RESUME OF STEEP GRADIENT RESEARCH AT RAE BEDFORD

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SUMMARY

R/STOL research at RAE Bedford is described, including the airfield facilities and aircraft used. A range of performance aspects are presented covering manual and automatic control in both azimuth and elevation. It is considered that the implementation of MLS is necessary before successful R/STOL operations can really be achieved. Thereafter, either improvements in engine and airframe design or else the use of a 'two-stage' flare might make the whole concept acceptable in all-weathers using realistic decision heights. Long term research will continue at RAE in an endeavour to establish the correctness of these assumptions.

I. INTRODUCTION

The Royal Aircraft Establishment at Bedford, England, first began looking at the problems of steep approaches in 1972 when there was still general enthusiasm internationally for STOL aircraft operations from runway lengths of 600 metres. RAE's interest ranged from basic aircraft handling to the problems of all-weather operations and experiments were carried out using both piloted simulation and flight trials. This work was supported by complementary studies carried out by the British aircraft industry on behalf of the UK government.

Gradually the emphasis world wide began to shift towards R/STOL (operation from 1500 metre runways) and then CR/TOL (capitalising on the existing performance of civil airliners). At the same time the prime aim of the UK research became noise orientated. This interest in noise abatement techniques of which steep approaches forms an important part, has been maintained ever since.

Although the RAE has no purpose built R/STOL aircraft, the aim of the flight trials (supported where appropriate by simulation) was to establish the advantages and/or limitations of current airframes and avionics so that design principles could be established to ensure the success of any future R/STOL aircraft and its operation. This paper describes some of the research carried out including the facilities used and the various steep approach techniques that were evaluated.

II. FACILITIES

The RAE has a large flat airfield with one large runway (27) 90 metres wide and over 3000 metres long and a crossing shorter runway (24) only 60 metres wide which was designated as the R/STOL landing strip. Both are ILS equipped, the former being to Category 3 standard. Runway 27 is also equipped with a complete Category 2/3 Approach and Runway lighting pattern appropriate for low visibility operations. A kinetheodolite optical tracking system is available to record flightpath performance in good visual conditions and a Bell SPN10 lock-follow radar is employed both to record flightpaths in poor visibility unsuited to kine operation and to provide experimental radio guidance signals via a data link. This allows investigations to be made into the effects of non-standard guidance beams on aircraft performance.

Finally two other approach aids used are a prototype doppler MLS elevation unit and a novel visual glidepath indicator known as the PAPI - Precision Approach Path Indicator (1).

The above, in combination with an equally wide range of airborne data recording facilities, analogue and digital, are used to carry out experimental flight trials.

Essentially six aircraft were used for the R/STOL flying programme and their prime characteristics are listed at the foot of the next page.

Photographs of the BAC 1-11, HS 125 and HS 748 which are still the prime research aircraft being used at the RAE are shown in Figures 1-3.

Figure 1 - BAC 1-11

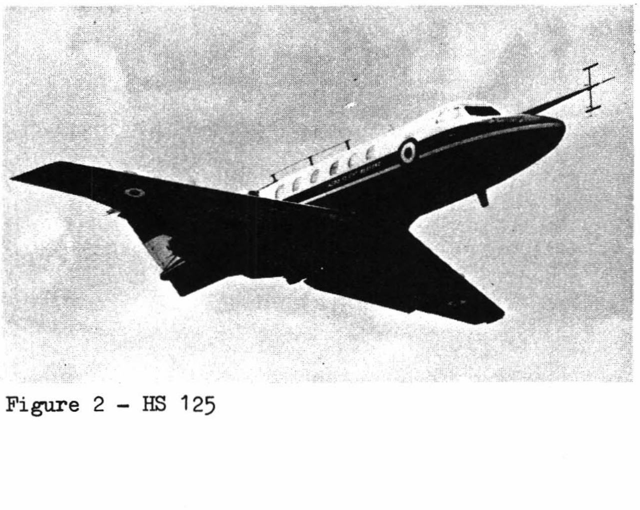

Figure 2 - HS 125

Figure 3 - HS 748

To investigate some of the all-weather aspects, use was made of a fixed base piloted simulator (2). Its prime feature is the visual display which presents to the pilot a night view of the approach and runway lighting as seen in poor visibility. This is generated digitally and contains colour information.

III. NOISE BENEFITS

The original aim of exploiting aircrafts' steep approach capability in the UK was to allow additional aircraft movements between small airfields close to city centres and major airports like London (Heathrow) without affecting the main traffic flow. This was to be achieved by using the volume of airspace currently unused. Studies (3) have since indicated that this is not as attractive as it at first seemed. However, with the importance attached to reducing noise levels around our airports, it is relevant to look briefly at the potential benefits that can be achieved using steep approach gradients, ie glidepath angles greater than the conventional 3 degree glideslope.

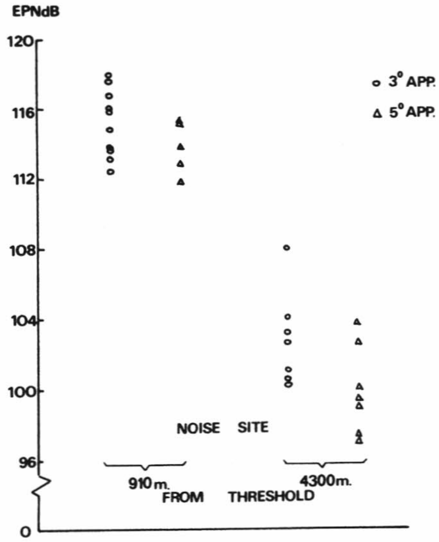

Figure 4 - VC10 Measured Noise Data

Figure 4 shows some noise data measured at Bedford for the VC10 aircraft (4). The weather conditions ranged from virtually calm to very windy (~ 22 kn) and hence there is quite a scatter in the results. The noise monitoring points were on the extended runway centreline at distances of 910m and 4300m from threshold respectively. EPNL measurements are shown for conventional 3 degree approaches and 5 degree steep approaches and the reduction in noise due to the latter technique is apparent even close to the runway. The same reference indicates that both the 80 and 90 EPNdB contour areas for a 5 degree approach would be less than half that for a 3 degree glidepath.

A theoretical study by British Airways (5) similarly shows that for our BAC 1-11 aircraft the area within the 90 EPNL contour is reduced from 7.2 sq km (3 degrees) to 0.3 sq km for a 6 degree approach and from 37.6 sq km (3 degrees) to 13.6 sq km (6 degrees) for the 80 EPNL case (Figure 5).

CLASS	JET TRANSPORT		EXECUTIVE JET	NAVAL FIGHTER	TURBOPROP TRANSPORT	
AIRCRAFT	VC10	BAC 1-11	HS 125	SEA VIXEN	ANDOVER	HS 748
NO OF ENGINES & TYPE	4 RR CONWAY	2 RR SPEY	2 RR VIPER	2 RR AVON	2 RR DARTS	2 RR DARTS
MAX LANDING WEIGHT	98,000 kgs	32,200 kgs	6850 kgs	15900 kgs	21600 kgs	16330 kgs
THRESHOLD SPEED	130 kn	119 kn	120 kn	133 kn	98 kn	85 kn
WING SPAN	44.5 m	27.0 m	14.3 m	15.2 m	29.9 m	30.0 m
WING AREA	261.2 sq m	91.2 sq m	32.8 sq m	60.3 sq m	77.3 sq m	75.4 sq m

TABLE 1 AIRCRAFT CHARACTERISTICS

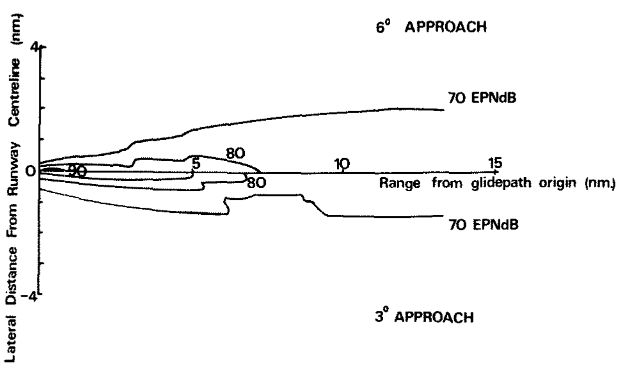

Figure 5 - BAC 1-11 (201 Series) Noise Contours for 3 Degree and 6 Degree Approaches.

It must be remembered that the optimum noise reduction is very much a function of the individual aircraft and its flap arrangement. For a given flap setting, the steeper the glidepath and hence the greater the power reduction, the larger the noise benefit. However, at the stage where additional flap is necessary to achieve greater approach angles, the increase in thrust to overcome the drag penalty can offset any expected noise gain.

The many pitfalls associated with naive interpretation of noise benefits however, are also illustrated in Figure 5 where it can be seen that the 70 EPNL contour area is larger for the 6 degree case than the 3 degree case. Thus, whilst the maximum noise levels have been attenuated, the sound has radiated over a larger area simply because of the extra aircraft height involved.

IV. APPROACH PERFORMANCE - PITCH

4.1 Maximum Steep Gradient Capability

(a) BAC 1-11 (201 Series)

The maximum gradient in free air is obviously a function of the aircraft's drag and the residual thrust from the engines when throttled back. Figure 6 shows a typical performance carpet for our BAC 1-11 201 series aircraft obtained by putting the relevant aerodynamic and engine data into the standard steady state equation:

$$T = (\gamma + C_D/C_L)\,W$$

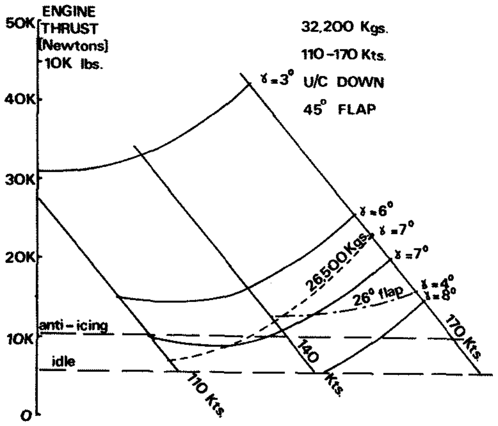

Figure 6 - Approach Gradient Capability of BAC 1-11

In addition to the maximum landing weight case, additional information is shown for 26,500 kgs, the minimum landing weight and hence the worst from the gradient aspect. Engine limits for anti-icing and idle power are also shown from which can be deduced the maximum practical values of approach gradient. At constant thrust, increasing the approach speed by 30 knots improves the gradient capability by approximately 2 degrees. The sensitivity of gradient to weight and flap setting is also indicated.

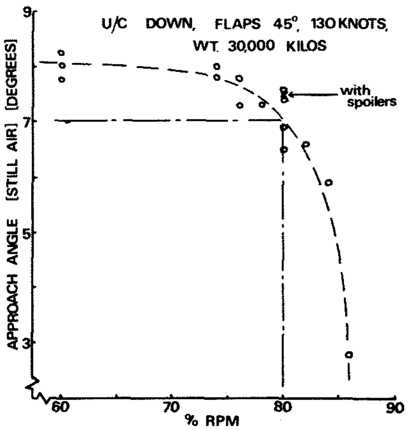

Figure 7 - Measured Steep Gradient Capability for BAC 1-11 (201 series).

Figure 7 shows some measured data for the BAC 1-11 where engine RPM was the independent variable and speed was held constant at 130 knots. It can be seen how sensitive the gradient is to the initial change in RPM from the nominal 3 degree approach value of 86%. Thereafter, the engine characteristics influence the shape and the performance levels off for RPMs less than 75%. The maximum gradient appears to be 8 degrees unless airspeed is increased or the spoilers are deployed. This appears to be in reasonable agreement with the previous carpet plot (Figure 6).

(b) HS 748 (Series 1)

Unlike the BAC 1-11 which normally operates even on a 3 degree approach with maximum (45 degree) flap, the twin turboprop HS 748 has an approach flap setting of 22½ degrees and an additional land flap setting of 27½ degrees. In order to achieve any reasonable level of steep gradient capability, the full land flap configuration had to be used with the associated speed restriction of 120 knots, as opposed to the normal 140 knots. The resulting speed gradient performance is shown in Figure 8 where the difference in the shape of the curve compared to the turbojet is immediately obvious.

Because RPM is governed, the independent variable in this case is final drive shaft torque which is available to the pilot in the cockpit. Making allowances for the scatter in the data, an essentially linear relationship exists between torque and gradient over the normal working range. Because of the propeller's ability to generate drag as well as thrust however, the slope of the curve increases rapidly below 20 psi, the final gradient being just greater than 8 degrees. Sensitivity to speed changes is also apparent, an increase from the usual approach speed of 95 knots to 115 knots increasing the potential gradient by 1½ degrees.

It was subsequently found that the flap mechanism could be relatively easily modified to yield an extra 2 degrees of flap angle and that because of the mechanical gearing involved, this produced an extra 20 degrees of tab. The resulting aerodynamic change was primarily an increase of drag and hence the steep approach capability improved considerably by some 1½ degrees (see Figure 8). However, the approach speed had to be restricted to 100 knots because of the non-standard application and this did present an operational problem.

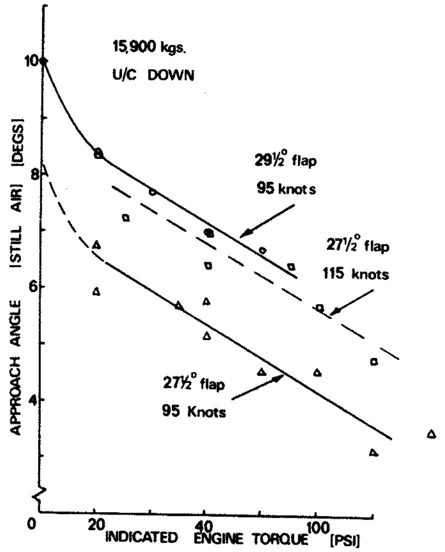

Figure 8 - Relationship between Still Air Approach Angle and Engine Torque for HS 748.

4.2 Realistic Approach Gradients

Establishing the maximum gradient capability of an aircraft does not of itself define the glideslope angle that is operationally acceptable. Many factors influence the choice, for example:

(a) Aircraft controllability, eg glideslope following, speed control;

(b) manoeuvre margin, eg glideslope capture, deceleration;

(c) automatic control response;

(d) wind limits, eg tailwinds, windshear;

(e) aircraft system limitations, eg de-icing;

(f) engine response at low RPMs, eg manual and autothrottle;

(g) missed approach performance;

(h) lateral handling aspects, eg side-steps;

(j) flare and landing, eg undercarriage stress limits, consistency, safety;

(k) equipment/system failures, eg engine failure,

and of course (l) pilot acceptability!

Some of these aspects will be discussed in more detail later (g,h,j) but several are worthy of comment now.

4.2.1 Wind Limits

Beginning with wind effects, for an aircraft attempting to fly a 6 degree approach at 120 knots, a mere 10 knot tailwind component requires an extra flightpath angle margin of ½ degree. With rates of descent of 20 ft/sec (1220 ft/min), ie double the rate for an ILS approach, the presence of a large windshear, say 10 knots/100 feet as existed in the DC10 accident due to a change in the windspeed component from 25 knot tailwind at 500 feet to a 4 knot headwind at 200 feet, (18) would produce an equivalent change of airspeed in only 5 seconds. Thus, either a fast reaction is required from the pilot or else a fast response from the autothrottle if fitted. (Very often the autothrottle limit is set forward of the flight idle limit purely to improve engine response.) For an aircraft like the BAC 1-11 201 series, the engine RPM is typically 86% for a 3 degree approach and 84% for a 6 degree approach (see Figure 7). A modest 20 knot tailwind would therefore reduce this further to approximately 80% RPM. The resulting time to accelerate the Spey turbojet engine from 80% RPM to maximum thrust would be 2-3 seconds and even longer would be required to significantly increase the aircraft's airspeed.

The minimum RPM to cope with engine off-takes obviously varies from aircraft to aircraft. For an aircraft like a Lockheed Tristar there is no such restriction (20) but for our BAC 1-11, 72% RPM has to be maintained in icing conditions. From Figure 8 this means a maximum gradient of 8 degrees.

4.2.2 Manoeuvre Margin

For conventional operations, the question of deceleration during an approach is becoming increasingly more important especially at major airports where, in an effort to reduce noise, aircraft are being flown in cleaner configurations and higher speeds closer to the runway. Although this need not carry over into steep approaches, there will always be occasions where a reduction in speed is called for and hence some margin must be allowed. It can be shown that a modest deceleration of 0.5 knots/sec is achieved only if the aircraft in question has a steep gradient capability 1.5 degrees in excess of the glideslope being flown. Thus, with a descent rate of 1200 feet/min, some 400 feet of height would be required for every 10 knots of speed reduction required. It follows that if the aircraft only has half the margin necessary, ie 0.75 degrees, then the deceleration becomes only 0.25 knot/sec and 800 feet is required to lose 10 knots - a severe limitation.

4.2.3 Aircraft Controllability

As far as speed control is concerned, a peculiarity of both the twin turboprop aircraft flown was the response to throttle (6,8). The engine control system is such that a change of throttle setting will result in a rapid change of propeller blade pitch. However, the corresponding increase in engine torque takes a lot longer to develop. The result is that the increased propeller drag slows down the aircraft initially before any acceleration takes place. The reverse effect takes place when the throttle is closed. Such a characteristic must be allowed for by careful use of the throttles during steep approaches. Figure 9 shows a typical speed trace from Reference 8.

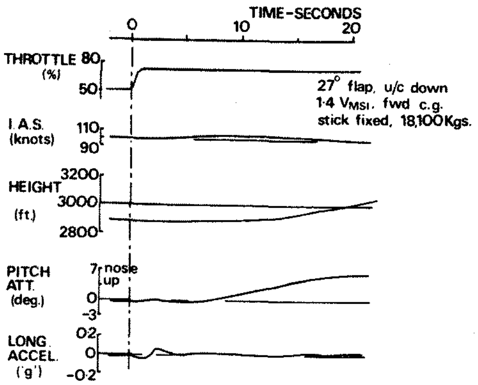

Figure 9 - Aircraft Response to Throttle Input for HS Andover

A typical turbojet aircraft does not possess the DLC generated by the propellers but at least its airspeed response to throttle change is conventional.

4.3 Automatic Control

Manoeuvring onto a steeper glideslope from level flight is far more difficult than for a conventional ILS approach because in addition to the required configuration changes (which may or may not be the same), larger power reductions and attitude changes are required especially in tailwind conditions. If the aircraft overshoots the glideslope then a higher descent rate must be achieved in order to recapture the centreline. Whereas for 3 degree approaches there is generally a large margin in hand for this situation, as steeper glideslopes are used so this margin reduces and the necessity for more exacting capture manoeuvres increases.

4.3.1 Conventional Autopilot - Glideslope Capture

The Smiths SEP6 autopilot as installed in the HS 748 is a rate-rate system, ie the rate of control surface movement is essentially a function of demanded attitude rate. The glidepath control law consists of glidepath error and error rate plus pitch attitude (6). Capture is initiated when the glidepath error becomes less than 30μA which for the current ILS beam sensitivity (225 μA/deg) at RAE is 0.13 degrees. A typical ILS capture manoeuvre is shown in Figure 10 where the overshoot, although slight, is obvious.

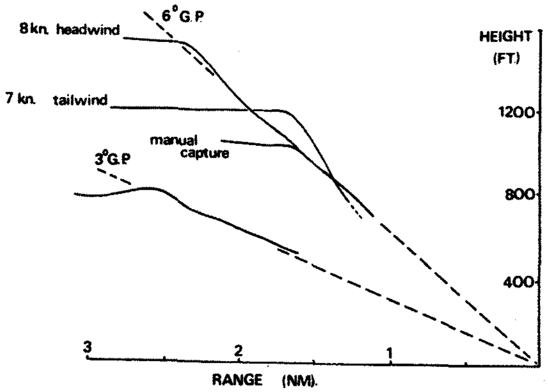

Figure 10 - Glideslope Capture Performance - HS 748

By using the tracking radar it was possible to simulate an ILS type glideslope of different beamwidths for an approach angle of 6 degrees. Typical captures are shown for an 8 knot headwind and a 7 knot tailwind. In all cases an overshoot is obvious and in the tailwind case the aircraft deviates well below the centreline and fails to recover the glideslope due primarily to the slow response of the pitch autotrim system.

4.3.2 Optimised Glideslope Capture Law

As part of a research programme to look at the technical aspects of two-segment approaches (7), an automatic glideslope capture law was required for use with the BAC 1-11 that would allow operation in all weathers with a 6 degree upper segment defined using DME range and baro height. For convenience the guidance was made linear rather than angular which made the capture performance independent of height and the capture initiation point was made a function of error rate. The height error signal was switched into the normal 'glide' input to the autopilot which meant that the basic system control law could be left unmodified and the inherent integrity of the autopilot retained.

Typical flightpaths are shown in Figure 11 for a tailwind and a headwind condition, the difference between the two being 24 knots of wind. By comparison with the approaches shown previously for the HS 748 and conventional autopilot for less severe wind conditions, it can be seen that a significant improvement in performance has been achieved.

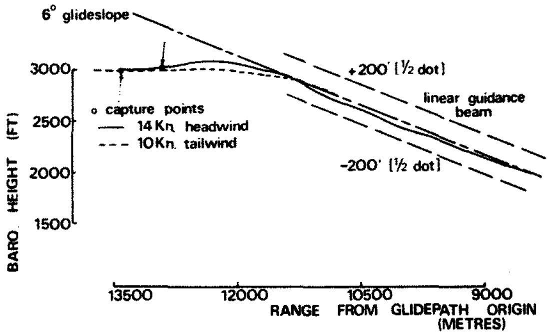

Figure 11 - Optimised Glideslope Capture law - BAC 1-11.

4.3.3 Automatic Approach Performance

Because the autopilot of the HS 748 had very little performance margin using a 6 degree glideslope, it was decided that for the all-weather investigations the approach angle should be restricted to 5 degrees. Glideslope performance was measured at a number of points during the approach including one at a range of 600 metres before glidepath origin, corresponding to a height of 174 feet and where the pilot would need to be assessing the visual cues if in fog conditions (see Section 7).

A sample of 24 approaches made in a range of weather conditions produced a mean height of 169 feet (ie 5 feet low) and the standard deviation was 8 feet.

For a 3 degree approach, the performance measured at the same distance from the runway for a sample size of 19 produced a mean height 5 feet above the ideal value of 103 feet and a standard deviation of 5 feet.

4.4 Manual Control

It is interesting to see that a manual capture of a steep glideslope for example using a flight director has to be much faster than an autocapture where the pilot is purely monitoring. Pilots generally like to stabilize on the glideslope as rapidly as possible and in the correct configuration. Figure 10 shows such a capture where the different time response is clearly evident. This does of course, mean that if the director control law is matched to the pilot, it will not be satisfied when an auto-capture is being used and this may annoy or worry the pilot. The solution is either to leave the director switched off or else to compromise and make the auto response slightly faster and equivalent to that of the director.

4.4.1 Approach Performance

It was obvious from the outset of the R/STOL research that an improved form of visual approach slope indicator (VASI) would be necessary in order to deliver the pilot down to the flare initiation height with great consistency. It was considered that the flare manoeuvre from a steep approach was more demanding than from a 3 degree approach and hence the pilot needed as much help as possible. From what has been said earlier (Section 4.1) it is also obvious that the pilot has less manoeuvre margin than for a 3 degree approach and hence deviations from the glideslope must be contained well within limits. From this requirement a Precision Approach Path Indicator (PAPI) (1) was developed in which, unlike the internationally known VASI, the transition between the red and white zone was made extremely sharp using a relatively simple optical arrangement. By arranging four units as shown in Figure 12, the angle between each being set to typically ½ degree, it is possible to define an angular 6 degree glideslope that can be flown accurately. 'On course' is defined by two red and two white lights. Deviations below the ideal glidepath are indicated progressively by three red and then four red lights showing. Conversely flying above the glideslope is indicated progressively by three or four white lights showing.

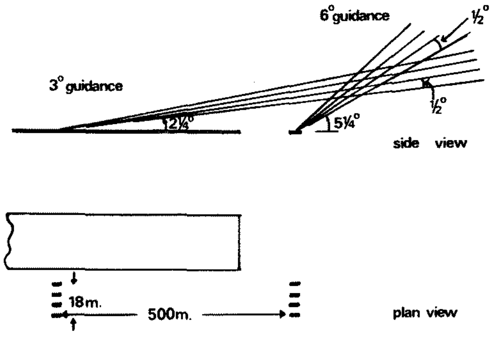

Figure 12 - Experimental Glideslope Indicator - PAPI (two-segment approaches).

Using this visual system, the HS 748 was flown by three pilots to produce a sample of 50 approaches. The standard deviation was essentially constant down to a wheel height of 20 feet and equal to 7 feet, ie equivalent to autos performance.

A sample of 32 approaches at an angle of 3 degrees by the same three pilots produced an SD of 6 feet over the same wheel height band, ie 100 feet down to 20 feet. The same form of angular guidance was used for the two approach angles. In both these cases, landings were made on the R/STOL runway with a defined touchdown zone (see Section 6).

As part of the investigation into the influence of runway markings on the landing, approaches were made to the other (06) end of the R/STOL runway where the surface was unpainted. PAPIs were again used for guidance. Surprisingly enough, the approach performance was also affected, the standard deviation for a sample of 40 approaches being consistently lower than previously with a value of only 2½ feet. Because this seemed like one of the inevitable 'rogue' results, the exercise was repeated but again with virtually the same performance. The only conclusion to be drawn is that with an unmarked runway, pilots can concentrate exclusively on the approach until the flare whereas with a defined touchdown zone, pilots begin 'refining' their approach in order to land at the desired point and hence increase the approach scatter at a wheel height of 100 feet.

V. APPROACH PERFORMANCE - AZIMUTH

A number of studies (3) were made to investigate the type of azimuth manoeuvre that would probably have to be flown by R/STOL aircraft in the TMA. It was felt that there would be a need for azimuth approach intercepts from wide angles and at short ranges. With parallel runway operation any overshoot of the centreline would have to be minimised especially in crosswind conditions. It was therefore considered relevant to evaluate the azimuth capture performance of the HS 748 which was equipped with a standard SEP6 AFCS. The full control laws are given in Reference 3.

Using the SPN10 tracking radar, it was possible to simulate azimuth guidance beams of different widths. In this way it was possible to investigate the effect of beam sensitivity on capture performance. The flying was in fact limited to validating digital simulations of the problem.

The basic variables were beamwidth, crosswind and intercept angle. Figure 13 shows the effect of intercept range on capture performance for a 90 degree angle and a standard localizer beamwidth. Also included are two other captures, one representing a 3½ degree beamwidth and the other a manual VMC join just to show a system design target. The 6 degree glidepath capture point is also indicated.

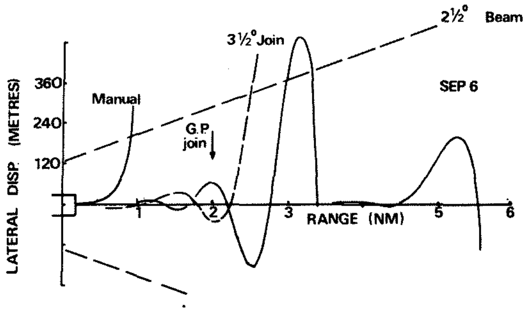

Figure 13 - Azimuth Capture Performance - HS 748

To be acceptable to the pilot, the aircraft had to be within ½ FSD of the localizer and converging with the centreline at the glideslope capture point.

The effect of a crosswind component is shown in Figure 14 for 90 degree intercepts at 4n miles beam capture and a nominal 3 degree beamwidth. With runways separated by 1500 metres as at London (Heathrow) airport, overswings of less than 100 metres are required in order to maintain lateral separation. Clearly this level of performance is not being achieved for the intercepts shown. However, it was found that with the particular control laws used, the optimum beamwidth was 3-3½ degrees and that by using 60 degrees intercept angles acceptable performance could be achieved down to a range of 2n miles, ie equivalent to the glidepath capture point for a 6 degree approach.

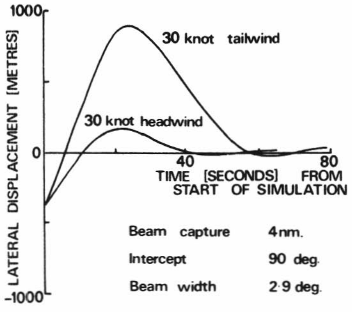

Figure 14 - Effect of Crosswinds on Azimuth Capture Performance - HS 748 Simulation.

VI. FLARES AND LANDINGS

Assuming that we can acquire and stabilize on a steep glideslope, the next major step towards pilot acceptability must be the actual landing. Beginning with the HS 748, Figure 15 shows a photograph of the landing area on our R/STOL runway. The dimensions are such that the crossbars are 60 metres apart and 12 metres wide. The PAPI origin is between the first and second crossbar. The pilots found that the transverse bars provided useful lateral and longitudinal displacement cues and also provided useful pitch and roll attitude cues during the rotation. The equivalent for night landings will be discussed later.

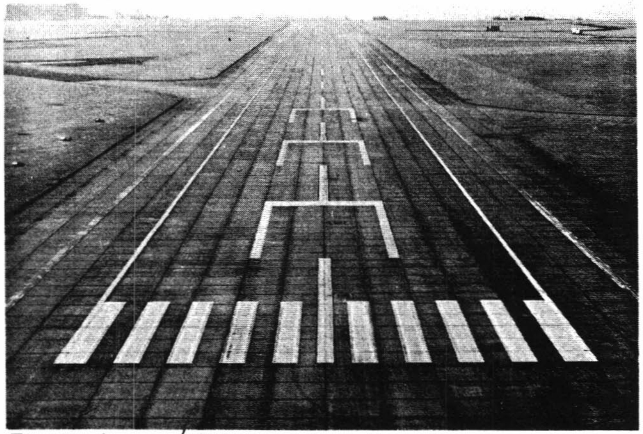

Figure 15 - R/STOL Touchdown Zone

6.1 Manual Landings

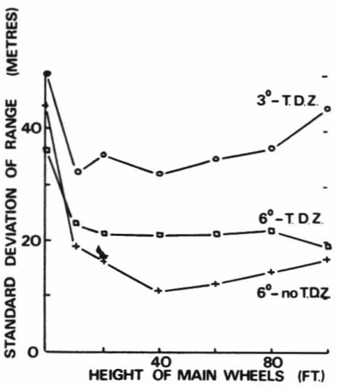

Figure 16 - Range at Touchdown - HS 748.

Figure 16 shows horizontal range as a function of wheel height beginning at 50 feet for sample sizes of between 30 and 50 and including 3 pilots. Visual PAPI approach guidance was used in each case. For the 6 degree and 3 degree approaches the range SD is very consistent down to a wheel height of 10 feet, thereafter increasing to 35 and 50 metres respectively at touchdown, ie an increase of 1½ times the approach value. By contrast, the approach to an unmarked runway yields a very low value at 50 feet but then progressively increases until at touchdown the SD is nearly 45 metres, ie nearly 4 times the approach value. Which result is preferable is difficult to say but perhaps more work is needed to establish an optimum set of TDZ markings.

For the 6 degree approaches, the mean wheel touchdown point was approximately 50 metres beyond the PAPI origin, ie between the second and third bars for the defined TDZ and virtually the same for all 3 pilots whereas for the unmarked runway, it was virtually 100 metres.

Rates of descent at touchdown were also measured using the kinetheodolite traces and are shown in histogram form in Figure 17. Although computed means and SDs are all very comparable, the histogram shows a definite shift in the distribution for landings from 6 degree approaches onto the marked TDZ - one touchdown rate being over 6 feet/sec. Because the pilots were all relatively experienced in R/STOL operations, this trend is rather worrying when thinking of an airline operation. Again it indicates the need to extend the TDZ to make it compatible with the type of aircraft.

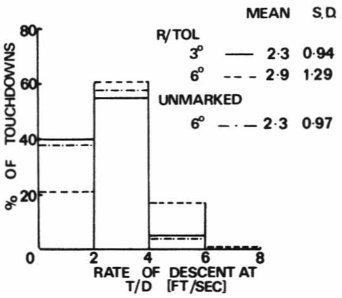

Figure 17 - Rates of Descent at Touchdown - HS 748

Flare height is extremely difficult to ascertain but by careful perusal of a number of parameters it is possible to establish criteria that can be used to determine flare height. Figure 18 shows the relationship between flare initiation height and glideslope angle which, as expected, is obviously non-linear, the height for the 6 degree case being some 3 times the value for 3 degrees. A 10 knot variation in approach speed did not seem to significantly affect the results.

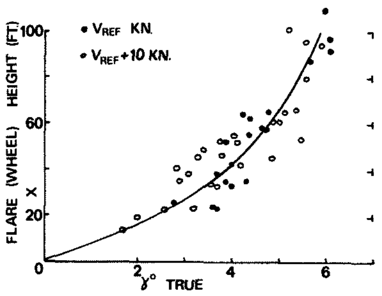

Figure 18 - Flare height for VC10

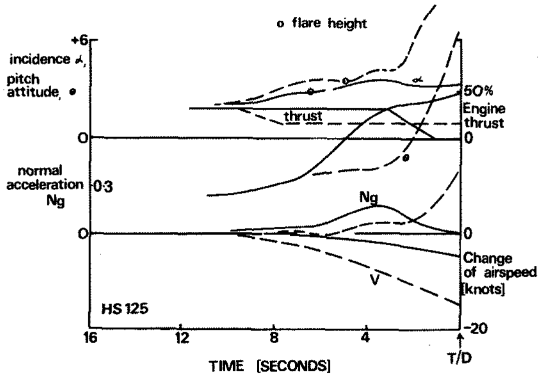

Figure 19 - Examples of Flare Time Histories Yielding Heavy and Light Touchdown Rates of Descent.

Figure 19 shows two landings that were made by the same pilot in the HS 125 from a 6 degree glideslope. The first, so-called ideal, flare begins at a height of 100 feet as might be expected from the previous Figure 18. Normal 'g' builds up slowly at first but is essentially triangular in shape. The throttle has been closed well below flare height and speed decays progressively throughout the manoeuvre.

By contrast, the second flare results in a heavy landing with a descent rate of 8 feet/sec. The throttle is closed just prior to flare height and it is suggested that the resulting trim change marks the additional pitch attitude that is really required to arrest the high rate of descent. The pilot fails to recognise the situation until about 40 feet at which stage he increases attitude and pulls 'Ng' continuously but fails to correct the situation in time. This would tend to suggest that it is essential to have stable flare entry conditions if the pilot is to make consistently good landings. Preferably power reductions should be left until well into the flare manoeuvre.

The BAC 1-11 has been used for both automatic and manual landing from steep approaches using pure elevator or elevator plus DLC. The DLC was in fact achieved using the spoilers on the wing and hence was far from the aerodynamic optimum. Their effective authority was ±0.17g. Nevertheless, benefits were achieved during the capture, approach and landing phases of flight - some unexpected - even for this relatively small aircraft. Figure 20 shows manual touchdown performance for 6 degree approaches with 3 degree data as a comparison. The expected reduction in scatter using DLC is not really evident but the control system linking the surfaces was relatively simple and the three pilots involved were all unfamiliar with the technique. Pilot workload was certainly claimed to be lower and landings were made in wind conditions considered out of limits for the normal elevator only system.

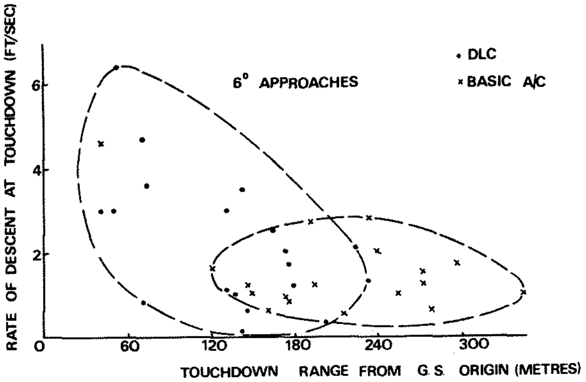

Figure 20 - Touchdown Performance Comparison for BAC 1-11 with and without DLC.

6.2 Partial Flares

During the course of the R/STOL research programme, the opportunity presented itself of using a Sea Vixen naval fighter aircraft to explore the problems of achieving consistent touchdown performance (9), albeit from 3 degree approaches. The aircraft undercarriage was stressed to withstand 12 feet/sec touchdown rates and hence possessed a valuable safety margin.

A number of flare techniques were examined, ranging from the conventional (unaimed, flared) to the aimed, unflared technique where the pilot attempts to land on a specific marking without reducing his approach descent rate. Visual guidance was used to generate accurate flightpaths.

Figure 21 shows a comparison of performance between the conventional flare and what seemed to be the optimum technique, the aimed partial flare. It is hoped that the effectiveness of the result (a 4:1 reduction in range scatter at the expense of a slightly increased mean ROD) might be applicable to civil aircraft, of the future if required to fly down steep glideslopes into short runways.

Results for aimed, unflared landings are also shown from which it can be deduced that the dramatic increase in touchdown rate has not yielded any further reduction in touchdown scatter.

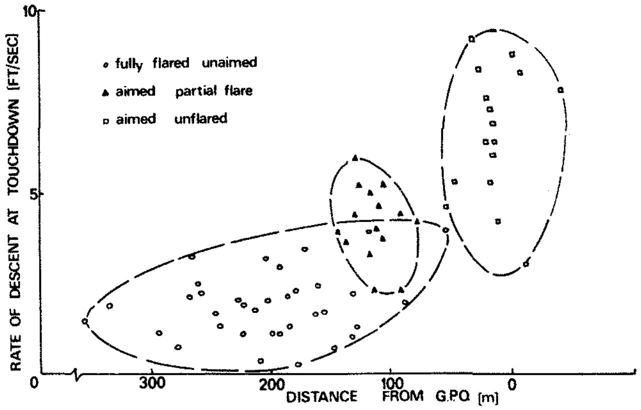

Figure 21 - Touchdown Performance Using Sea Vixen - 3 degree Approaches

6.3 Crosswind Landings

We have to date only limited performance data concerning crosswind landings following a steep approach. However, the pilots felt that a crosswind component of 15-16 knots represented the maximum practical limit compared to the 25 knot limit for landings from 3 degrees. The reduced time to kick-off the drift and the increased aileron rate required to maintain wing-level are the prime considerations.

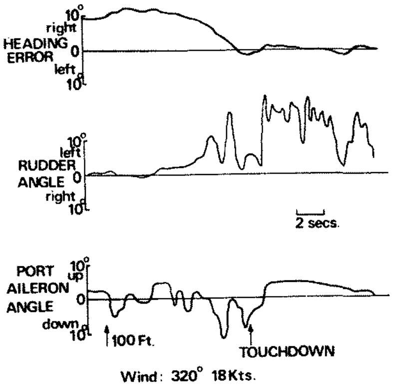

Figure 22 - A typical crosswind landing from a steep (6 degree) approach - HS 748.

Figure 22 shows a typical landing made in a strong (18 kn) crosswind condition. The large rudder and aileron input and their rapid fluctuations are clearly evident.

VII. ALL-WEATHER OPERATIONS

All-weather aircraft operation is an extremely complex subject but one area is particularly important, namely the determination of decision height - that height at which an overshoot must be initiated if adequate visual reference with the ground has not been established such that the landing can be carried out safely. Specific areas of interest connected with decision height are the height loss during an overshoot, the time taken to carry out lateral corrections and the visual cue that the pilot needs to help him land in poor visibility. These are briefly discussed below.

7.1 Height Loss During Overshoot

From a traditional certification point of view a major component of the decision height computation is the height loss during the missed approach and from Reference 10, as applied to Category 2 certification, a value equal to the mean plus 5 SDs has to be included. Figure 23 shows some measured data for the BAC 1-11 in which height loss has been plotted against rate of descent at the initiation (throttle open) point. Some constant 'g' curves have been drawn for comparison purposes. These go-arounds were made at a nominal height of 500 feet following steep descents and the pilot, although ostensibly carrying out instrument go-arounds, had nothing preventing him looking outside his cockpit if he so wished. It follows that there was minimal stress on the pilot and little necessity for him to optimise his performance.

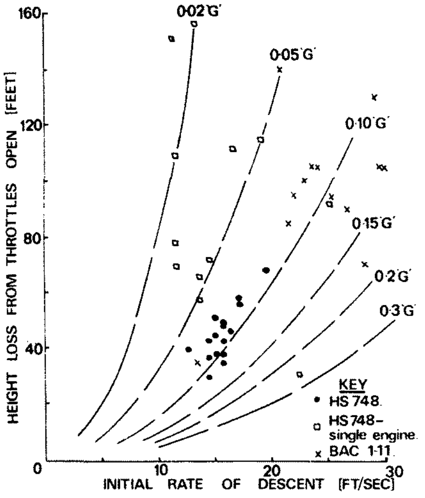

Figure 23 - Missed Approach Performance - BAC 1-11 and HS 748.

From the data it can be seen that the nominal height loss is typically 90 feet but the individual points show considerable scatter. In fact the mean was 98 feet and the SD was 14 feet. Thus, if a (mean + 5 SD) criteria is adopted the minimum decision height must be of the order of 170 feet, assuming that all other terms in the equation, ie instrument errors, recognition errors, obstacle clearance limits, etc are zero.

For the HS 748 aircraft, both two-engine and single engine operating manoeuvres were recorded in a range of weather conditions, using essentially V_{AT} + 10 knots approach speed. Attempts to get closer to the IMC situation at least for the two-engine case was achieved by obscuring the subject pilot's peripheral vision using side-screens and his forward vision by using a 'fogblind' (11) as shown in Figure 24. Each pilot was briefed to initiate a go-around at 200 feet (radio) if the blind had not been raised and the ratio of missed approaches to landings was typically 3:1.

This aircraft presented peculiar problems in that as explained earlier, full land flap had to be used to achieve a steep gradient capability and hence two notches of flap had to be selected (ie 27½ degrees to 15 degrees) to achieve the correct climb-out configuration. The individual results

Figure 24 - Airborne Fogblind in HS 748

of the trials, also shown in Figure 22, produced a mean of 45 feet and an SD of 10 feet which leads to a minimum decision height of 95 feet. If, however, the height loss is measured from the 200 foot decision height as opposed to the 'throttle-open' point then the mean and SD become 62 feet and 14 feet respectively, increasing the decision height to 132 feet. These values still unfortunately do not take into account the certification requirement of including at least one engine out WAT limited case in the sample.

The asymmetric case was investigated at a height of 1500 feet above the airfield, the aircraft descending at 1000 feet/min (nominal 6 degrees) and one engine was autofeathered by P2 at the moment of overshoot. In such circumstances the performance was so marginal that failure to raise the undercarriage reduced the climb rate from 500 feet/min to 200 feet/min. In addition, a considerable force was required on the rudder pedal to maintain heading and subject pilot workload was so high that often no attempt was made to raise the wheels. Figure 23 shows these additional runs involved. The general scatter is obviously extremely large and the inclusion of an adverse result in the decision height sum would virtually indicate a 200 ft height. However, it must be remembered that these runs were necessarily exploratory and hence not exactly representative of an operational situation.

7.2 The Side-Step Manoeuvre

Another factor that can influence the choice of decision height is the side-step performance of a particular aircraft. If the aim is to operate down to a low decision height, then the pilot cannot contemplate having to perform a lateral manoeuvre at such a late stage in the approach. Hence, the complete aircraft guidance system must deliver the pilot accurately down to the decision height such that by merely continuing the approach, a safe landing can be made on the runway.

Reduced quality in either the aircraft avionics or the guidance system will lead to flightpath errors which, if the pilot has to correct them in order to continue the approach, he will need additional height/time and also a manoeuvrable aircraft.

Data existed for the 3 degree approach case (12) but none for the steep approach situation. Thus, a comparison was made between the two glideslope angles using the HS 748. Approaches were made to the R/STOL runway with the subject pilot's forward vision obscured by the fogblind. The safety pilot flew the aircraft down the approach and established the required level of displacement from the runway centreline. At the required height the fogblind was raised and the subject pilot asked to either carry out the necessary alignment manoeuvre or else execute a go-around.

From the results, there appeared to be no difference between the times taken to correct the given offset on a 3 degree and 6 degree approach. Bank angles used were typically 8-10 degrees.

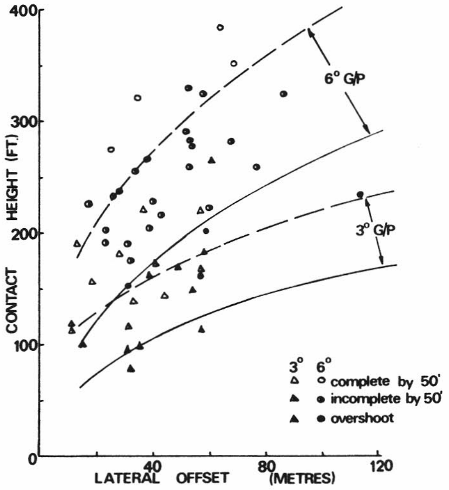

Figure 25 - Side-step performance - HS 748

Figure 25 shows the height at which the pilot saw a particular offset and then corrected it prior to reaching a nominal flare height of 50 feet. Boundaries are shown representing both the heights from which corrections can be executed safely and the limiting heights below which the corrections would be incomplete at the start of the flare. It can be seen that due to the increased rate of descent for the steep approach, an offset of 60 metres for example requires an extra 130 feet of height compared to the 3 degree case. Thus, to avoid this significant disadvantage, guidance systems used for R/STOL low visibility approaches and the associated aircraft avionics must be of high quality.

7.3 Visual Aids

7.3.1 R/STOL Patterns

An equally vital part of all-weather operations is that of the visual cues that are needed by the pilot in poor visibility in order to continue the approach and land safely. Investigations into these aspects were primarily made using a piloted flight simulator with a digitally generated outside world display (2). Because the concept of a STOL runway was that of short narrow strips close to a city centre, it followed that conventional approach and runway lighting was unsuitable. Figure 26 shows a pattern that was evaluated on the simulator and which is designed to contain the essential features of a conventional pattern whilst minimising the ground area required. The touchdown zone is equivalent to the white markings referred to earlier; the length of approach lighting has been reduced from

900 metres down to 450 metres.

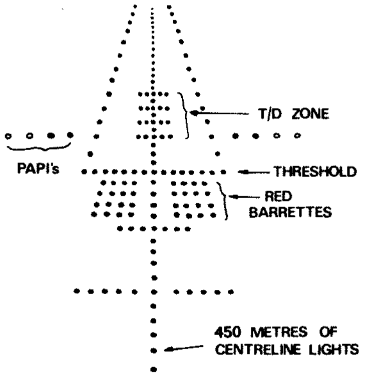

Figure 26 - Experimental R/STOL Lighting Pattern.

7.3.2 Effect of Decision Height on Visual Cues

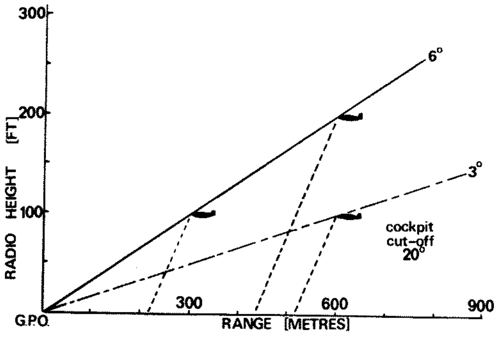

Figure 27 - Effect of Decision Height on Range of Aircraft from Runway.

Figure 27 shows a comparison of a 3 degree and a 6 degree glideslope for different heights on the approach. A cockpit cut-off angle of 20 degrees has been assumed. It can be seen that if a decision height of 100 feet can be achieved for a 6 degree approach, then the aircraft is much closer to the glidepath origin and for a given slant visual range (SVR) the chances of making good visual contact with the runway is increased compared to the conventional situation. Unfortunately, the data presented earlier suggests that 200 feet is probably more realistic, in which case the aircraft is not only as far out as the 100 ft 3 degree case but also much higher and hence more likely to be within the dense fog layers that exist at such heights (13). As a result, the pilot is less likely to make visual contact with the ground even with a conventional lighting pattern.

7.3.3 Effect of Visual Segment on Approach Success

Figure 28 shows the variations of approach success (the ratio of number of landings to the number of approaches) with the visual segment seen at decision height for the R/STOL lighting pattern and a conventional pattern. For a 300 foot decision height, the conventional pattern is providing superior results because of the extra approach lighting available. However, by the time the decision height has been reduced to 100 feet the R/STOL pattern is the optimum. The benefit appears to be due to the presence of the threshold and the glidepath origin in the pilot's field of view at decision height for the R/STOL pattern. For the conventional pattern, once the visual segment has fallen below 200 metres, there is just a meaningless set of TDZ lights with no definite range cue in sight.

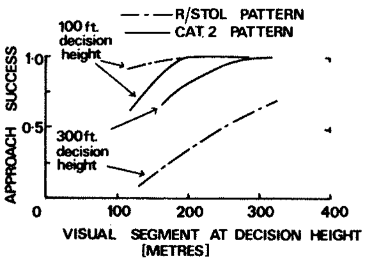

Figure 28 - Effect of Decision Height on Approach Success - Piloted Simulation.

7.3.4 Flare and Landing

Another factor that emerged from pilot comment was that the TDZ lighting should be continuous from the threshold so that no 'black hole' effect exists in poor visibility. More details of matching runway to fog characteristics are given in Reference 13.

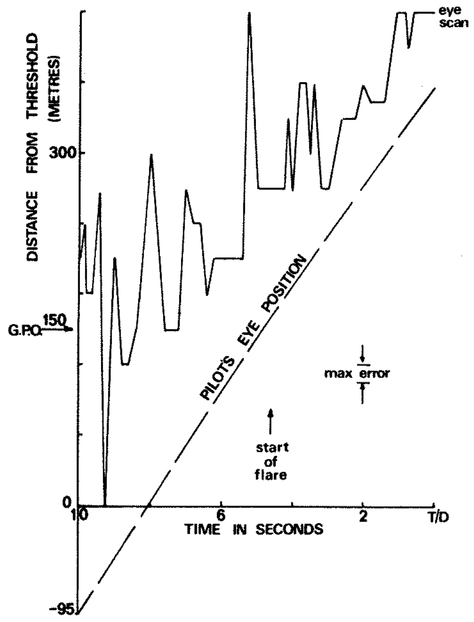

Figure 29 - Eye Scan During a 5 degree Flare - HS 748

Figure 29 shows a typical eye movement trace (19) obtained for a pilot landing the HS 748 from a 5 degree visual approach. It can be seen that the pilot is looking ahead of the aircraft by a distance of no more than 350 metres and that during the flare this shortens to less than 200 metres. If this result can be generally substantiated, it suggests the possibility that such landing can be made in RVRs down to below 400 metres before the pilot begins to seriously lack visual cues.

VIII. ALTERNATIVE APPROACH TECHNIQUES

From what has been said so far, it would appear that steep approaches can produce definite aircraft noise benefits as well as perhaps possible fuel savings and operational flexibility in the TMA. Pilots generally found the quick descent from the circuit height very acceptable compared to the long drag in for the conventional case. However, the flare was definitely considered to be more difficult and therefore the associated stress on the pilot based on heart rate measurement was higher during the approach phase. This is illustrated in Figure 30 derived from Reference 14, where one pilot flew a series of approaches in the VC10. The heart beats are averaged over 30 second epochs, the landing occurring in the middle of one such period.

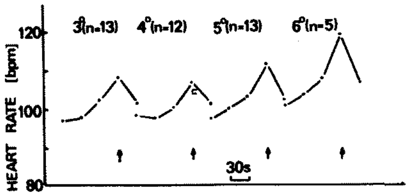

Figure 30 - Comparison of mean heart rates for different visual approach and landing profiles, VC10

It can be seen that there is a progressive increase in the averaged 'peak' reading from less than 110 beats/min for 3 degrees to nearly 120 beats/min for the 6 degree case. These results were obviously not all measured on the same occasion and hence not all of the variations need be due to the approach technique but at least a definite trend is discernible.

To overcome this problem and also some of the operational problems referred to earlier, it would seem desirable to reduce the aircraft descent rate at some point on the approach prior to the flare - a so-called two-segment approach.

For present day medium and large civil airliners, it would seem that transitions from a steep approach onto the final 3 degree segment are impracticable below 1000 feet if ample time is to be allowed to stabilise on the glidepath prior to the decision height. For smaller aircraft like the HS 748 and the HS 125, transition heights around 500 feet might be feasible (15,16).

During the course of experimentation a technique known as the double flare was discovered (17) which is really a two-segment approach with a low transition height around 150-200 feet. By choosing such a height, it was found that there was no need to stabilise airspeed on the lower segment and the rate of descent was reduced early enough to make the entry to the flare conventional. Thus, two sources of pilot stress were removed immediately. In addition, it appeared to be applicable to all sizes of aircraft: the main noise benefits were retained and there was no gross undershoot of the runway, like two-segment approaches.

A brief trial was carried out using the BAC 1-11 to look at the landing performance for single and double flare steep approach techniques and PAPIs were arranged to provide the necessary visual guidance (Figure 12). Two pilots performed seven approaches each and it can be seen from Figure 31 that the rates of descent look more consistent for the double flare with less tendency for a heavy landing. There is, however, virtually no difference in touchdown distance between the two techniques.

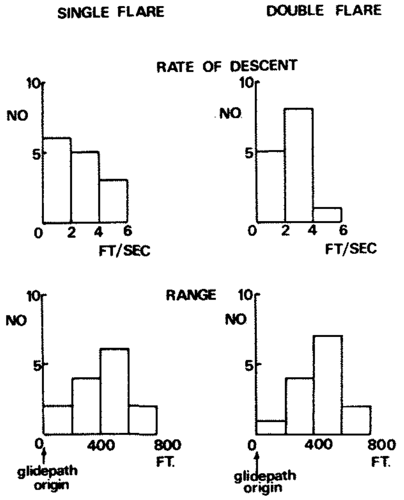

Figure 31 - Comparison of Touchdown Performance for Single and Two-stage Flare - BAC 1-11.

The main problem of the double flare occurs in the IMC situation. Information given in early sections indicates that a decision height of around 200 feet seems realistic for steep approaches (high descent rate) and conventional aircraft. The disadvantages of this have been discussed already. Assuming that all the relevant aircraft systems are still operating correctly, reducing the descent rate at this height would then allow a more conventional decision height to be used, ie 100 feet but this would mean that the aircraft would be rotating during the time when the pilot is beginning to search for visual cues. Such a technique would be acceptable with a fail operational automatic system but the high integrity and precision required indicates the necessity for using an MLS guidance system. This would appear to be at least a decade or so away.

IX. FUTURE RESEARCH

During the last two years, effort on R/STOL research has been reduced but it is intended to maintain a low but consistent level of activity extending the experience which has already been acquired using a prototype doppler MLS elevation unit. A complete MLS ground system will hopefully be commissioned at RAE Bedford during 1977/78 and this will allow some of the potential benefits of wide angle guidance to be explored. In the azimuth plane, this can be expected to yield short range captures of the runway centreline without overshoot in all weathers, whilst in elevation the so-called two-stage flare could become a reality. It is also hoped to further extend our experience of steep approaches using DLC which has to date shown promising results. At all times the implications of such techniques on future aircraft systems, eg cockpit displays, autopilot, engines, etc will have to be considered and their compatibility with all-weather operations must be ensured.

X. CONCLUSIONS

This paper has attempted to briefly outline the scope of R/STOL research at RAE Bedford by presenting some of the results obtained to date for the various aircraft involved. From the data it would seem that the successful advent of R/STOL operations very much depends on the successful introduction of MLS guidance. Then with the use of relatively conventional avionic system design techniques, it should be possible to achieve the required levels of flightpath accuracy necessary for flight in a busy TMA environment. This improvement in approach accuracy coupled with equivalent development in engine and airframe design, eg faster response and the use of spoilers or flaps as a primary control surface, should lead to the ability to operate safely down to realistic decision heights in all weathers with real benefits measured in terms of approach success rate. In the absence of such improvements the landing technique known as the two-stage flare might still make steep approaches operationally acceptable. The steady progress that is being made in developing new visual aids, eg PAPIs appears to be adequate to meet the needs of future R/STOL flying.

In an effort to prove whether these conclusions are correct, long term research will continue at RAE Bedford.

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