Simulator Investigation of the VTOL Transport

D. K. MENDELA*
Hawker Siddeley Aviation, Hatfield, England

In order to explore the handling and performance qualities of a future civil VTOL aircraft some fairly extensive flight simulation trials have been carried out. The simulated aircraft was a slender delta fitted with four banks of lift engines representing sixteen lift fan engines located on both sides of the fuselage. Thrust vectoring and thrust modulation were assumed for aircraft control in VTOL phases of flight, and conventional aerodynamic surfaces in wing-borne flight. The simulator cockpit was equipped with the conventional dual flying controls and instrument panels typical of current jet airliners, but with some minor modifications to suit the VTOL role. Engine controls were modified as necessary, and a simple head-up display was incorporated. An analogue computer having some 400 amplifiers was used, for aircraft simulation in six degrees of freedom. Test pilots with current jet VTOL aircraft and helicopter flying experience participated in the piloted trials. The results of these trials indicated that the introduction of fail-safe autostabilization system into VTOL transport may be necessary in roll, pitch, yaw and in height. Very steep and vertical flight profiles, considered necessary to meet noise abatement rules during city center operations were studied and these proved to be feasible. Double lift fan engine failures could be controlled providing, at least, attitude demand autostabilization system in roll and in pitch was available. Particular attention was given to the cockpit controls layout, and to head up display. A gradual introduction of more advanced instruments and electronic visual displays into V/STOL aircraft may become necessary and the present Terminal Guidance and Air Traffic Control will need adaptation for VTOL operations.

Introduction

AN acute shortage of advanced research jet VTOL aircraft, the relatively high cost of operating the existing aircraft purely for research purposes, and considerably higher risks involved in flying them close to the limits imposed by control characteristics and limited engine life, dictate an almost constant demand to use flight simulators for research in the VTOL field. In order to ensure successful operation of a future VTOL airliner, special emphasis will have to be paid to its handling and performance characteristics. Present air traffic control systems, aircraft guidance systems and navigation methods, almost certainly will need examination and, where necessary, be either modified or adapted to the specific task of VTOL operations. New weather minima will have to be established and new safety rules will have to be put forward.

In all these areas the research flight simulator could become a very useful and a relatively inexpensive tool for preliminary studies prior to the commencement of actual flight investigations.

Research work by NASA Langley[1] concerning flight instruments presentation and displays paved the way for a decision on the layout of instruments for the simulator cockpit and in choosing the patterns for the head-up display. Earlier work by Northrop Norair Corporation into V/STOL simulation[2] brought to light a number of problem areas that must be faced in V/STOL aircraft operation and its simulation. Simulator and flight trials carried out by NASA Ames[3] to investigate problems encountered in using the engine thrust for control of VTOL aircraft threw more light on problems with VTOL aircraft reaction controls. Control power usage investigated for the VJ101 VTOL aircraft[6] may well serve for future comparisons of simulator work with flight test work. Valuable contributions in the area of handling criteria came from NASA Ames,[7] United Aircraft,[4] Boeing Aircraft Company[9] and many other organizations. An earlier test on the effect of exhaust gas recirculation[8] contributes further towards an understanding of the VTOL aircraft propulsion system, and a recent study on the use of VTOL aircraft for short-haul transportation[10] deserves particular attention.

Many other references are available, but those mentioned were found to be of immediate value for application in simulation study undertaken for particular VTOL transport.

Purpose of Investigations

The main purpose of the simulator investigations was to explore handling and performance qualities of a proposed fan jet VTOL transport aircraft using typical flight profiles for inter-city operation. The profiles chosen were governed by a noise abatement requirement that stipulates a noise level not to exceed 90 PNdb outside a circular area of 1500 ft radius from the center of the landing or take-off pad. The following areas of VTOL aircraft operation were thus examined: possible flight profiles, control systems, cockpit controls, and instrumentation including head-up and head-down presentations, guidance problems and pilot aids, autostabilization requirements, engine failures, autostabilization failures, pilot workload, controls usage, engine usage, and visual references needed and their limitations.

Description of the Flight Simulator

The simulator used was provided with dual-seat cockpit, representing in size the Hawker Siddeley Trident cockpit, but with controls and instruments adapted for the VTOL aircraft simulation role. The flight controls were provided with a variable electro-hydraulic feel unit allowing a wide range of stick and pedal forces to be realistically represented. The cockpit was coupled to a fairly large analogue computer using approximately 400 amplifiers for solving the equations of motion in six degrees of freedom, for generating visual display, and for controlling the electro-hydraulic feel unit. It

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* Head of Research Simulation Studies. Member AIAA.

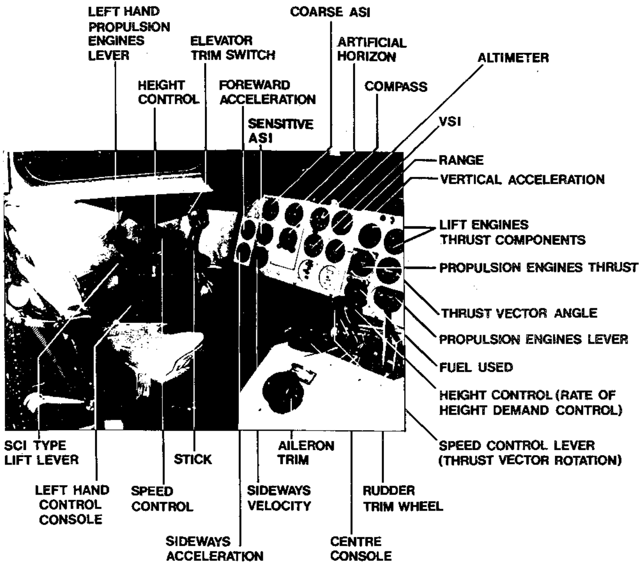


Fig. 1 Cockpit controls and instrument panel.

also included a special computer to simulate, realistically, four banks of lift fan engines, each bank representing four separate engines. A description of the simulator in more detail is given in the following seciions.

Instrument Panel

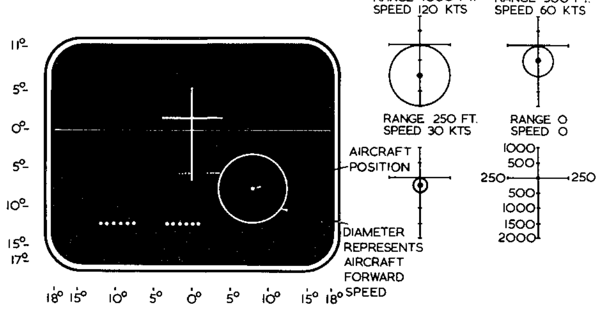
A conventional flight instrument panel, representative of the VTOL aircraft, was installed (Fig. 1).

Visual Display

A modified version of visual display was used and viewed by the pilot through a large collimating lens placed about 12 in. from his head (Fig. 2). The visual display pattern was typical of the Calvert type runway lighting system and provided a field of vision of +11° and −17.5° in elevation, and ±18° in azimuth. The runway display was free to move in all the six degrees of freedom, and was simulated to be 6000 ft long.

Head-up Display

Simple head-up display was provided by an oscilloscope. The images of a fixed cross and a moving circle of a pink color, generated by the oscilloscope, were visible to the pilot in addition to the existing visual display of the runway. The center of the moving circle represented the aircraft traveling relative to a fixed cross representing the center of the pad on the ground. The head-up display circle (indicating the aircraft position) was arranged in such a manner so that it progressively changed its diameter proportional to aircraft forward ground speed.



TYPICAL DECELERATION TRANSITION AS SHOWN ON HEAD UP DISPLAY.

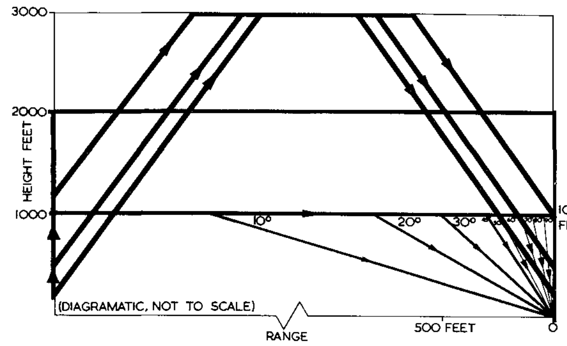


Fig. 3 Range of flight profiles studied.

Control Column

The control column was of a conventional fighter type with a handgrip modified by the incorporation of two separate switches. The left switch, thumb operated, was used for longitudinal trim. Operation of this switch resulted in corresponding fore and aft column movement. The right switch was used for the control of lift fan engine thrust vector in lateral direction within the range of ±10°. Stick forces were provided by the electro-hydraulic feel unit and were varied with speed squared.

Rudder Pedals

The rudder pedals were conventional, with a total travel of three in. Pedal forces were provided by the feel unit.

Center Control Console

The center control console included the following: lift engine lever set (consisting of a height control lever of the rate of height demand type, and a small lever for control of forward speed by rotating the lift fan engines thrust vector), propulsion engine thrust control lever, elevator, aileron and rudder trim wheels, and roll, pitch and yaw trim indicators.

Left-Hand Control Console

This console included a lift engine lever set, again consisting of the main height control lever with its attached smaller lever for control of thrust rotation, and a propulsion engine thrust control lever.

Helicopter-Type Lift Lever

This control lever was located for operation by the pilot's left hand, as in the Short SC-1 experimental VTOL aircraft. This lever was used only for demonstrations of helicopter type control in VTOL transport.

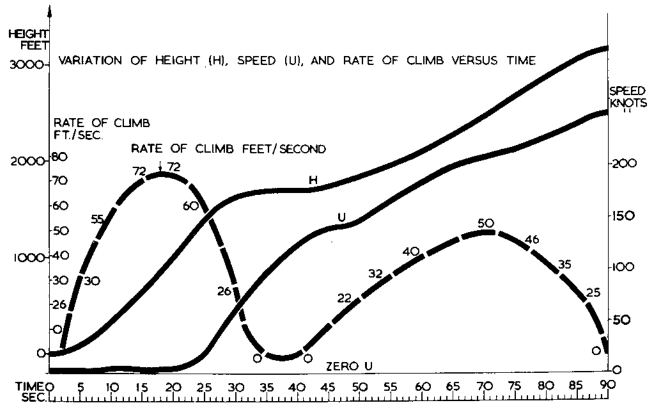


Fig. 4 Typical takeoff, pilot A.

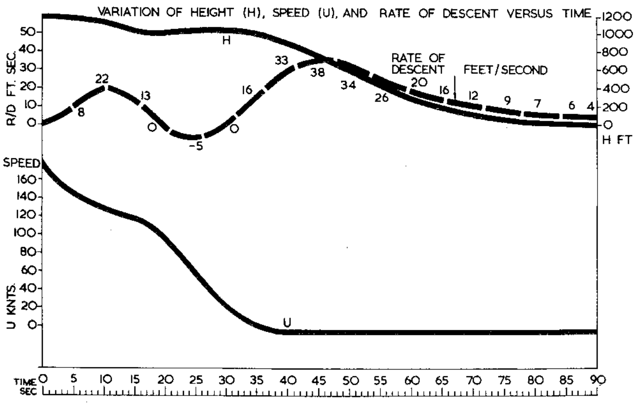


Fig. 5 Typical landing, pilot A.

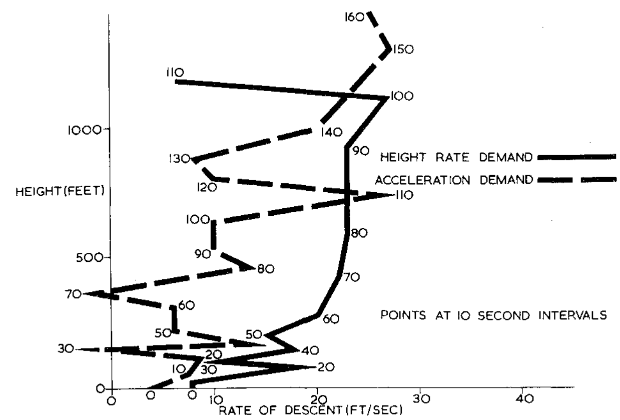


Fig. 7 Height vs rate of descent during landing; pilot A.

Analogue Computer

A combined analogue computer of a size equivalent to 400 operational amplifiers plus a set of nonlinear equipment was used for solving aircraft aerodynamic and control equations, for simulation for the four lift fan units, for visual display generation, for control of the variable-with-speed electro-hydraulic feel unit and for Euler angles and axes transformation.

Recorders

Recording was by two 24 channel ultra-violet recorders, two $X - Y$ plotters and one magnetic tape recorder.

Aircraft Configurations Studied, and Investigations Carried Out

The simulated aircraft was a proposed slender delta civil VTOL aircraft fitted with sixteen lift fan engines and two underwing propulsion engines and having an all-up weight in the order of 100,000 lbs. For pitch-and-roll control differential thrust modulation of lift fan engines was used, and for yaw control differential thrust vectoring was employed. Height control was achieved by direct changes in lift fan engine thrust. Aerodynamic data used was based on a series of wind-tunnel tests. Current data on the interference lift thrust losses and inlet momentum drag were also incorporated.

Simulated flights were carried out with and without attitude demand autostabilization system in roll and in pitch and with the rate demand system in yaw including the effect of phasing out these systems at different forward speeds during transition, assessment of the autostabilization system was made, considering engine limitations. Acceptable thrust-to-weight ratios involving trials of several different cases of interference lift thrust losses were investigated.

The pilot's ability to hover, ascend or descend vertically in calm air in cross-wind and in random turbulence of varying magnitude and direction was studied. Complete verti-circuits were flown in order to gain pilot experience in variable atmospheric conditions. Single and double lift fan engine failures were tested in all the critical stages of simulated flight in calm air, turbulence, and crosswind. Height controllability was examined. The effect of changes in control break-out forces, stiffness, damping, inertia and controls travel was studied. Assessment of sideslip suppressor in calm air, in cross-winds of differing magnitudes and directions, and in turbulence, was also made.

Typical Findings

In order to assess the proposed VTOL aircraft handling and performance characteristics under reasonably realistic conditions, various flight profiles were flown on the simulator, as shown in Fig. 3.

Special emphasis was, however, paid to the so-called high profiles considered necessary to meet noise abatement rules during city-center operations. This involved vertical ascent to a height of at least 1000 ft, accelerating transition into conventional high-speed cruise flight, cruise, decelerating transition to a high hover at a height of at least 1000 ft above the landing pad, followed by initially fast vertical descent of the order of 2000 ft/min which was gradually reduced to a low vertical velocity of approximately 100 ft/min at touchdown (see Figs. 4 and 5). In order to follow accurately vertical ascent and vertical descent the use of a head-up display was necessary. Typical variation of height and speed with time is given.

The value of the simulator during such trials would perhaps be best demonstrated by quoting several examples of the results obtained. In a particular example, landing accuracy that was achieved with the help of the head-up display can be seen in Fig. 6.

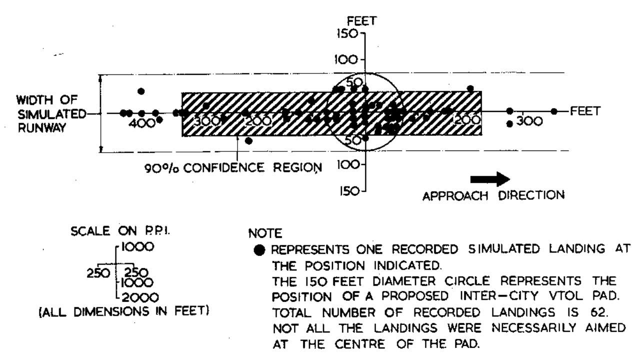


Fig. 6 Landing accuracy achieved.

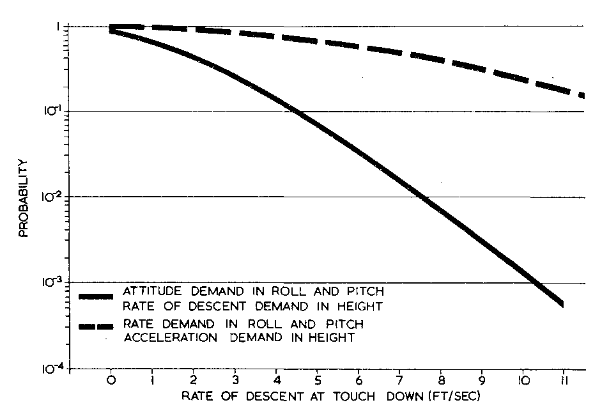


Fig. 8 Probability of exceeding a given rate of descent at touchdown.

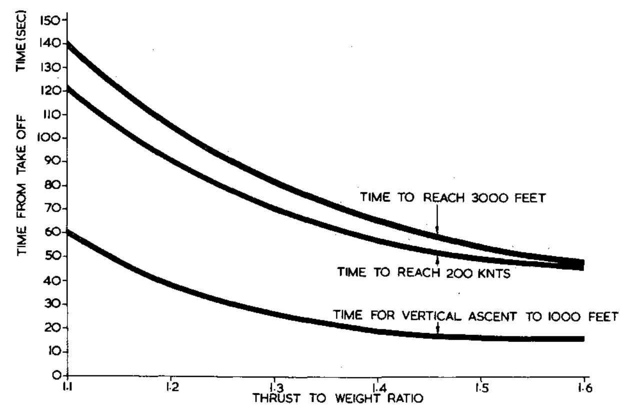


Fig. 9 Time to climb to a given altitude vs thrust-to-weight ratio; pilot A.

Although this figure shows considerable scatter of touchdown points, it should be clarified that not all the landings were aimed exactly at the center of the pad. The type and scale of the head-up display had strong influence on the amount of landing accuracy that could be achieved. However, recent tests carried out with the developed version of head-up display show that all the landings can be made within the 200-ft-diam pad.

The effect of providing more elaborate autostabilization systems in the VTOL transport, and in particular by replacing rate demand system by the attitude demand with height stabilization, was demonstrated by comparing vertical velocity achieved during vertical descent for the two cases (see Fig. 7). Much smoother variation of rate of descent was achieved when height rate demand control was used.

Improvements in control during vertical descent achieved by the introduction of autostabilization in height control were positively demonstrated. The amount of accuracy of stimulated landing executions is best shown by the probability of exceedance curve presented in Fig. 8. It can be seen that one in ten landings will be made at a touchdown velocity of 4.5 fps or more for an aircraft equipped with rate of descent demand in height control and with attitude demand in roll and in pitch. In contrast, one in ten landings will be made at rate of descent of 13 fps or more if only rate demand in roll and in pitch is provided and no height stabilization is used.

The effect of thrust-to-weight ratio on the time of climb to a given height as demonstrated on the simulator with the pilot in the control loop, is given in Fig. 9. It can be seen that with a thrust-to-weight ratio of 1.35, it will take 24 sec to climb vertically to a height of 1000 ft, a speed of 200 knots will be reached in 62 sec, and a climb-away height of 3000 ft will be reached in 74 sec from lift-off.

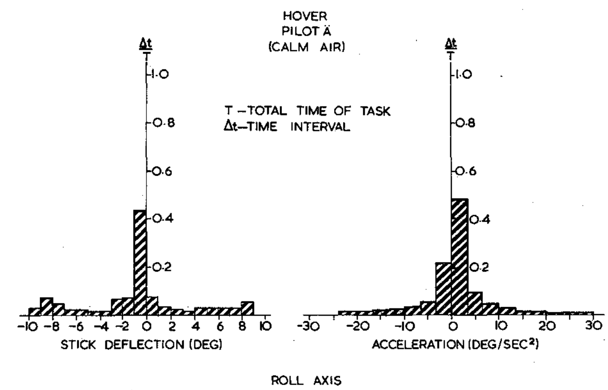


Fig. 11 Amplitude density; roll axis; hover.

Aircraft controls usage was best demonstrated by recording control movements on magnetic tape and then presenting the processed results as spectral densities against frequency (Fig. 10), and as amplitude densities against stick deflection and against aircraft, angular acceleration. (Figs. 11 and 12).

The spectral density distributions of stick deflection and angular acceleration show considerable differences in pilot performance during hover and vertical descent. The results reflect varying pilots' experience in simulator flying. It is emphasized that the results are given for the control system of the attitude demand type in roll and in pitch. For unstabilized control system a wider range of frequencies is expected.

Engine usage during typical VTOL flight was also recorded, and typical results can be seen in Fig. 13. A definite difference in engine usage between the four distinct banks of engines is shown.

The typical aircraft performance achieved in VTOL phases of flight is shown in Figs. 14 and 15. It can be seen that to reach 1200 ft from lift-off will take 65 sec or more during one ascent out of a hundred. The time of 165 sec will thus be exceeded in vertical descent from 1000 ft once in a hundred landings.

The aircraft control characteristics in relation to the current control criteria and recent results by NASA[7] and others are presented in Fig. 16 and 17. Fairly good agreement with NASA results was achieved for the attitude demand system (pilot rating 2). Wide differences were observed for the accelerating system (pilot rating between 7 and 10), thought to be due to the absence of motion on the simulator.[7] Hence, motion is essential in investigation of control systems where pilot workload is high and also in the investigation of marginally acceptable controls.

Rather excessive roll control power (1.8 deg/sec²) was used for the simulated aircraft. Such high roll control power, although available, was well in excess of the AGARD and the other control requirements.[7] Pilot rating given for the HSA

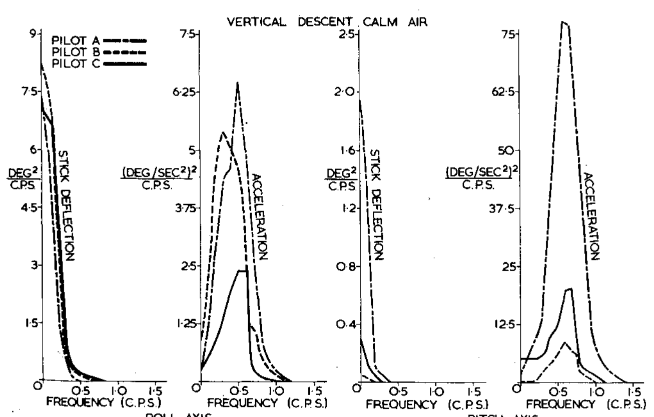


Fig. 10 Spectral densities; roll and pitch axis; vertical descent.

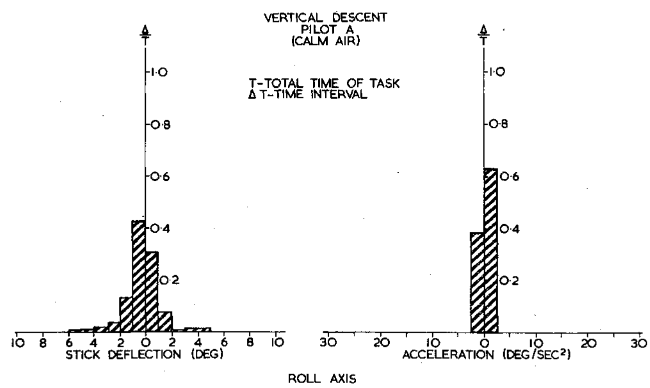


Fig. 12 Amplitude density; roll axis; vertical descent.

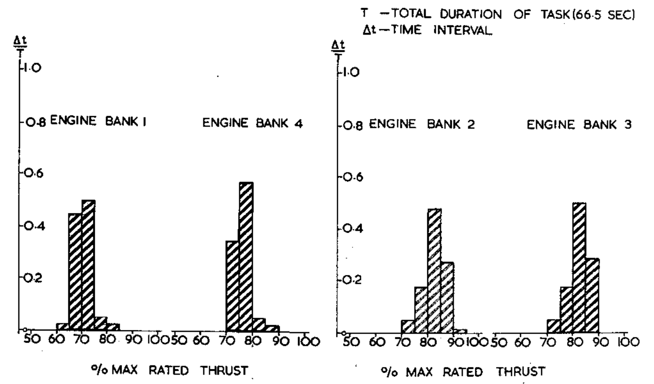


Fig. 13 Lift engine thrust usage; calm air; vertical descent.

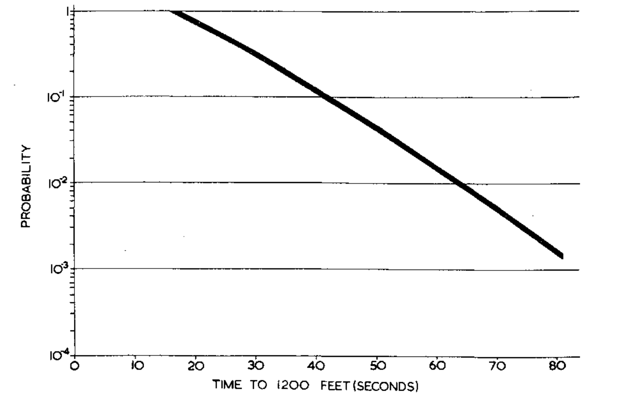


Fig. 14 Probability of exceeding a given time to reach 1200 ft from lift-off.

simulator is thus in agreement with the requirement, confirming validity of the simulator results.

It is emphasized that the results presented in this paper are offered primarily to illustrate the points raised. Warning is, however, given that although typical, these results may not necessarily represent the simulated or proposed VTOL aircraft.

Summary of Test Results

The autostabilizer required some optimization before acceptable characteristics were achieved. Initially the autostabilizer was gradually phased out at speeds between 80 knots and 120 knots. Above 120 knots the autostabilization of rate demand was brought in, in roll and in pitch, and this was then phased out when the lift engines were switched off—into conventional aircraft control system with pure rate damping.

Sudden switching off of the autostabilizer resulted in large disturbances. For this reason gradual phasing out of the autostabilizer was eventually adopted.

Sideways positioning maneuvers, by banking the aircraft, proved to be more difficult than by using side acceleration control,[3] especially close to the ground when more precise maneuvers were required. This was no problem at higher altitude when accuracy of the position was not so important. The benefits of such control at altitudes higher than 200 ft were not so obvious.

With the rate of descent/ascent demand of aircraft height control, vertical descents were simple, and low rate of descent at touchdown could be repeatedly achieved to as low a value as 50 ft/min.

Particular attention was given to the investigation of the cockpit controls layout. The main purpose of this was to arrive at the most acceptable set of controls for the pilot, within the limitations of the simulator. Hence, right-hand and left-hand operation of lift and propulsion engine controls were studied. The over-all preference was given for left-hand control of lift engines and propulsion engines while strong preference was given to holding the control column in the right hand. The helicopter type lever for lift engine control, although extensively tested, was not liked as much as the HS Harrier type height control lever, to which a smaller speed control lever was attached. The helicopter type control column was preferred by all the pilots participating except one who opted for the wheel.

A basically "T" type presentation of flight instruments was decided upon, in view of the pilots' past flying experience. The instruments provided on the simulator were thought to be sufficient for preliminary study. However, further rearrangement may be necessary and more advanced instruments and visual displays may have to be eventually incorporated. This applies equally to head-up and head-down displays.

To assess the thrust to weight ratio needed for inter-city operation, several different cases of interference thrust losses were extensively tested. The height or speed losses during transition as experienced in this study with inadequate thrust to weight ratio could be embarrassing in actual flight operations.

The lift fan engine failures were investigated in calm air, in cross-wind and in turbulence. Single lift fan engine failures could hardly be detected, and they presented no handling problems. The most adverse simultaneous double failure of the lift fan engines was usually detected by the pilot after about two sec. The pilot could, however, control this new situation although his workload was considerably increased.

A large number of flight profiles were carried out in cross-winds of varying intensity and direction. The maximum cross-wind simulated was 60 ft/sec. The effect of cross-wind on aircraft handling was found to be quite marked. The limitations of visual display and lack of versatility of the present head-up display prevented a more elaborate investigation of descent from high altitude by gradual rotation of the aircraft into the wind which was initially at 90° to the approach path. The wind direction was thus limited during such tests to 45° only.

The limitations of visual display in large yawing maneuvers were quite serious. It was thought that such maneuvers, possible in cross-wind, with sideslip suppression, will need further investigation with a more realistic visual display of a much wider field of view, than the display used.

The effect of random turbulence on aircraft handling has not yet been resolved accurately enough. Absence of cockpit motion made such tests totally unrealistic and unrepresentative of normal flight conditions. Further simulator investigations with a moving base are therefore required, and more

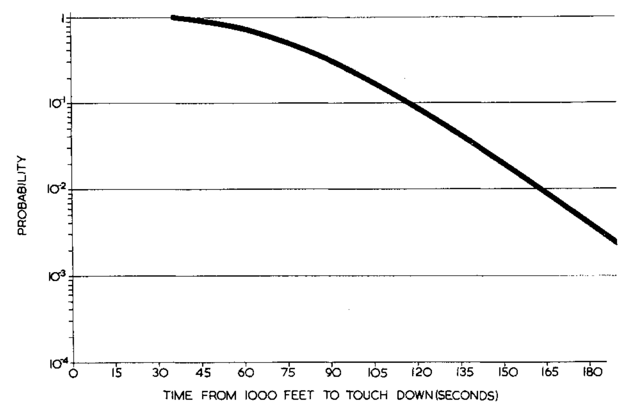


Fig. 15 Probability of exceeding a given time to touchdown from 1000 ft.

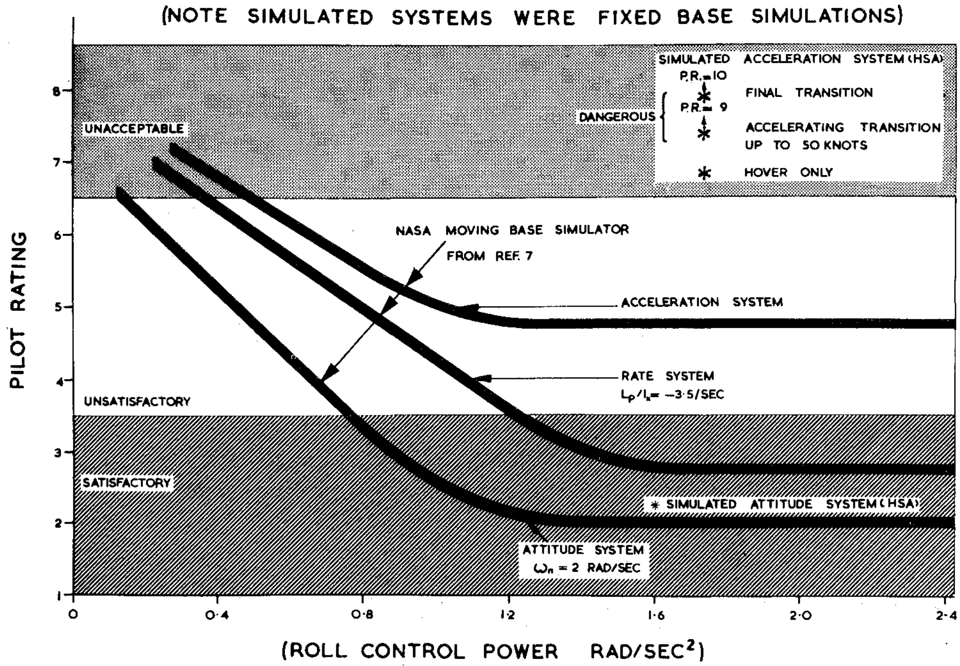


Fig. 16 Comparison of acceleration, rate and attitude systems; pilot rating vs control power.

realistic inter-city turbulence data should be provided for the simulation in the future.

The hover and positioning maneuvers prior to touchdown presented no problems with the autostabilization system as simulated (i.e. with attitude demand systems in roll and in pitch, rate demand system in yaw, and rate of height demand system in height control). This system contributed substantially to marked improvement in aircraft handling.

The problem of phasing out (and in) of the autostabilizer during the transition was also investigated. Although phase-out speeds of between 80 and 120 knots were used initially, the advantages of keeping the autostabilization in as long as is possible during accelerating or decelerating transitions were soon realized. The best type of control was achieved by retaining the autostabilization in roll and in yaw until the lift fan engines switch-off sequence, and then reverting gradually to conventional flight autostabilization, and in pitch by retaining attitude demand system right throughout the whole speed range, while ensuring adequate authority in pitch attitude.

Lift engines shutting down and lighting procedures were originally accompanied by large trim changes in pitch. These were eventually reduced to an acceptable level by the proposed autostabilizer. Twenty-thousand feet was chosen as the minimum distance from the landing pad at which the lift fan engines should be started. This distance was necessary in order to allow the pilot sufficient time to carry out all

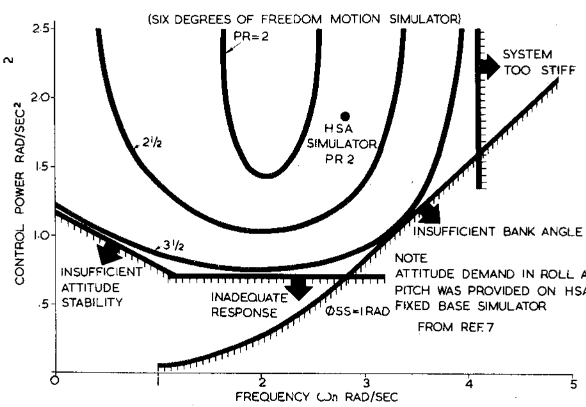


Fig. 17 Roll control boundaries; control power required vs frequency (ωn).

necessary drills before beginning the final decelerating transition, which was usually 6000 ft from the landing pad.

Conventional cruise flight at speeds below minimum drag speed and without autothrottle, was speed-unstable, demanding a different technique in order to fly the aircraft accurately. The introduction of autothrottle brought vast improvements in speed stability.

The possibility of sharing the tasks between the first and second pilot was also investigated. The major task of flying the aircraft rested with the captain (left-hand pilot), the second pilot assisted the captain with the secondary tasks only, and acted only on instructions from him. The sharing of the actual flying task between the two pilots was unsuccessful and was thus abandoned.

Conclusions

The simulator test results confirmed that there is a need to introduce head-up and head-down displays on the proposed VTOL transport aircraft to assist the pilot in the more demanding tasks and in particular to improve landing accuracy. The importance of simplicity in the presentation of head-up and head-down displays was stressed. The visual cues of only limited angle of view, which were available on this simulator, were found to be inadequate for accurate and safe visual landings. A preference for a wide angle visual display was expressed by the pilots. However, regardless of the limited field of view available to the pilot, it was concluded that the head-up and head-down instrument displays should become of primary importance in future VTOL aircraft.

Lack of motion in the simulator used was thought to be responsible for severe degrading of some of the marginally acceptable aircraft control characteristics. However, fixed base simulator results are considered as valid for an aircraft with good handling characteristics without too much demand on the pilot. Provision of engine noise and aerodynamic noise, was of considerable advantage in adding to the realism of VTOL aircraft simulation.

The importance of providing realistic "feel" in the control system was also established. Introduction of a reliable, power operated control system feel unit in the simulator was found to be essential. Proper representation of friction, break out forces, control system damping, and stiffness was found to be far more important than was originally realized. Deficiencies in these areas could seriously affect simulation validation and simulator findings, especially in VTOL phases of flight.

Investigations of acceptable cockpit controls have proved the value of the research simulator for such purposes. The simulator provided a reasonably quick and efficient tool in the investigations of a number of promising schemes by several experienced test pilots. The problem of demonstrating the advantages or deficiencies of various schemes was equally simplified.

The simulator of this type also proved to be an excellent tool in demonstrating the VTOL transport concept to a large number of people of varying interests and experience. It proved to be a useful device in promoting the VTOL concept to both the technical and civil authorities, when a particular aspect of civil VTOL transport operation could be quickly and often, convincingly, demonstrated. In addition, this could be achieved economically and in complete safety.

The pilots who participated in these investigations were chosen with particular care and all had sufficient simulator flying experience to give a balanced assessment. It is suggested that airline pilots should be invited to participate in future VTOL transport research simulator trials.

However, where the simulation validation is concerned, more general experimental work is still needed, and more efficient interchange of information is required between research and flight centers.

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A Fluidic Low-Speed Air-Speed Indicator

Richard J. Miner*
NASA, Washington, D. C.

Crossflow and parallel flow techniques were investigated. The parallel flow technique was chosen. A prototype has been wind-tunnel tested. It has a near linear response from 0.3 to 90 fps. This sensor is light in weight, simple in operation and has no moving parts. Efforts are underway to optimize the sensor performance and develop a flightworthy unit. Reynolds number scaling was used to relate the sensors behavior in water with colored dye as a tracer.

Introduction

THE advent of the V/STOL aircraft has generated the need for instrumentation unique to the operation of these aircraft. One of the parameters which would be particularly useful during takeoff and landing is relative wind speed. Because of the nature of these aircraft, very low air speeds in all three orthogonal directions occur during their operation near the ground. At present, no practical wind sensing instruments are available for this purpose. The conventional pitot tube air-speed sensor is simple and reliable and performs very well down to the takeoff and landing speeds of conventional aircraft. However it is generally unsuited for measuring air speeds below about 20 or 30 mph.

Several other concepts have been developed for sensing low air speeds. The concepts involve hot wire or film instruments, ultrasonic pulse, ion tracers, cup anemometers and two pitot tubes mounted on the ends of a spinning boom. These concepts are either cumbersome, unreliable or have a high threshold of sensitivity. What is needed is a technique for measuring very low wind velocities which is sufficiently rugged, yet markedly lower in cost and complexity than an equivalent electronic or electro-mechanical technique.

Two concepts using fluidic techniques were formulated for measuring very low wind speeds. In these concepts, the wind is impressed on an air jet which produces an amplified pressure signal directly related to wind speed. The two concepts are categorized as: 1) parallel-flow sensors in which an air power stream is directed parallel to the wind component being measured. 2) cross-flow sensors in which an air power stream is directed perpendicular to the wind component being measured.

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