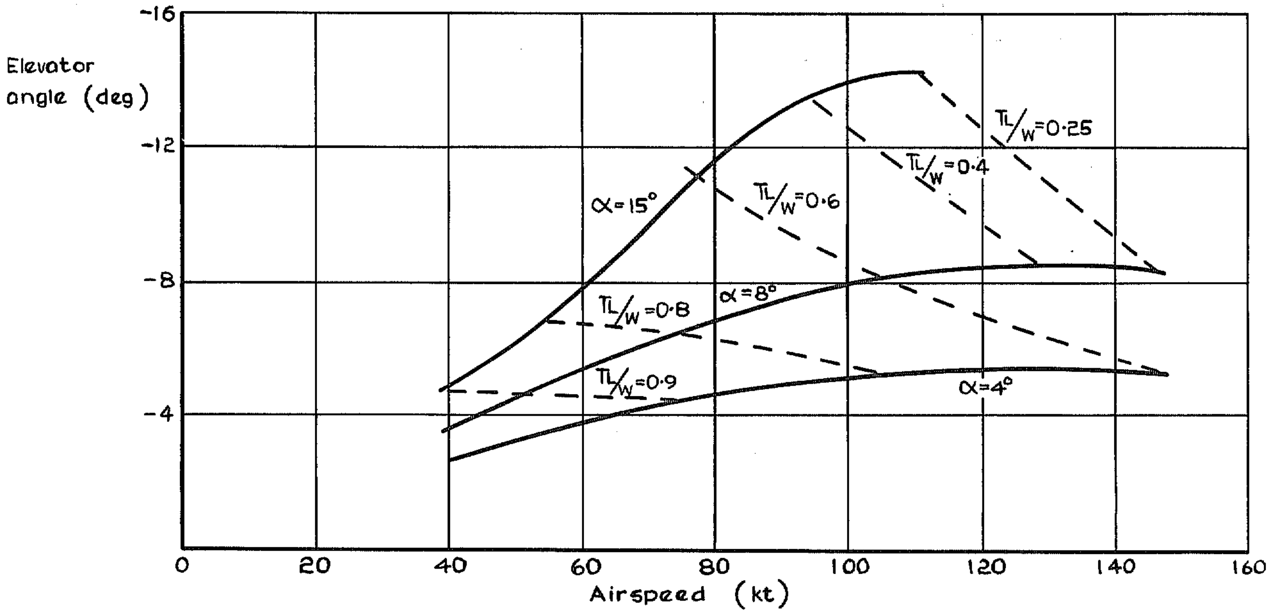

FIG. 6. Elevator angle to trim *versus* airspeed for several values of incidence and thrust/weight ratio for straight and level flight.

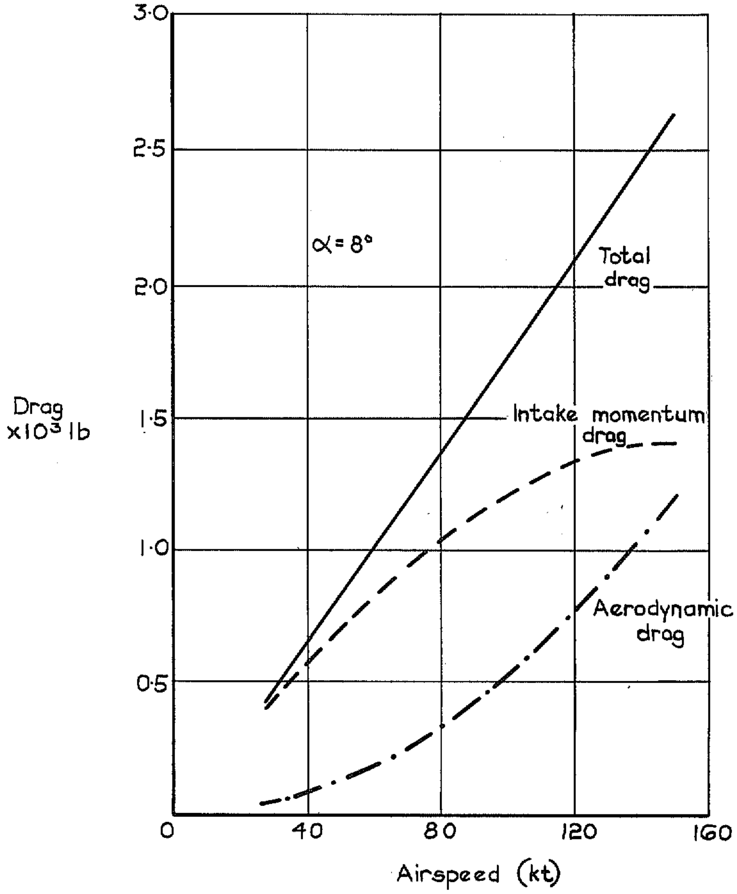

FIG. 7. Contributions of aerodynamic and intake momentum drag to total drag for a range of trimmed speeds at 8° incidence.

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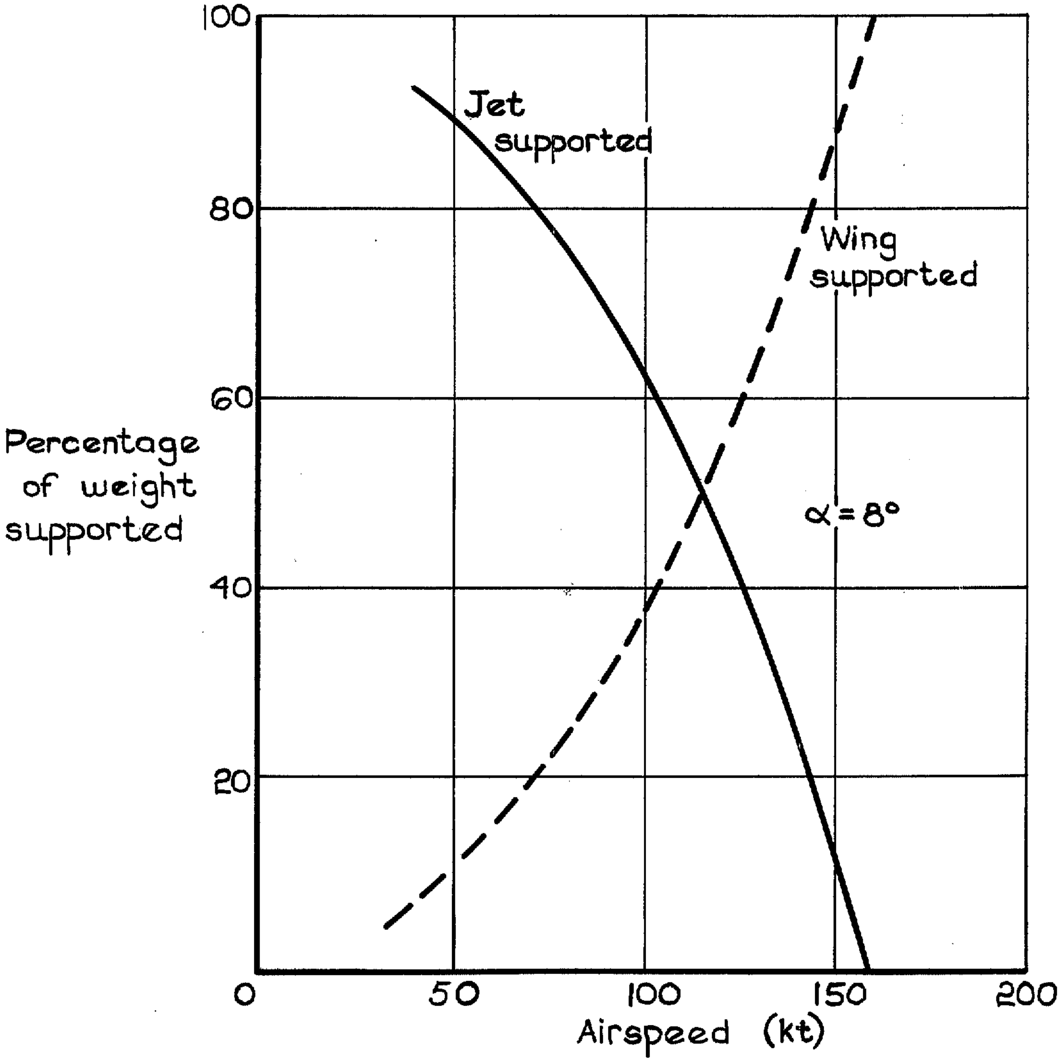

FIG. 8. Proportions of weight supported by wing and jet at a range of speeds at 8° incidence.

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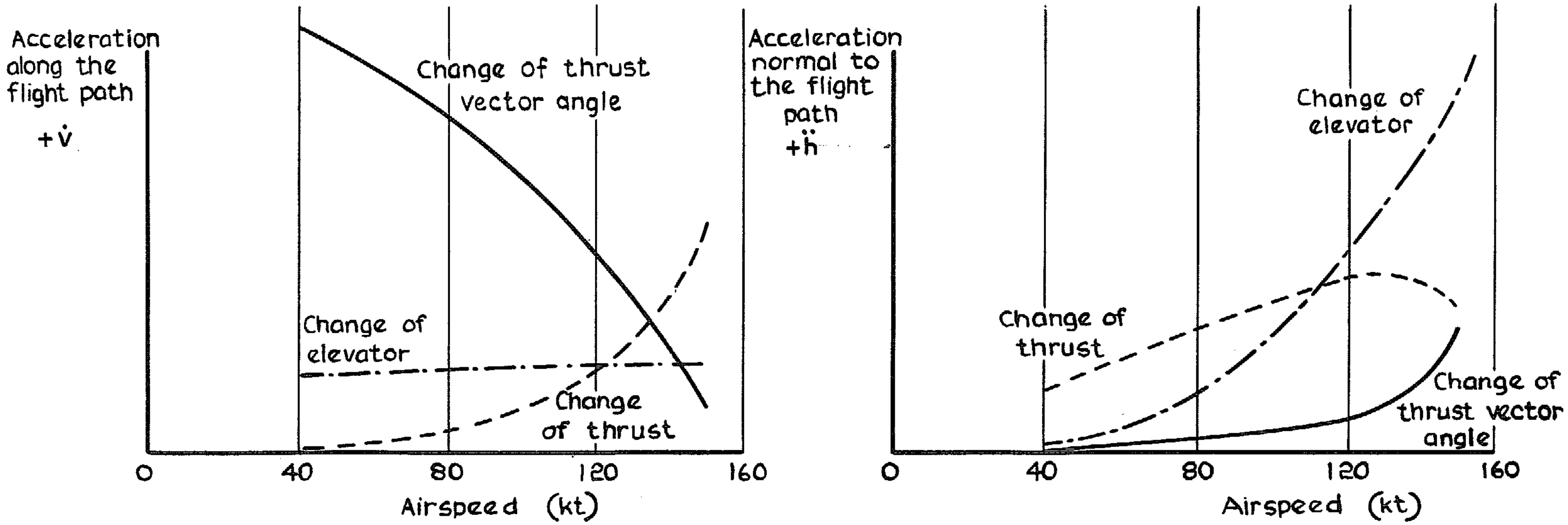

FIG. 9. Short term effect of comparable changes in thrust vector angle, throttle and elevator controls on accelerations along and normal to the flight path for a range of partly jet-borne speeds at 8° incidence.

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Attitude Sensibly Constant Technique.

HEIGHT CONTROLLED BY: Throttle.

SPEED CONTROLLED BY: Nozzle angle.

SPEED BAND IN WHICH THIS TECHNIQUE CAN BE USED: 100–80 kt and below.

REASON FOR UPPER SPEED LIMIT: Change of thrust gives too big a speed variation.

REASON FOR LOWER SPEED LIMIT: No lower speed limit; becomes better all the time.

COMMENTS ON INCIDENCE: Incidence variations greatest at low speeds. This can lead to stall or pitch up problems. On P 1127 due to pitch up in bracket 120–80 kt, technique *might* be unsuitable until down to about 70 kt.

COMMENTS ON ATTITUDE: Problems with control if large trim changes present with either rev/min or nozzle angle. This *could* be particularly limiting on P 1127 which has both.

GENERAL COMMENTS: Nozzle and rev/min controls must be co-ordinated. Power is a left hand function and nozzle angle is so tied up with incidence and speed that it seems more natural to include this with the right hand function of attitude control, i.e. throttle controlled by left hand and nozzle controlled by a button on the stick would be ideal for this method of control.

This method is probably the most promising single method of control.

Thrust Vector Angle Constant Technique

HEIGHT CONTROLLED BY: Throttle.

SPEED CONTROLLED BY: Stick.

SPEED BAND IN WHICH THIS TECHNIQUE CAN BE USED: About 100 kt and below.

REASON FOR UPPER SPEED LIMIT: Nozzle too far from vertical therefore big ias/rev/min interaction.

REASON FOR LOWER SPEED LIMIT: None; better all the time as ias reduces.

COMMENTS ON INCIDENCE: Can lead to very big incidence increases in descent, especially if high on glide path and rev/min is quickly reduced (could lead to stall or pitch up).

COMMENTS ON ATTITUDE: Large attitude changes are not needed for small or slow ias changes.

GENERAL COMMENTS: Not such a powerful control of ias as nozzle angle movements, since attitude changes are normally more limited due to incidence side effects. View *can* deteriorate seriously with deceleration.

Throttle Constant Technique.

HEIGHT CONTROLLED BY: Stick.

SPEED BAND IN WHICH THIS TECHNIQUE CAN BE USED: 150 kt to 85 (ish).

REASON FOR UPPER SPEED LIMIT: None.

COMMENTS ON INCIDENCE: A desired mean is easily set up regardless of weight (very valuable advantage on operational single-seat aircraft—no graphs or computations needed to set up optimum conditions).

SPEED CONTROLLED BY: Nozzle angle.

REASON FOR LOWER SPEED LIMIT: Incidence variations required to give glide path control get too big.

COMMENTS ON ATTITUDE: Attitude variations are only small.

GENERAL COMMENTS: Proved in flight in P 1127 to be the easiest technique over speed range 150–90 kt. Throttle fixed concept allows known margin of reserve power for flare/overshoot/emergency to be always available.

NOTE. The pilots always called the thrust vector angle 'nozzle angle' which is the term used to describe the position of the exhaust nozzles of the P 1127 aircraft.

FIG. 10. *Pro-forma* issued to pilots taking part in the constant, partly jet-borne speed exercise, completed by Pilot C.

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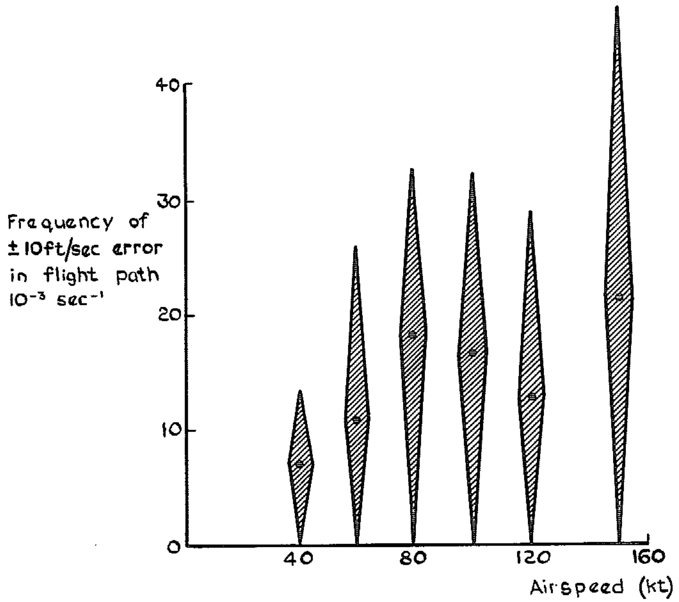
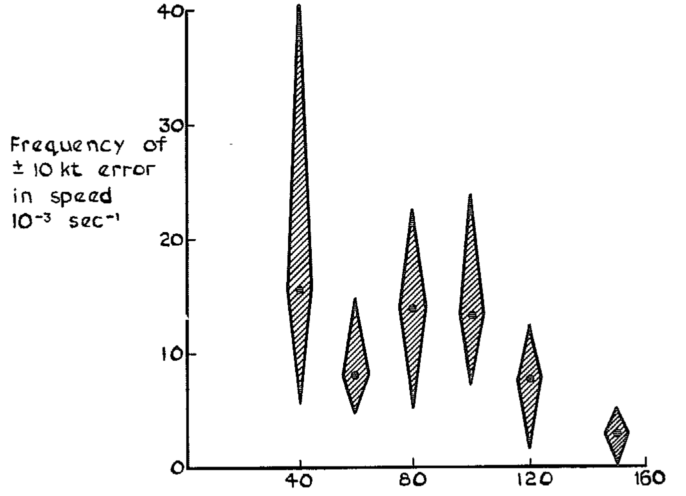
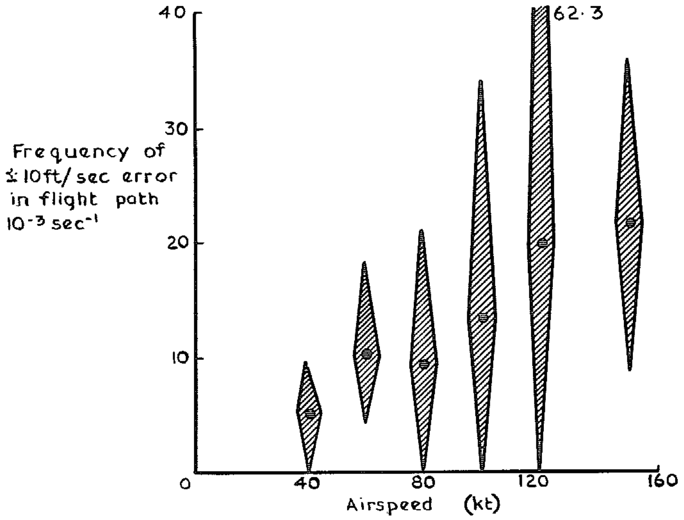


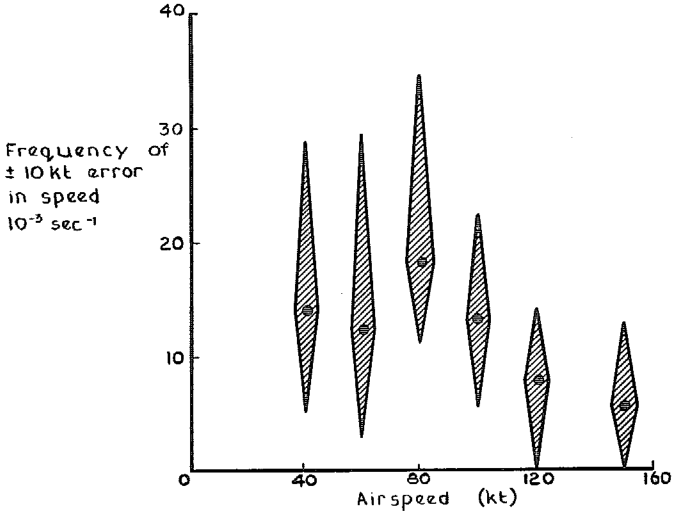
(a) Flight path



(b) Speed



(a) Flight path holding



(b) speed holding

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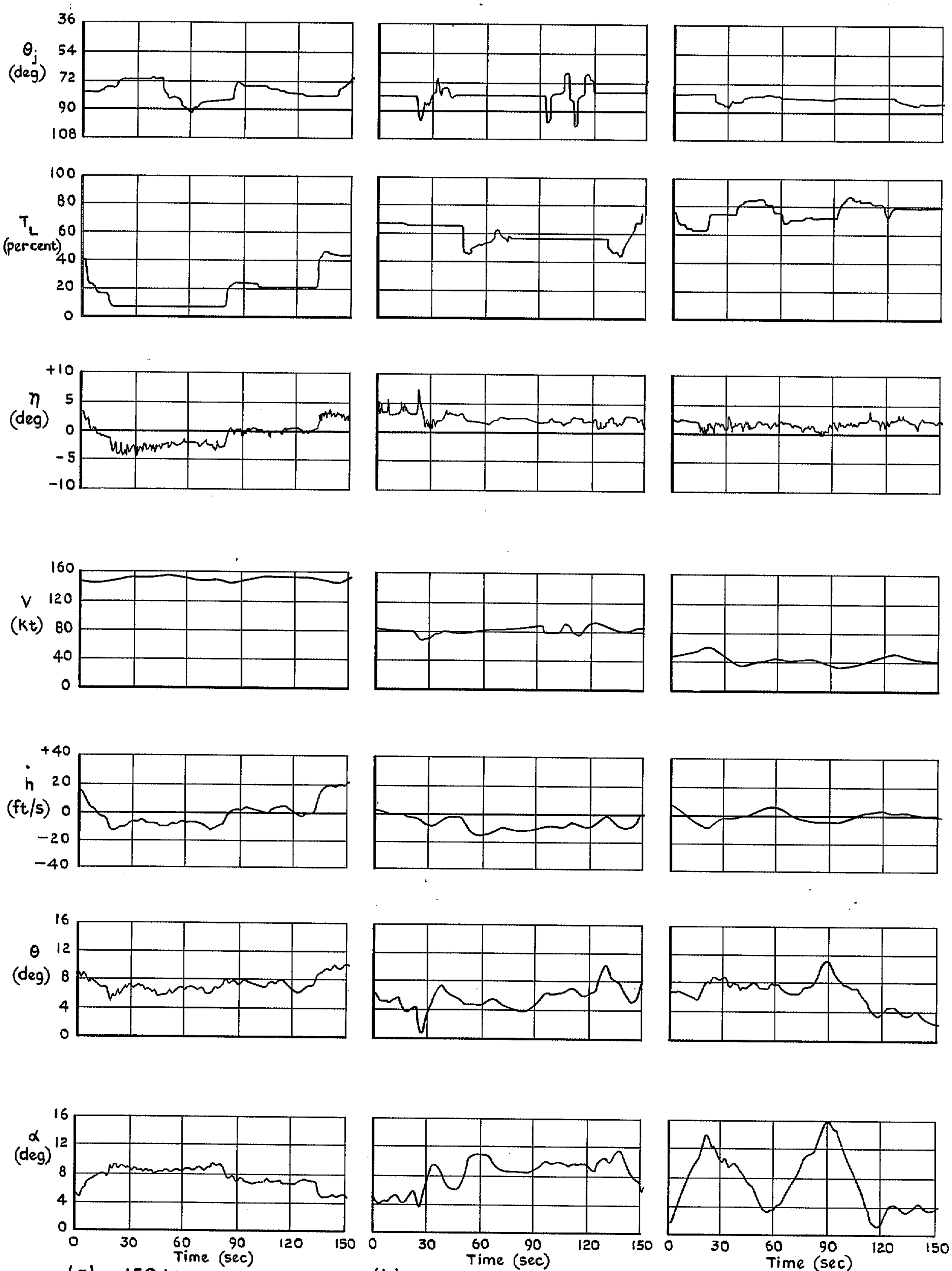

(a) 150 kt (b) 80 kt (c) 40 kt

FIG. 13. Typical time histories of general flying at three speeds by Pilot A, using the attitude—sensibly—constant technique.

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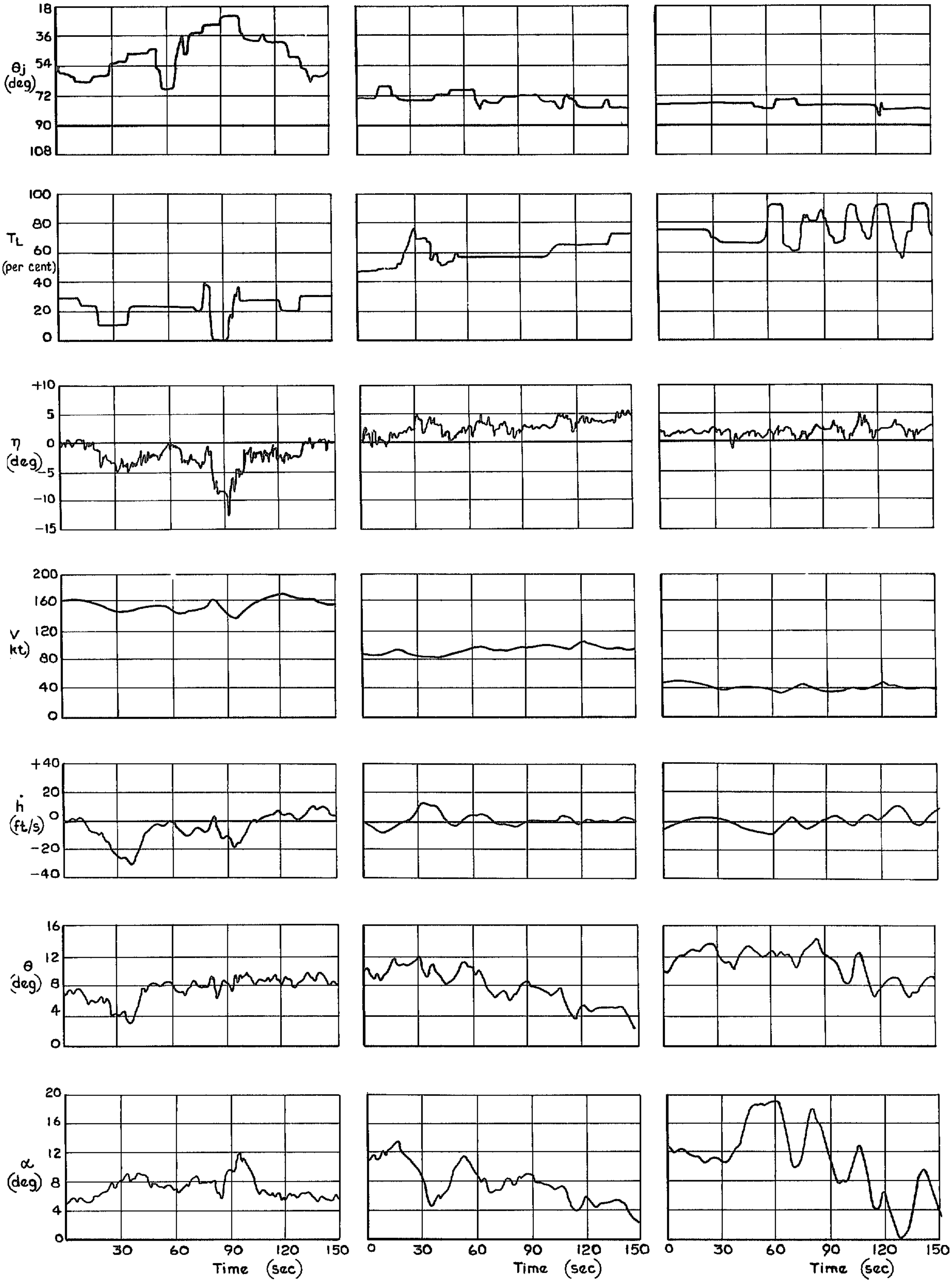

(a) 150 kt (b) 100 kt (c) 40 kt

FIG. 14. Typical time histories of general flying at three speeds by Pilot F using the attitude—sensibly—constant technique.

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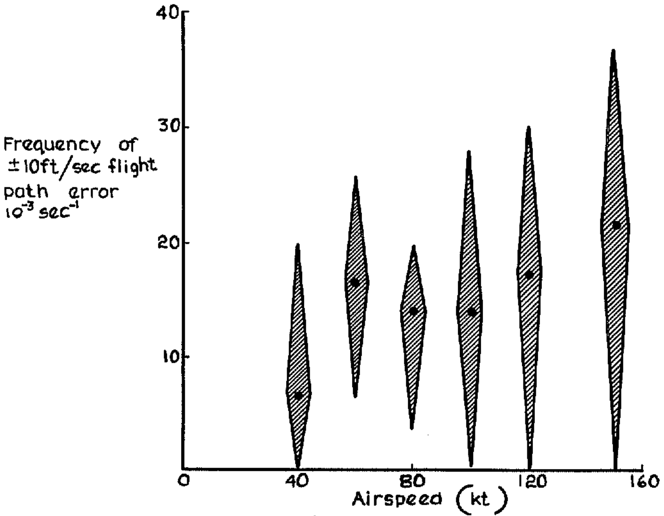
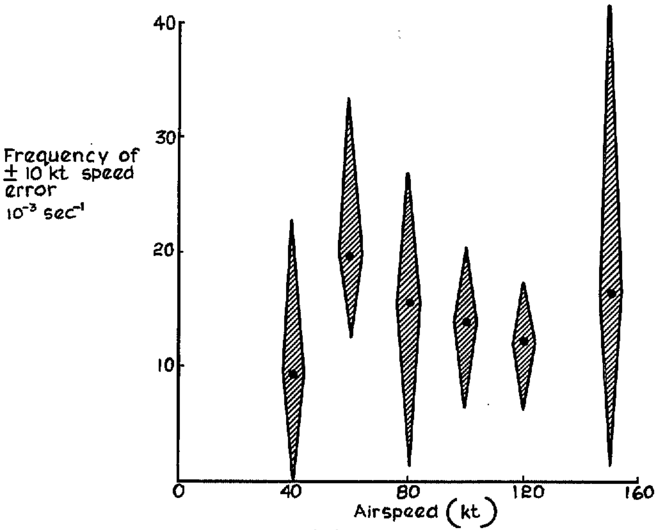


(a) Flight path holding



(b) Speed holding

FIG. 15. Frequency of error exceeding ±10 ft/sec flight path and ±10 kt speed for attitude—sensibly—constant technique.

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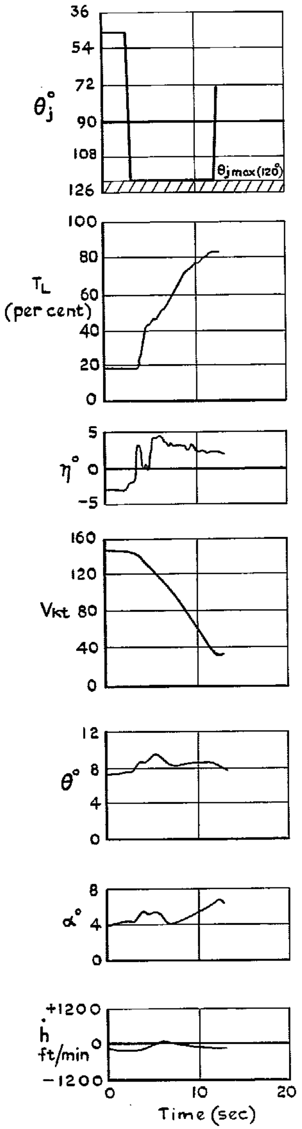

FIG. 16. Decelerating transition performed by selecting $\theta_j = 120°$.

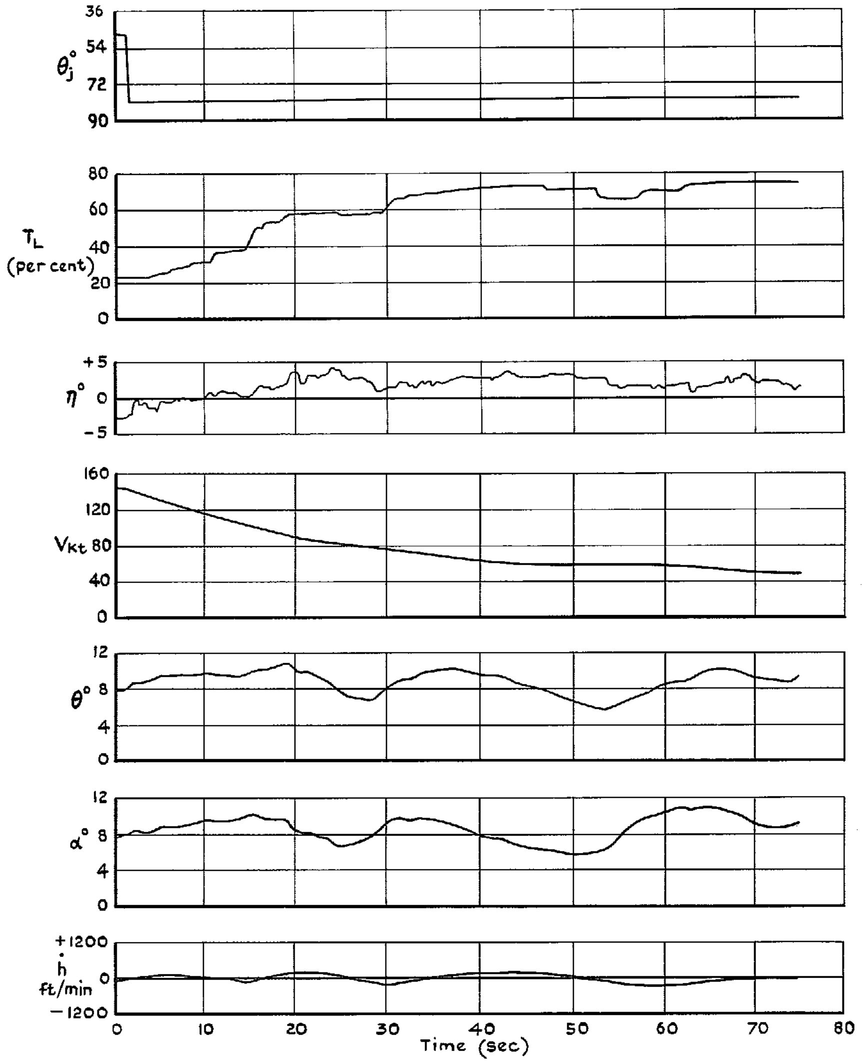

FIG. 17. Decelerating transition performed by selecting $\theta_j = 81°$.

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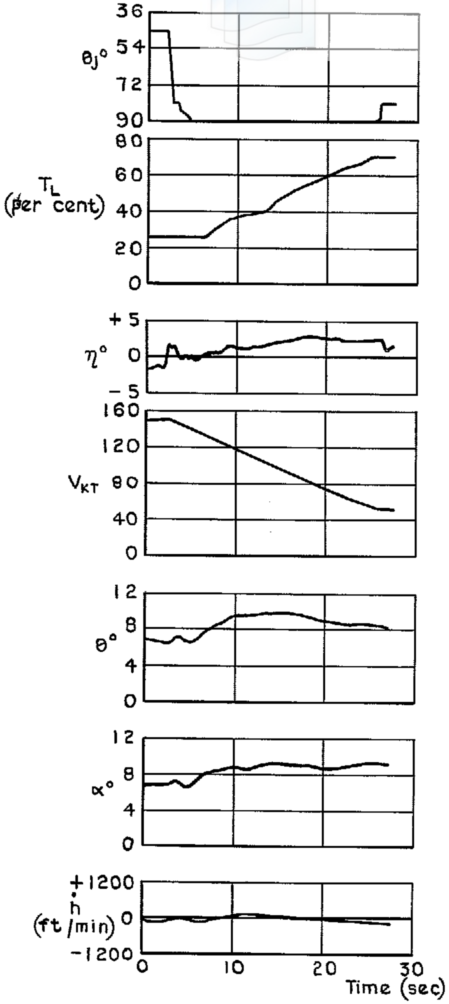

FIG. 18. Decelerating transition performed by selecting $\theta_j = 90°$.

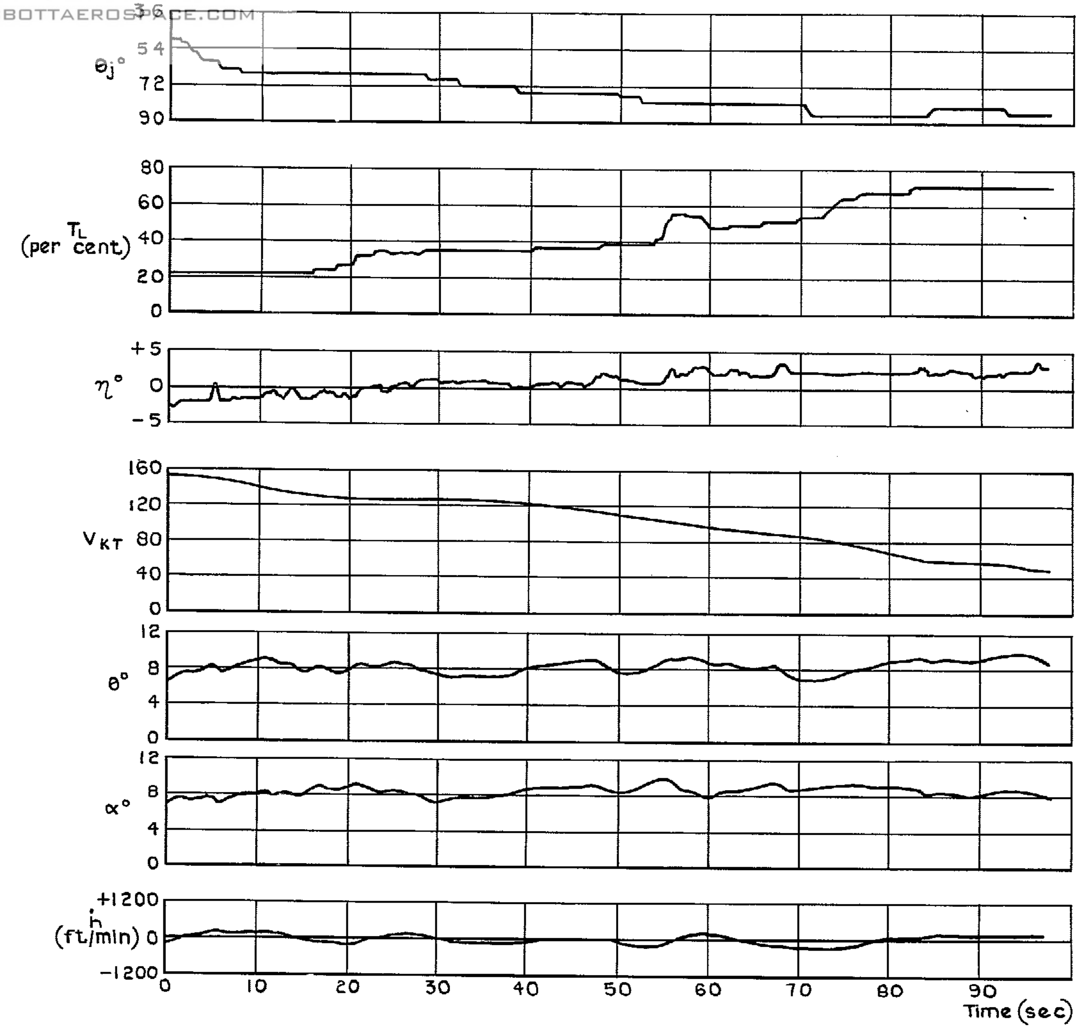

FIG. 19. Decelerating transition using the controlled deceleration technique.

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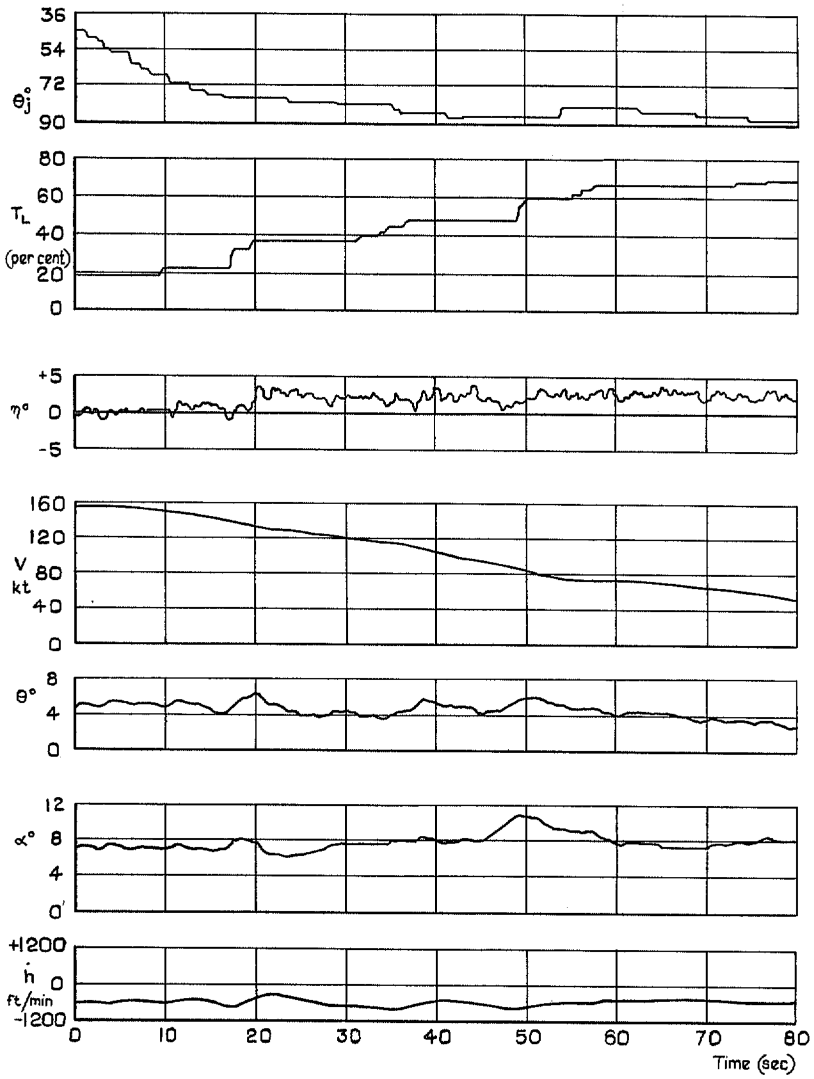

FIG. 20. Decelerating transition at constant rate of descent in which the pilot aimed to complete the transition in 1000 ft height change.

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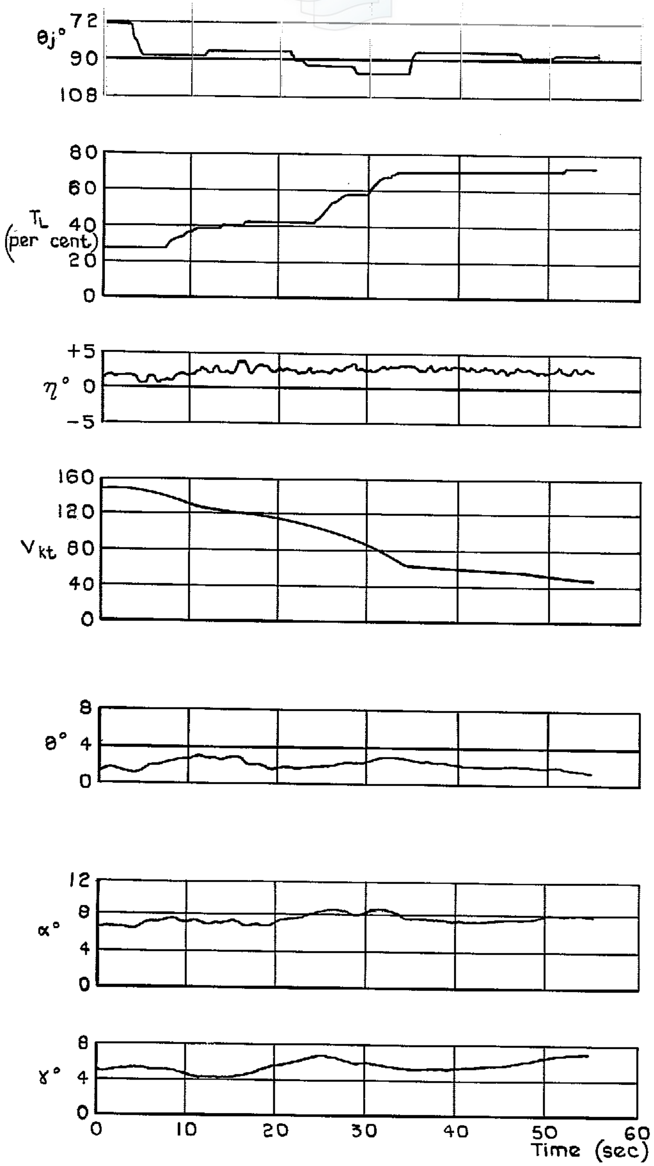

FIG. 21. Decelerating transition maintaining constant glide path angle.

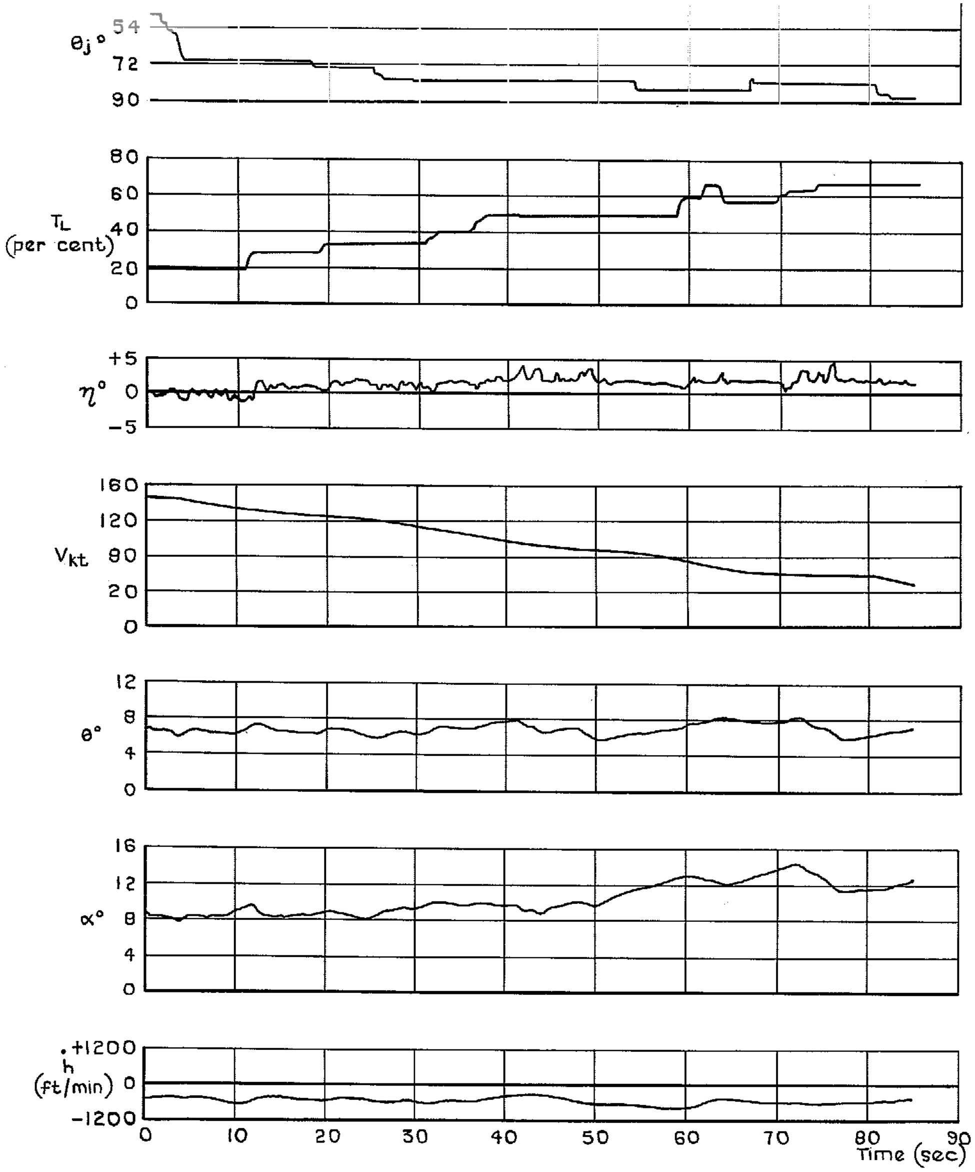

FIG. 22. Decelerating transition showing increase of incidence as speed falls.

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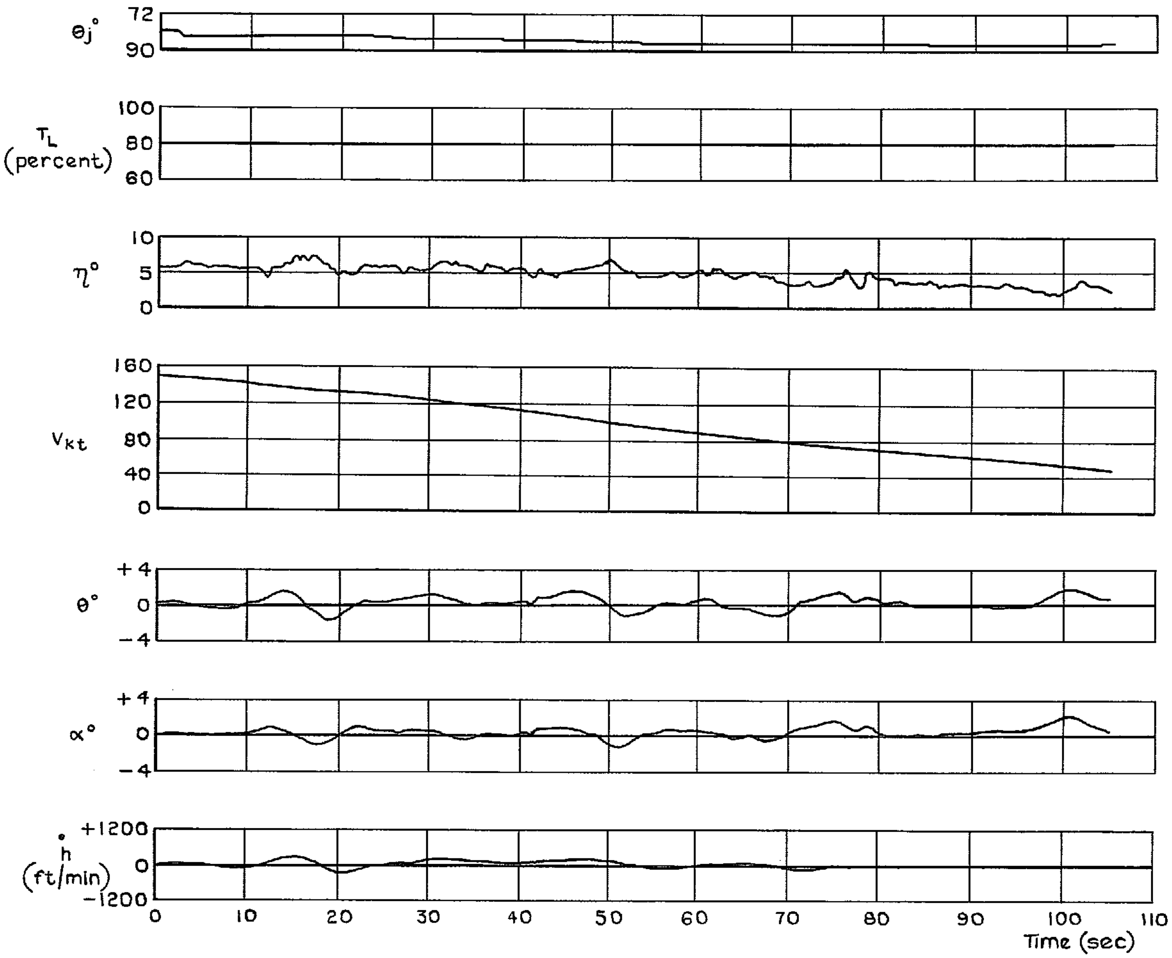

FIG. 23. Decelerating transition maintaining zero incidence.

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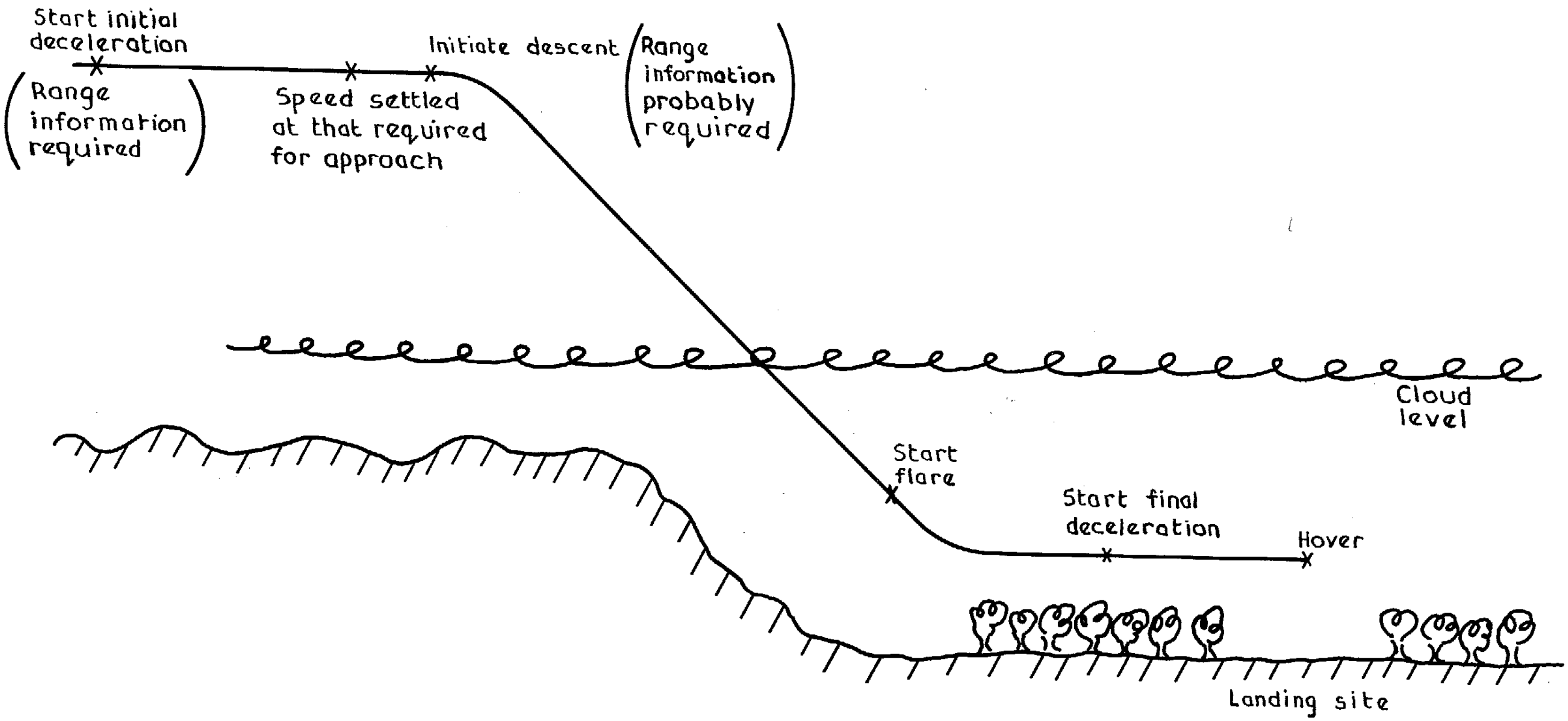

Not to scale

FIG. 24. The stepped approach technique.

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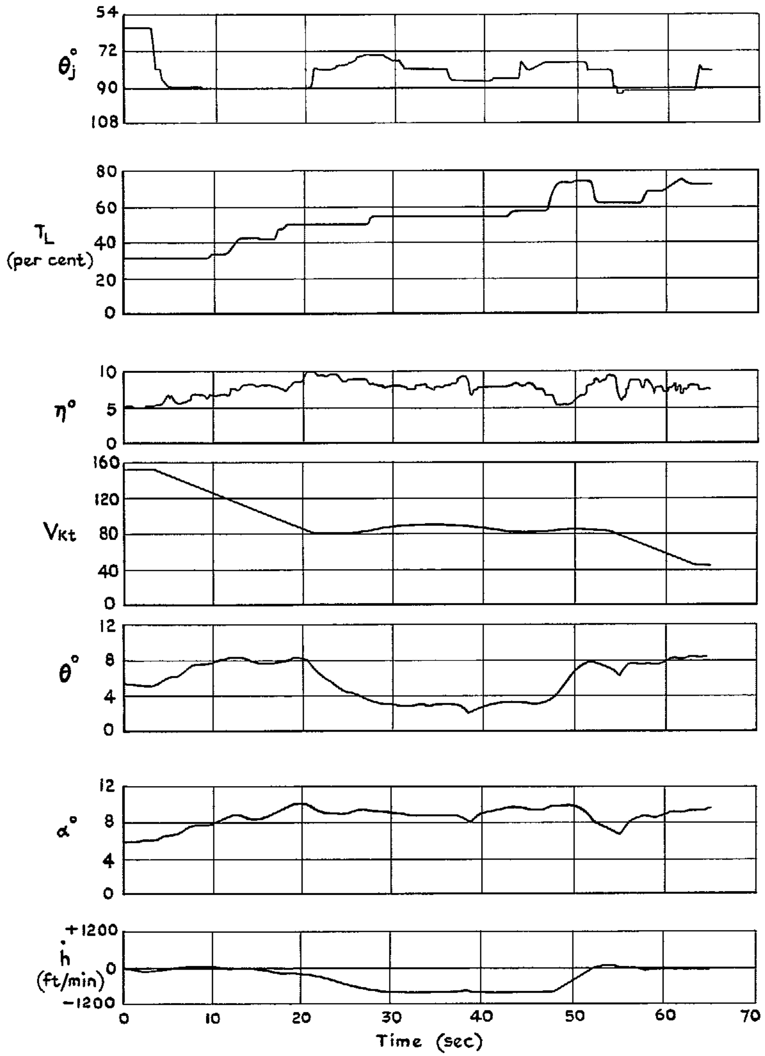

FIG. 25. The stepped approach technique performed with the three stages overlapping.

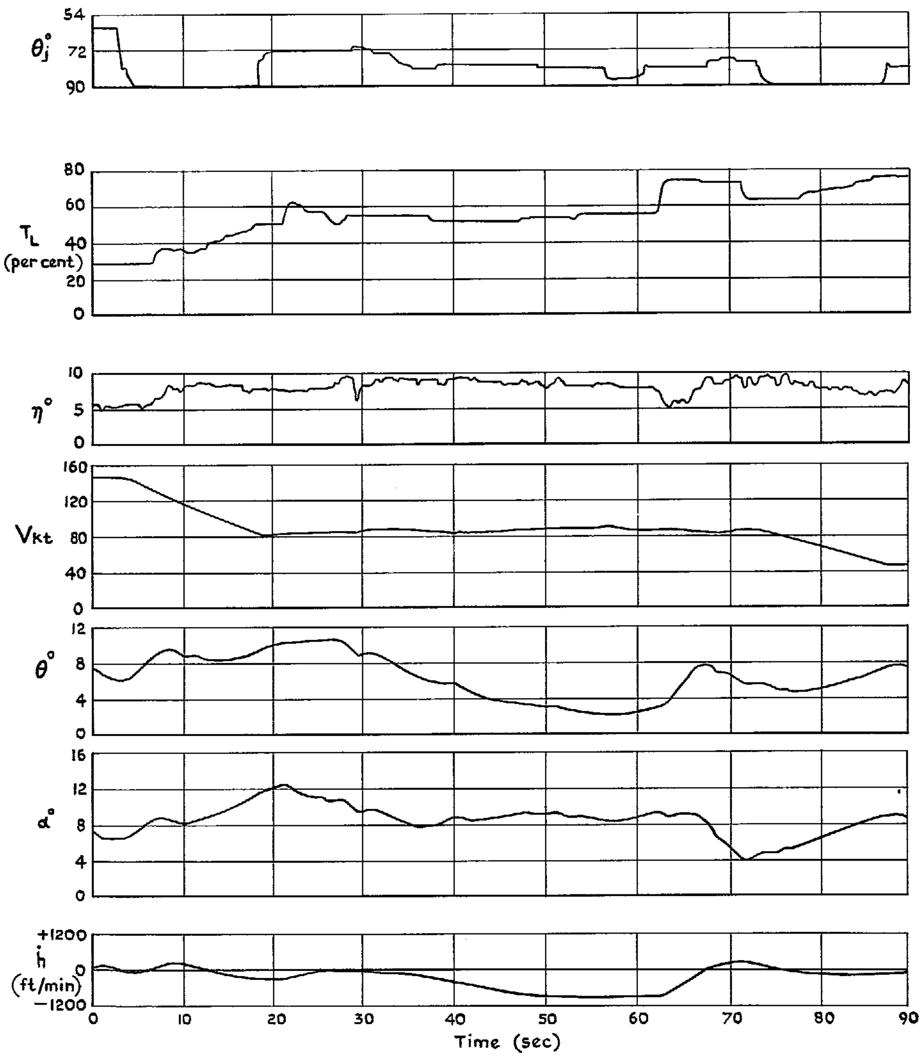

FIG. 26. The stepped approach technique performed keeping the three stages separate.

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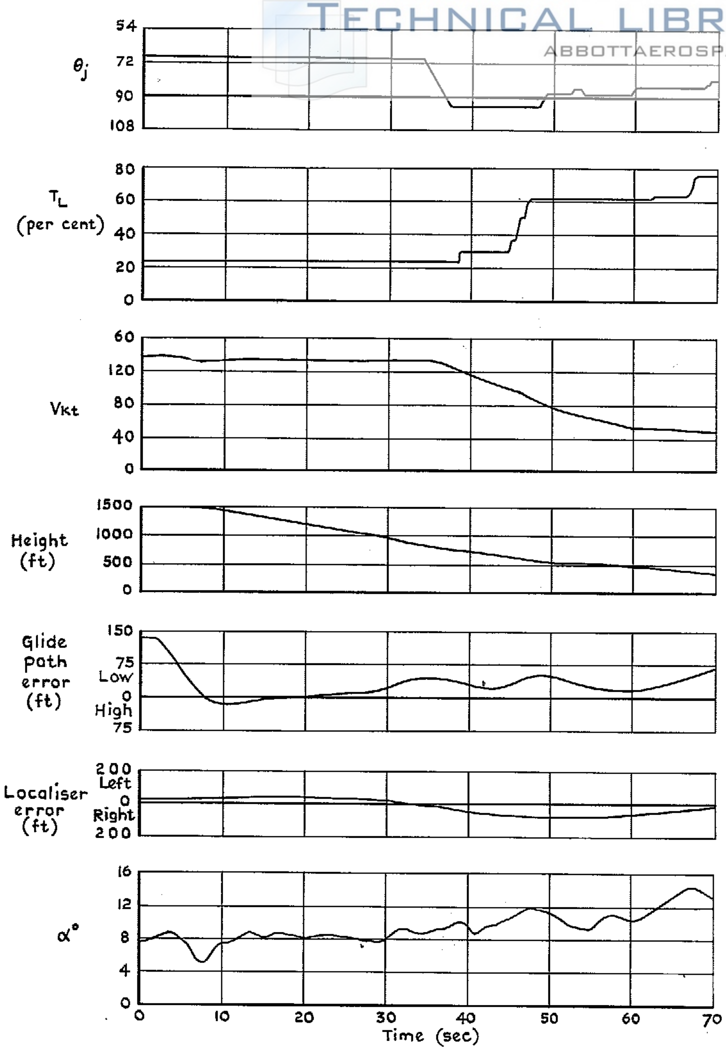

FIG. 27. Decelerating transition performed while following an ILS beam.

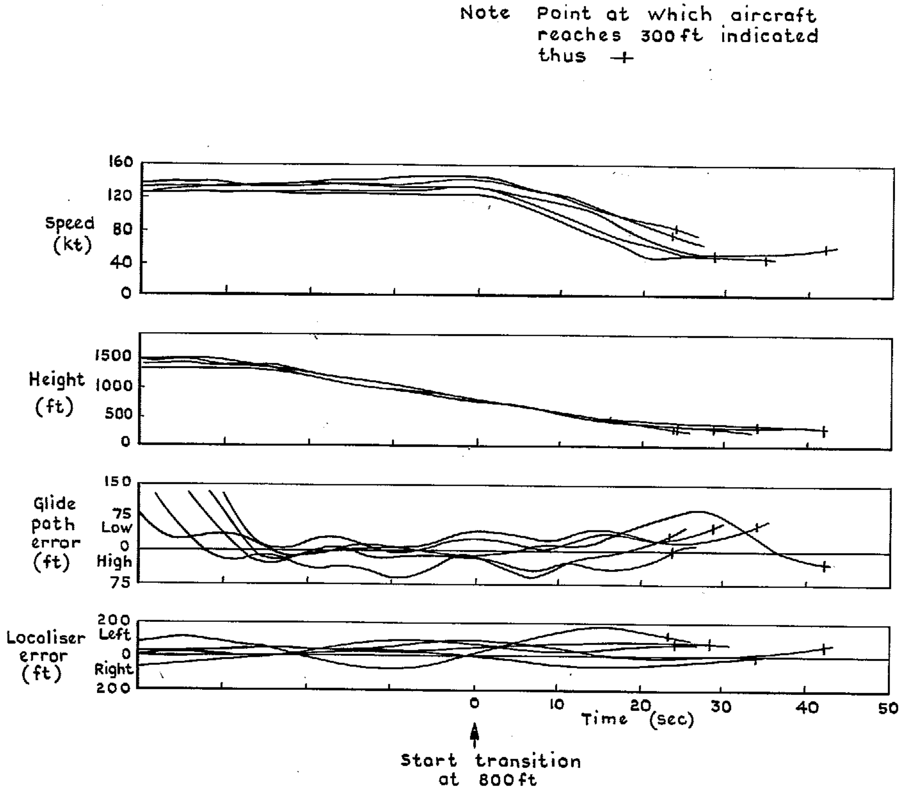

FIG. 28. Approaches and decelerating transitions performed with ILS.

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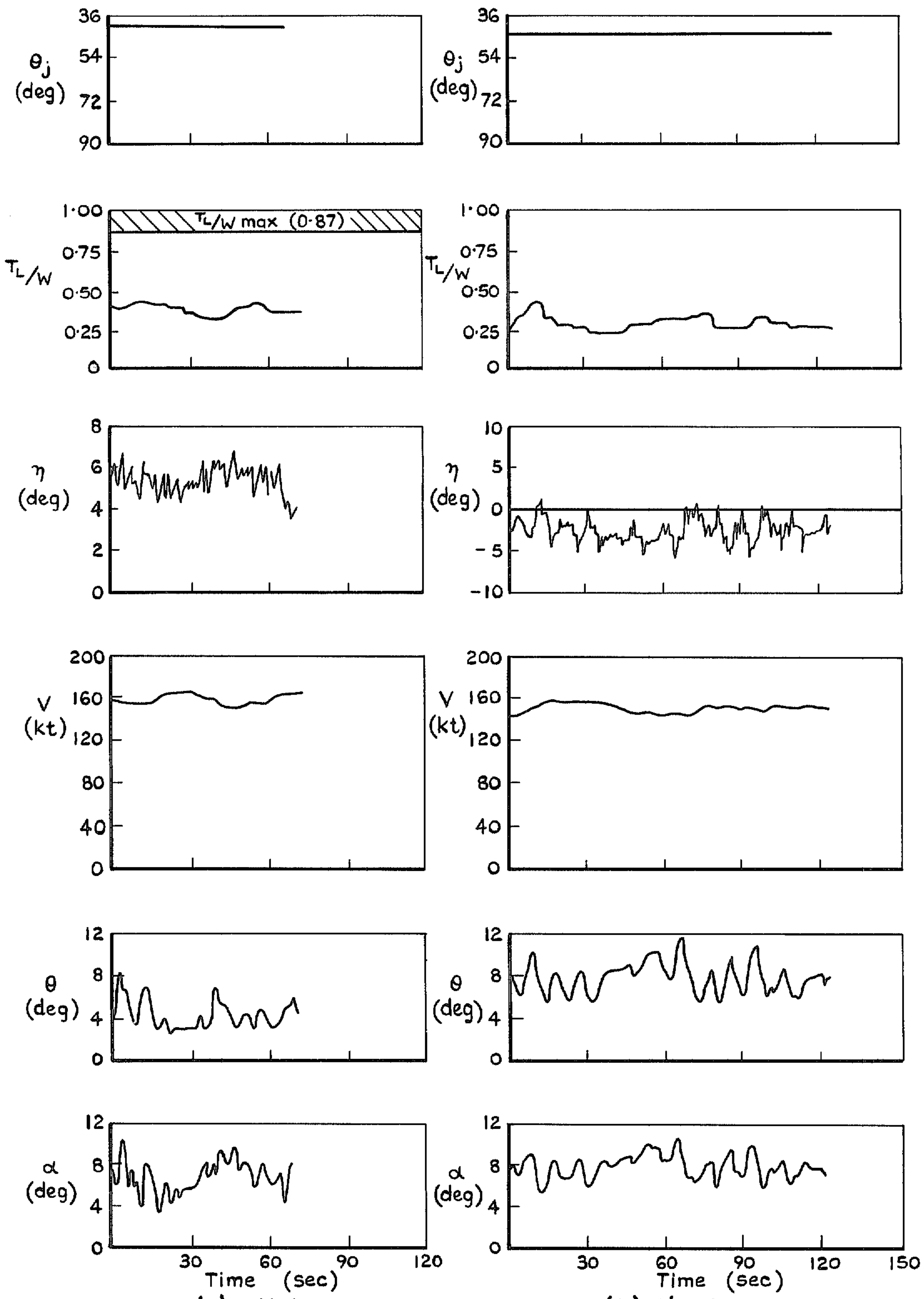

(a) Flight (b) Simulator

FIG. 29. Comparison of flight and simulator time histories by Pilot E in level flight at 150 kt with thrust vector angle fixed.

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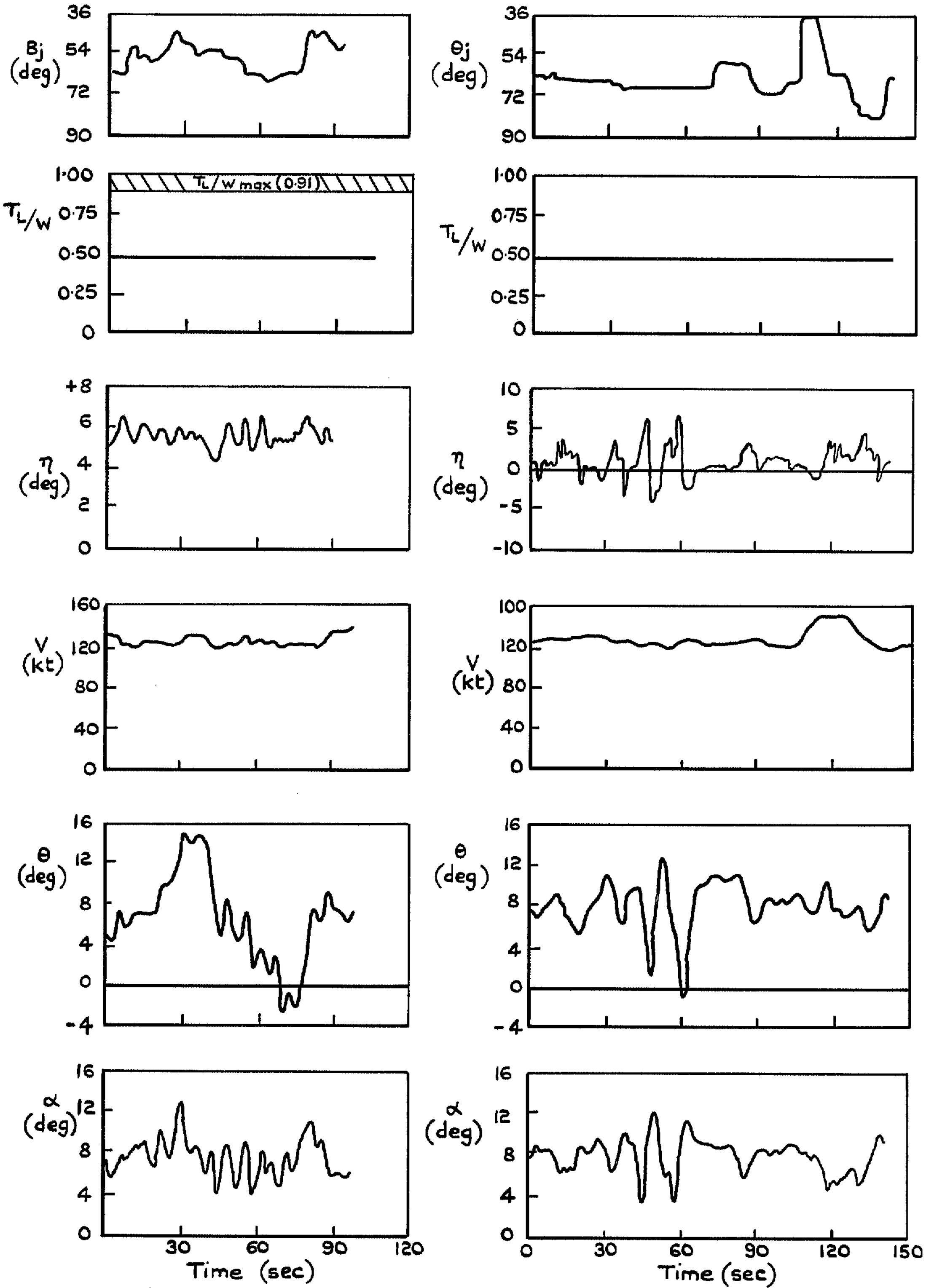

(a) Flight

(b) Simulator

FIG. 30. Comparison of flight and simulator time histories by Pilot E in level flight at 120 kt with throttle fixed.

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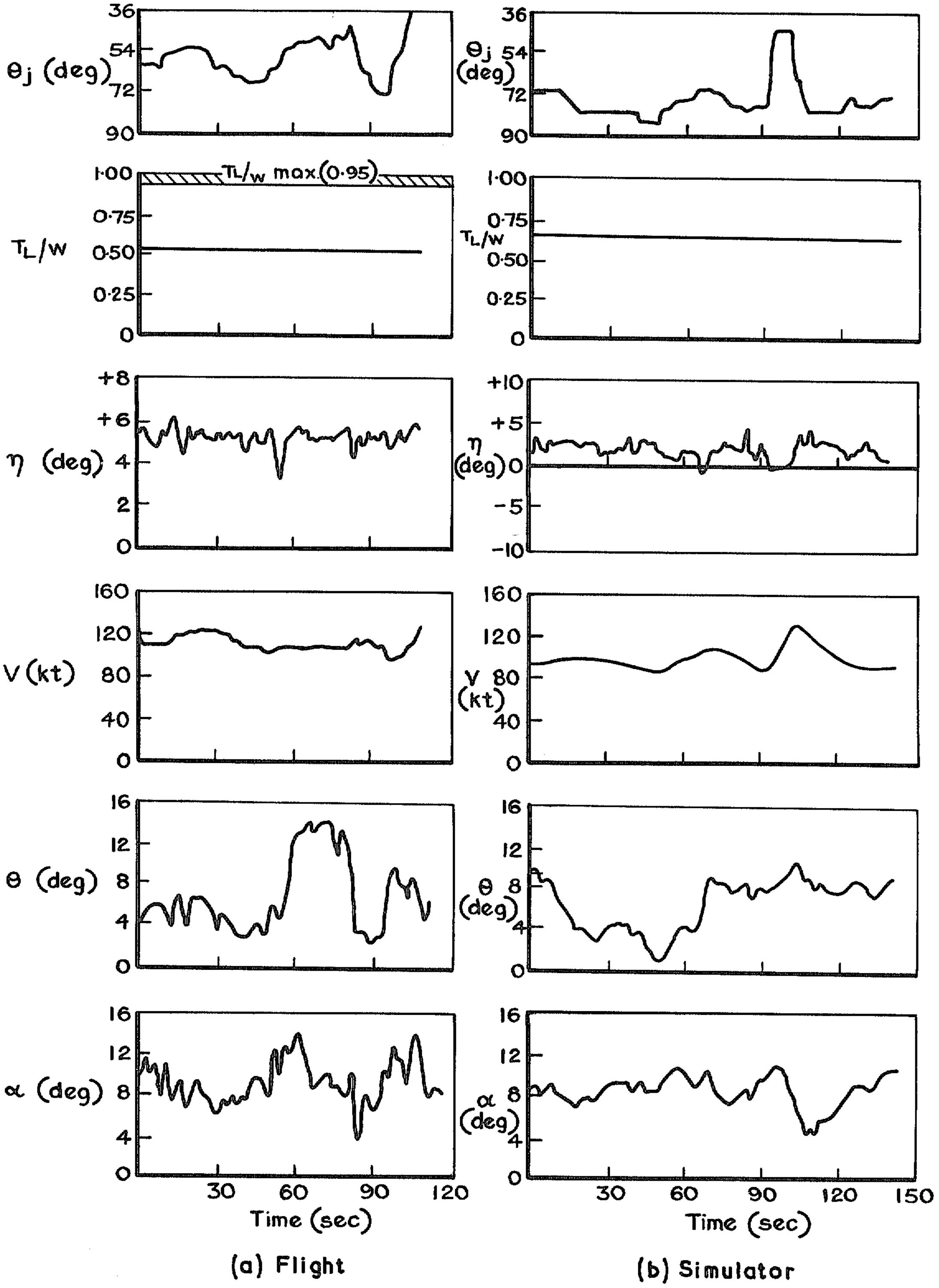

(a) Flight

(b) Simulator

FIG. 31. Comparison of flight and simulator time histories by Pilot E in level flight at 100 kt with throttle fixed.

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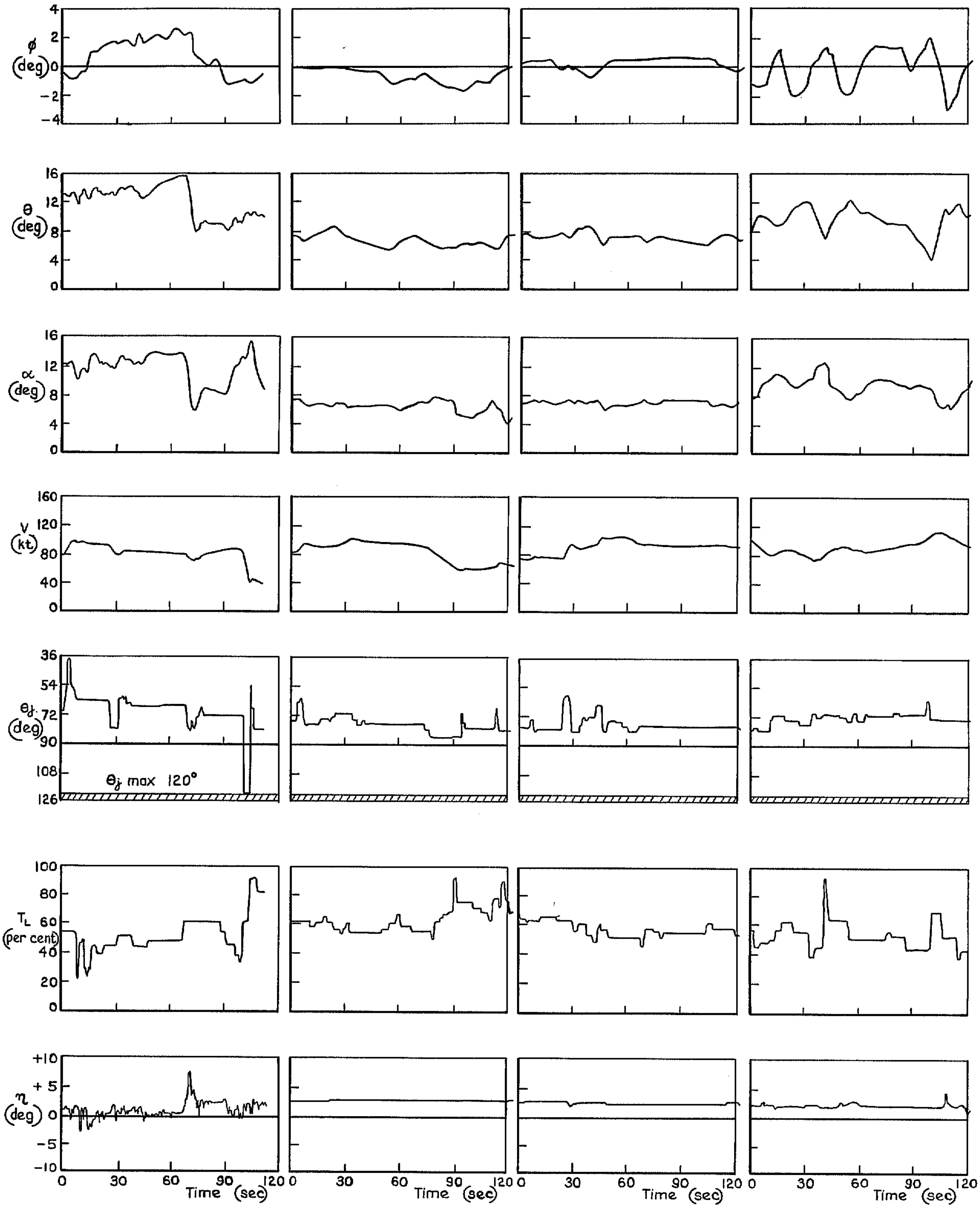

(a) With motion and visual display. Run 4

(b) With motion; no visual display. Run 3

(c) With visual display; no motion Run 1

(d) No motion nor visual display. Run 2

FIG. 32. Time histories of handling at constant speed by an experienced VTOL pilot (Pilot B) with four different motion and visual cues.

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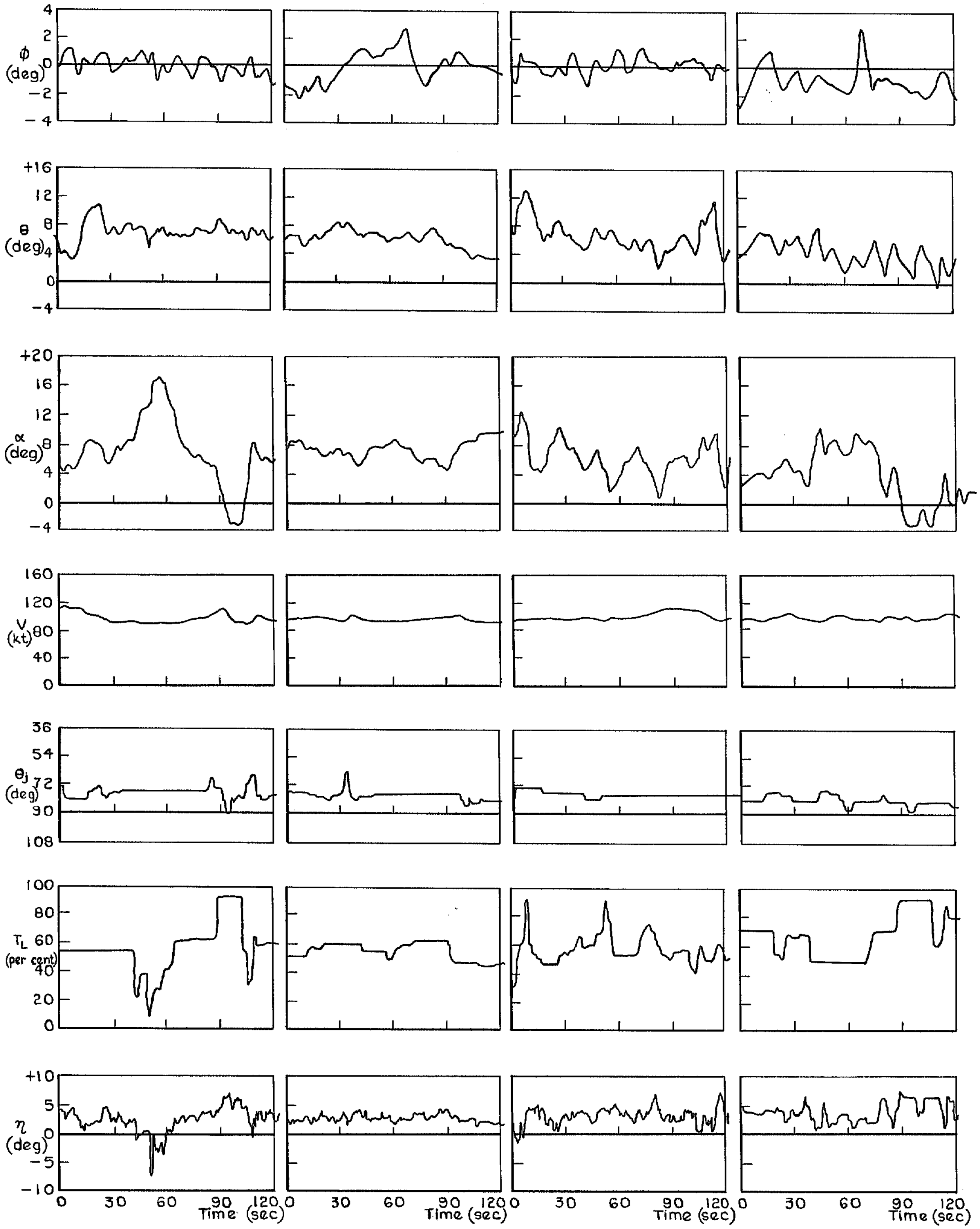

(a) With motion and visual display Run 4

(b) With motion; no visual display Run 2

(c) With visual display, no motion Run 3

(d) No motion nor visual display Run 1

FIG. 33. Time histories of handling at constant speed by an inexperienced VTOL pilot (Pilot F) with four different motion and visual cues.

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