Summary and Analysis of Feasibility-Study Designs of V/STOL Transport Aircraft

Wallace H. Deckert* and David H. Hickey†
NASA-Ames Research Center, Moffett Field, Calif.

Studies of the technical feasibility of V/STOL concepts for commercial short haul transport aircraft[1] emphasizing the technical aspects of aircraft design have been completed. Various VTOL and STOL short haul transport concepts are compared in terms of design gross weight, direct operating cost, gust sensitivity, and perceived noise levels; the impact on this comparison of design range requirements, austere design philosophy, advanced technology, nonproductive time, and other considerations is included.

Design Criteria

AIRCRAFT were required to have a 500 statute mile nonstop range while operating at minimum, or near minimum, direct operating cost. Cruise speed was not specified. Reserve fuel was the fuel required for a 30 min hold at an altitude of 5000 ft on a standard day at the airspeed for maximum endurance, plus the fuel required to complete a go-around due to an aborted landing. Aircraft were designed for 60 to 120 passenger payloads based on 200 lb per passenger (including baggage) plus a revenue cargo payload of 10% of the passenger payload. Commercial field lengths for the STOL aircraft were 1000 and 2000 ft corresponding to approach speeds of about 55 and 85 knots, respectively. Propulsion systems were selected on the basis that the system could be commercially available by 1970. Revised versions of presently designed engines were permitted. The thrust/weight ratios, for trimmed VTOL aircraft on an 86°F day at sea level were 1.15 for all engines operating and 1.05 with the critical engine inoperative. An engine emergency contingency rating, based on increasing normal takeoff gas generator power by 10%, was used to defray the penalty for loss of an engine. The parametric design control requirements were stipulated to decrease with number of passengers (or aircraft weight and size). For 120 passenger aircraft desired control design requirements for VTOL and STOL aircraft, respectively, in rad-sec,^{2} were 0.96 and 0.20 in roll, 0.48 and 0.18 in pitch, and 0.40 and 0.16 in yaw. Additional design criteria are presented in the study final reports.[1-3] Reports on other V/STOL studies related to this subject are also referenced.[4-6]

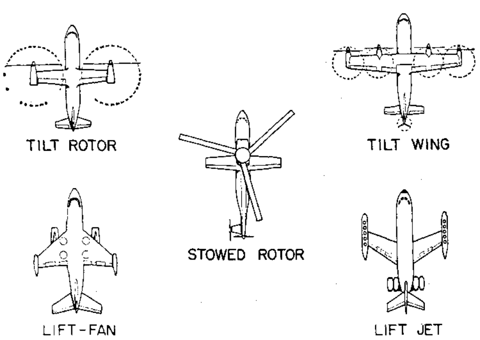

Fig. 1 VTOL concepts under study.

Presented as Paper 67-938 at the AIAA 4th Annual Meeting and Technical Display, Anaheim, Calif., October 23–27, 1967; submitted January 27, 1969; revision received August 29, 1969. Contracts awarded by Ames Research Center, NASA, to The Boeing Company, Lockheed Aircraft Corporation, and Ling-Temco-Vought Inc.
* Research Scientist.
† Research Scientist. Member AIAA.

Results and Discussion

Comparison of Aircraft

The VTOL and STOL concepts studied are shown in Figs. 1 and 2. The VTOL aircraft are categorized as follows: rotor concepts—one tilt rotor and one stowed rotor design; propeller concepts—three design variations of the tilt wing concept; lift fan concepts—three design variations; and lift jet concepts—one design. The STOL aircraft are categorized as follows: propeller concepts—two variations of the deflected slipstream concept; lift fan concepts—two variations of the fan-in-wing concept plus one propulsive wing design; and turbojet or turbofan concepts—one design using a jet flap and the other an externally blown flap. Each of the VTOL and STOL aircraft are optimized designs resulting from a comprehensive parametric study.

60 passenger aircraft

The design gross weight of the VTOL and STOL 60 passenger aircraft are presented in Fig. 3. STOL aircraft are for a 2000-ft commercial field length. The minimum and maximum design gross weights from the various aircraft designs within each category are shown with the range in weights represented by the crosshatched line. The heaviest VTOL aircraft is the direct lift jet (80,000-lb gross weight). The rotor, propeller, and lift fan VTOL designs are quite competitive in terms of gross weight with minimum gross weights ranging from 62,300 lb for the propeller VTOL to 71,800 lb for the lift fan VTOL. STOL aircraft are from 22 to 25% lighter than the corresponding VTOL aircraft. Within the STOL group, a propeller STOL aircraft

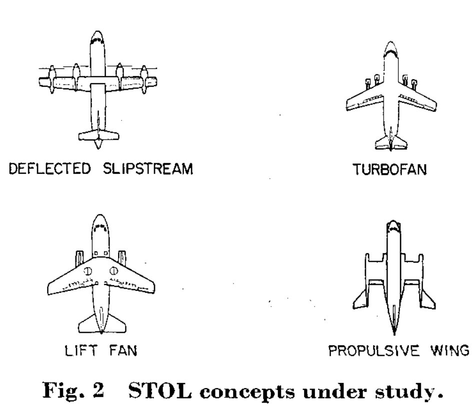

Fig. 2 STOL concepts under study.

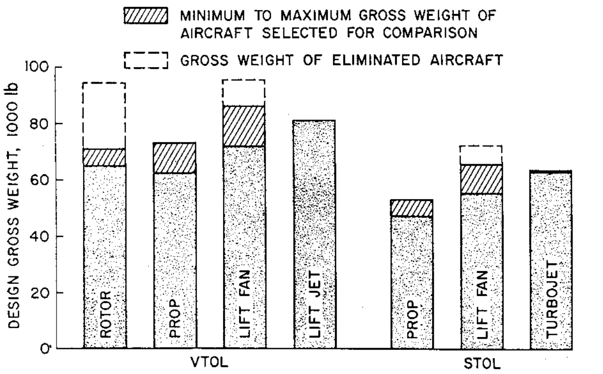

Fig. 3 Design gross weight of 60 passenger aircraft.

is the lightest aircraft with a gross weight of 46,900 lb. The dashed lines show the design gross weights of aircraft included in the NASA-Ames study but eliminated from this presentation. One is a tandem stopped and stowed rotor design with a gross weight of 94,500 lb, but a design featuring a single stowable rotor with a gross weight of 71,000 lb is included. The large variation in the gross weights of these two stowed rotor designs reflects the state of the art for this type of VTOL aircraft. The design eliminated from the lift fan VTOL category is a pure fan-in-wing design. That is, the same gas generators that drive the lift fans during low-speed flight also provide thrust for cruise. This particular design approach led to large diameter lift fans, compromised wing design, and an unduly heavy, nonoptimum lift fan aircraft. The pure fan-in-wing aircraft was eliminated in favor of the composite lift fan aircraft design featuring separate gas generators for cruise flight (and thrust deflectors to provide lift in low-speed flight). The lightest composite lift fan design has a gross weight of 71,800 lb compared to a 95,300-lb gross weight for the eliminated pure fan-in-wing aircraft. The STOL version of this particular fan-in-wing family has also been eliminated.

The cruise speeds corresponding to minimum direct operating cost of the 60 passenger aircraft are shown on Fig. 4. The propeller STOL aircraft have cruise speeds that vary from about 285 knots, the lowest cruise speed of all aircraft, to about 370 knots, which is comparable to the cruise speed of the low disc loading VTOL aircraft. This large variation in cruise speed indicates that the direct operating cost of propeller STOL aircraft is relatively insensitive to design cruise speed. The highest cruise speed is 520 knots for a lift fan STOL (propulsive wing type) and is a result of the prediction of a high critical Mach number for this design. A preliminary small-scale wind-tunnel investigation indicated that the critical Mach number for the propulsive wing may be as high as 0.90. However, by application of advanced design techniques, it may also be possible to realize critical Mach numbers approaching 0.90 for other V/STOL concepts as well as for the propulsive wing concept. It is significant that the heaviest VTOL and STOL aircraft with high disk loading are also the fastest. High cruising speeds have a beneficial effect on direct operating costs.

Direct operating cost (DOC) was computed by the standardized ATA method modified to reflect maintenance costs peculiar to V/STOL aircraft and was based on a lost or nonproductive time of $10\frac{1}{4}$ min. Results show, for 60 passenger aircraft operating over a 500 statute mile stage length, that the direct operating costs of the rotor, propeller, and lift fan VTOL aircraft are competitive. The DOC of STOL aircraft is 25 (propeller types) to 41% (jet types) less than the DOC of VTOL aircraft. For STOL aircraft designed to a 2000-ft field length, lift fan and turbojet STOL aircraft are competitive with propeller STOL aircraft. At short stage lengths the higher cruise speeds of the lift fan and lift jet VTOL aircraft have less effect on block speed.

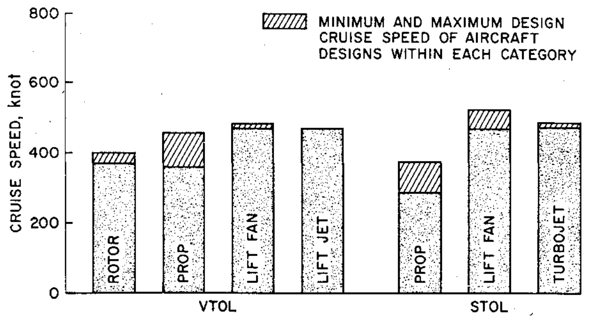

Fig. 4 Cruise speed of 60 passenger aircraft.

Thus, for a 100-mile stage length, the DOC of the rotor and propeller VTOL aircraft is less than the DOC of the lift fan and lift jet VTOL aircraft. The various STOL aircraft remain competitive within the STOL group. The DOC of the various types of STOL aircraft is from 16 to 25% less than the DOC of the most economical VTOL aircraft.

120 passenger aircraft

The design gross weight of the VTOL and STOL 120 passenger aircraft is presented in Fig. 5. At the 120 passenger size the various aircraft within the VTOL and STOL groups are even more competitive in terms of design gross weight. The design gross weight of the rotor and propeller aircraft increases with payload at a greater rate than that of the higher disk loading types. The gross weight of the lift jet VTOL aircraft (which weighed more than other types for 60 passenger aircraft) is similar to the gross weight of the other VTOL aircraft. The cruise speeds of the 120 passenger aircraft are similar to the cruise speeds of the 60 passenger aircraft.

Direct operating cost calculations for the VTOL and STOL 120 passenger aircraft for a 500-mile stage length show that the 120 passenger lift jet VTOL aircraft is more competitive as suggested by the design gross weight trend. Within the STOL group, some of the high disk loading STOL aircraft are more economical than the propeller STOL aircraft. The DOC of the most economical STOL aircraft (lift fan type) is 34% less than the DOC of the most economical VTOL aircraft (propeller type). DOC trends for the 120 passenger aircraft operating over a 100-mile stage length are similar to those discussed for the 60 passenger aircraft.

Gust sensitivity

Since short haul aircraft spend much of their flight time at low altitudes, gust sensitivity is of great importance. Poor riding qualities could affect economy if lower cruise speeds were required in turbulent conditions and for passenger acceptance (thereby decreasing passenger load factor). The gust sensitivity of 60 passenger aircraft was calculated based on a 5000-ft altitude, a 50-ft/sec vertical gust, and a rigid aircraft. Results show that lift fan VTOL and

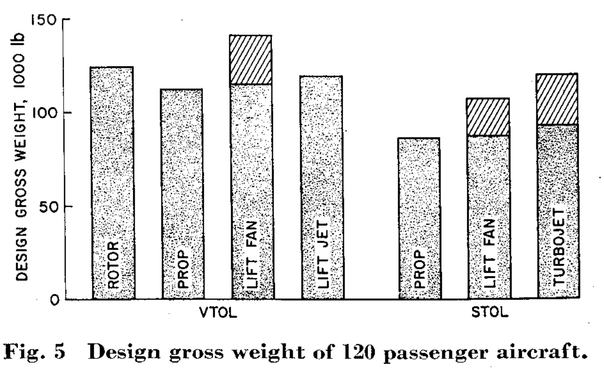

Fig. 5 Design gross weight of 120 passenger aircraft.

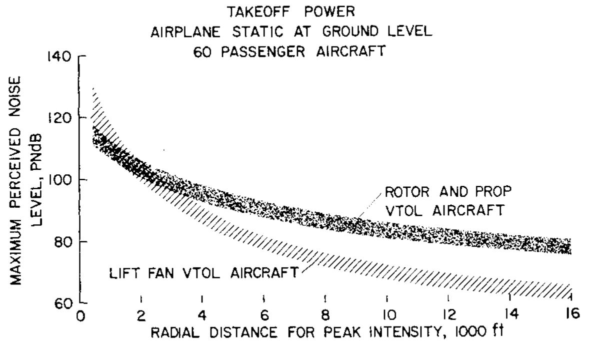

Fig. 6 Attenuation of perceived noise levels with distance.

lift jet VTOL aircraft, which have high wing loading and low-aspect-ratio swept wings, have the least gust sensitivity.

Perceived noise levels

Perceived noise levels for 60 passenger aircraft on the ground at takeoff power were calculated for a 500-ft distance from the aircraft in the direction of peak intensity. The maximum perceived noise levels vary from 99 PNdB for a propeller STOL aircraft to 129 PNdB for a lift jet VTOL aircraft. Perceived noise levels for the VTOL aircraft vary from 109 PNdB for a rotor VTOL aircraft to 129 PNdB for the lift jet VTOL aircraft. The perceived noise for the quietest STOL (propeller type) is about 10 PNdB less than for the quietest VTOL (rotor type). It is emphasized that the preceding discussion is only for the relatively close-by 500-ft distance.

The attenuation of perceived noise levels with distance for 60 passenger VTOL aircraft on the ground at takeoff power is presented in Fig. 6. Distances are radial from the aircraft in the direction of peak intensity. The maximum perceived noise levels for the rotor, propeller, and lift fan VTOL aircraft are about the same at a distance of 1500 ft and the lift fan aircraft are quieter at greater distances. This is because high-frequency noise attenuates at a greater rate than low-frequency noise, and lift fan VTOL aircraft generate the higher frequency noise. At 10,000 ft, the perceived noise level is 80-85 PNdB for rotor and propeller VTOL aircraft and 67–73 PNdB for lift fan VTOL aircraft. Maximum perceived noise limits of 98 PNdB for city centers and 68 PNdB for residential areas at night have been suggested. Accordingly, rotor VTOL aircraft would be close to acceptable for city center operation but inacceptably noisy unless many miles from residential areas; lift fan VTOL aircraft would be unacceptable for city center operation but acceptable when only about 2 miles from residential areas.

It is concluded that a concentrated research effort to reduce the noise from all types of VTOL and STOL aircraft is necessary, public acceptance criteria are needed, and caution is required before labeling one VTOL aircraft noisier or quieter than another.

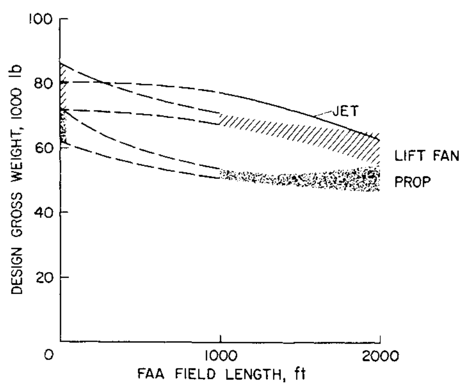

Fig. 7 Effect of field length on design gross weight of 60 passenger aircraft.

STOL field length

The effect of field length on design gross weight of the 60 passenger aircraft is shown in Fig. 7. The design gross weight variation for 1000-ft STOL aircraft is greater than for 2000-ft STOL aircraft. At 1000 ft, the propeller STOL aircraft are lighter than the other types and the lift fan STOL aircraft are lighter than the turbojet-jet flap STOL aircraft. The envelopes for the three types of STOL aircraft, namely propeller, lift fan, and jet, include all the aircraft designs except that for the 2000-ft turbofan STOL aircraft with externally blown trailing-edge flaps. This design was eliminated as a candidate for a 1000-ft STOL aircraft because, although the externally blown flap high lift scheme results in an attractive 2000-ft STOL aircraft (85-knot approach speed) with a design gross weight of 62,800 lb, the relatively modest aerodynamic benefits associated with the externally blown flap prohibit design of a competitive 1000-ft STOL aircraft. The curves in Fig. 7 are dashed between 1000-and 0-ft field lengths because the curves are not necessarily smooth as shown. For example, the 1000-ft propeller STOL aircraft use aerodynamic control surfaces. The control system for a 500-ft propeller STOL aircraft would be similar to that required for VTOL; hence, a 500-ft propeller STOL aircraft would weigh more than shown in Fig. 7.

The effect of field length on the direct operating cost of 60 passenger STOL aircraft for a 500-mile stage length was computed. As with design gross weight, the DOC of the propeller STOL aircraft is less than for other types and the DOC of the lift fan STOL aircraft is less than that of the turbojet STOL aircraft. Within concepts the DOC for 1000-ft STOL aircraft is less than the DOC of VTOL aircraft. This is particularly evident for the propeller STOL aircraft which achieve high lift coefficients by augmenting wing aerodynamics as opposed to augmenting lift by use of direct thrust. For example, the DOC of the 1000-ft propeller STOL aircraft is about 22% less than that for the propeller VTOL aircraft.

Selection of promising STOL concepts

For 1000-ft field lengths, propeller STOL concepts must be considered most promising at this time because of their lighter weight and lower DOC. For 2000-ft field lengths, propeller, lift fan and turbojet concepts are very competitive economically; however, lift fan and turbojet concepts should be better because of their higher cruising speed and passenger appeal. In the future, with additional research and more advanced concepts, such as the augmentor wing, turbojet and lift fan STOL aircraft may become competitive for 1000-ft field lengths.

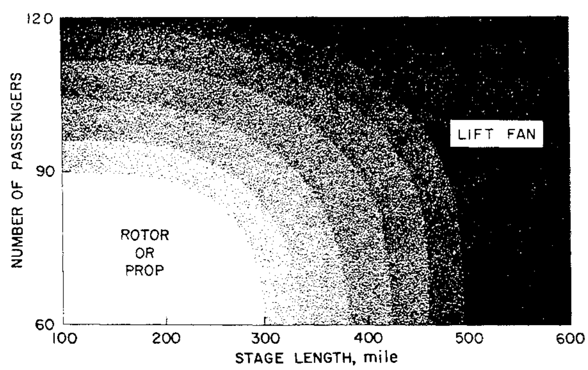

Fig. 8 Summary of VTOL Aircraft.

Selection of promising VTOL concepts

Figure 8 is a summary curve showing promising missions for various VTOL concepts in terms of stage length and payload. Rotor and propeller VTOL concepts are promising for 60 passenger aircraft operating over 100-mile stage lengths. Lift fan VTOL concepts are promising for 120 passenger aircraft operating over 500-mile stage lengths. Although competitive in other ways, the lift jet VTOL design of this study is eliminated on the basis of large near-by perceived noise levels (129 PNdB at 500 ft). On the basis of only direct operating cost computations, rotor or propeller VTOL concepts would be selected over lift fan VTOL concepts. However, DOC calculations are useful as one guideline—not as a single absolute criterion. For 60 passenger aircraft operating over a 500-mile stage length, the DOC of lift fan VTOL concepts is about 8% higher than the DOC of low disk loading concepts. However, based on passenger appeal, in terms of higher cruise speed and lower gust sensitivity, lift fan VTOL concepts are selected over low disk loading VTOL concepts. Lift fan VTOL concepts are shown to become more promising at shorter stage lengths as payload is increased because the rate of increase in design gross weight with payload is less for lift fan VTOL concepts.

A wide competitive region exists between the two mission areas discussed above. These boundaries can be defined, or concepts eliminated, only by additional research encompassing all VTOL concepts.

Impact of Study Assumptions and Design Criteria

Effect of maintenance on direct operating cost

DOC computations were based on the standardized ATA method with the exception that each contractor estimated maintenance costs believed to be appropriate for a particular VTOL and STOL aircraft. The DOC due to maintenance varies from about 13 to 33% of the total DOC and results defy correlation with either the type of aircraft or gross weight. It is apparent that the science or art of assessing maintenance costs needs improvement. The DOC component due to maintenance was subtracted from total DOC to examine results based on no maintenance costs. The relative position of each VTOL and STOL aircraft category (rotor, lift fan, etc.) remains unchanged despite an increased DOC variation within each category of aircraft. Thus, overall, the study results remain valid despite wide variations in maintenance costs.

Effect of design range requirements

The basic design range for the NASA-Ames short haul study was 500 statute miles. Gross weight change as a function of design range for a tilt wing VTOL and a lift fan VTOL aircraft was determined. Design gross weight changed about 5% when the basic 500-mile range was decreased to 300 miles or increased to 700 miles for both types of VTOL aircraft. Since cruise fuel amounts to only about 5% of gross weight, large variations in design range yield only small variations in gross weight. Thus, the relative study results should apply to design range requirements anywhere from 300 to 700 statute miles.

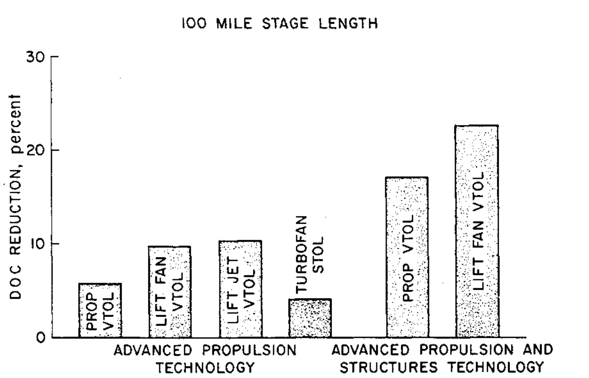

Fig. 9 Direct operating cost reduction due to advanced technology.

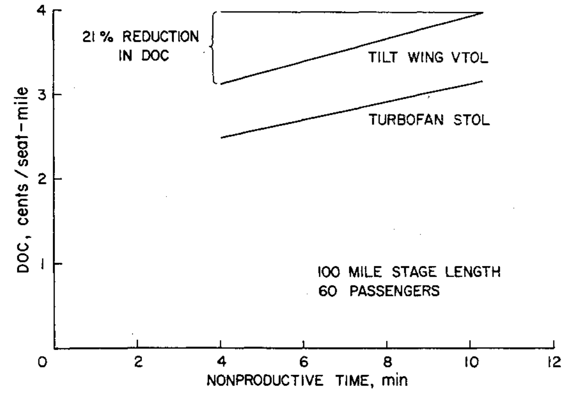

Fig. 10 Sensitivity of direct operating cost to nonproductive time.

Effect of austere design philosophy

The design criteria of the study required aircraft to be self-supporting, to be equipped with passenger accommodations comparable with those of current commercial aircraft, and to carry reserve fuel for a landing go-around about a long approach pattern plus reserve fuel for a 30-min hold. An austere design philosophy was applied to a 60 passenger tilt wing VTOL aircraft with a design gross weight of 71,700 lb. The result was a design gross weight reduction from 71,700 to 56,500 lb for the same payload and range which corresponded to a reduction in direct operating cost of approximately 20%. Changes incorporated were the deletion of air-stairs and auxiliary power unit, the deletion of revenue cargo (10% of passenger payload requirement replaced with 6 additional passengers) deletion of food galley and one of the two washrooms, the use of ultra-lightweight seats, and the reduction of fuel by eliminating go-around fuel reserve and taxi fuel.

Based on these results, passenger accommodations and reserve fuel requirements for V/STOL short haul transport aircraft must be carefully scrutinized to assure that the minimum practical direct operating costs are achieved.

Effect of advanced technology

Technology considered to be appropriate for the year 1980 was used to establish possible future trends in selected designs. Two separate studies were conducted. First, advanced technology was applied to only the propulsion systems maintaining 1970 airframes. Secondly, advanced technology was applied simultaneously to propulsion systems and structures. The reduction in direct operating cost due to advanced propulsion technology applied to four short haul designs is presented in Fig. 9. DOC reductions from 4 to 10% were forecast with lift fan VTOL and lift jet VTOL aircraft having greater potential gains than propeller VTOL or turbofan STOL aircraft. The advanced propulsion technology was based primarily on increasing turbine inlet temperatures from 2600° to 3200°R, on increasing engine pressure ratio from 20 to 28, and on the utilization of advanced lighter materials. Application of the advanced technology reduced engine weight by 29% and decreased specific fuel consumption by 10%.

Figure 9 also shows the results for the simultaneous application of advanced propulsion technology and advanced structures technology to two VTOL designs. The predictions were DOC reductions of 23% for lift fan VTOL

APPROACH	DESCENT TAN γ	$\dot{u}$	Δt	LEVEL FLIGHT TAN γ	$\dot{u}$	Δt	TOTAL TIME
——	.176	.088	91	—	—	—	91 sec
— —	.264	0	30	0	.264	31	61 sec

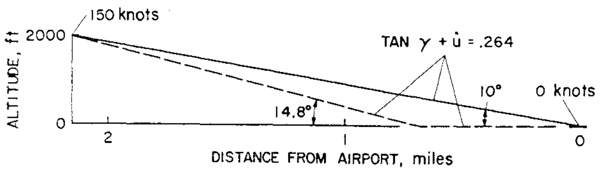

Fig. 11 Landing approach profiles for VTOL aircraft.

aircraft and 17% for propeller VTOL aircraft. The major improvement in structures was due to the use of fiber reinforced composite materials. For example, an advanced wing structure was composed of 39% boron composite structure and 61% aluminum which resulted in a wing weight 24% lighter than an all aluminum wing.

Based on these results, 1980 technology will make V/STOL commercial transports increasingly attractive. It is probable that advanced technology will benefit jet VTOL concepts more than propeller VTOL concepts.

Effect of nonproductive time and landing approach considerations

Results presented in Fig. 10 for a VTOL and a STOL 60 passenger aircraft operating over a 100-mile stage length show that direct operating costs are extremely sensitive to the lost or nonproductive time associated with near terminal operations. In fact, reducing nonproductive time from 10 to 4 min reduced the DOC of the tilt wing VTOL aircraft and the turbofan STOL aircraft by 21%. The impact of nonproductive time assumptions on direct operating cost has two very important aspects, namely, 1) appropriate absolute values of nonproductive time must be used in demonstrating the over-all economic feasibility of V/STOL short haul transports and 2) for purposes of comparing various VTOL and STOL aircraft to each other, at least appropriate relative values of nonproductive time must be used. Nonproductive times suggested in the literature vary greatly, ranging from 0 for VTOL concepts to 15 min for STOL concepts. These nonproductive time assumptions have a large impact on the relative attractiveness of VTOL aircraft compared to STOL aircraft. The wide variations in nonproductive time and differing operational techniques suggested in the literature indicate a lack of knowledge of the near-terminal capabilities and operational techniques of V/STOL aircraft. This is an area for fruitful analysis and research in aerodynamics, navigational aids, pilot displays, approach techniques, terminal facilities, etc.

In order to examine the near terminal problems more closely and substantiate the DOC values already presented, a rudimentary analysis was conducted. This analysis exposes some basic facts about near terminal operation which must be recognized and considered in a systems analysis. A nonproductive time of about 10 min, as used for all aircraft in this study, is representative of approach patterns permitted by present day navigational aids and aircraft. The following analysis assumes that improved navigational

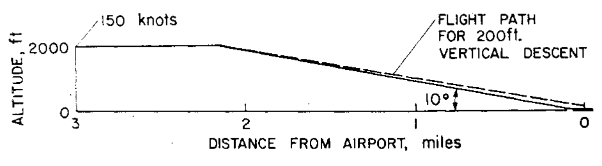

Fig. 12 Landing approach profiles from point 2000 ft above and 3 miles away from runway.

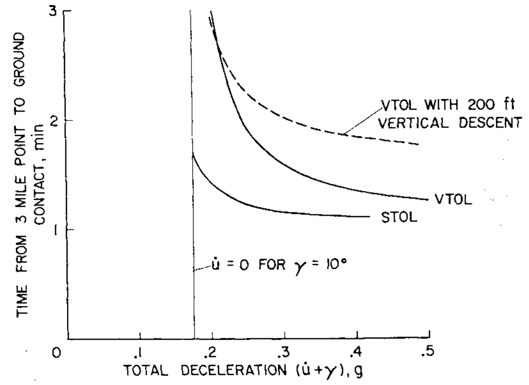

Fig. 13 Sensitivity on deceleration on time for descent.

aids and terminal facilities will be available to expedite the aircraft to a point 2000 ft above the ground and some arbitrary distance from the airport. We can then define a minimum time to descend to the airport. Parametric study shows that minimum time is obtained by utilizing the total deceleration capability of the VTOL aircraft for decelerating in level flight at the elevation of the landing pad (since vertical descents over the landing pad are time consuming). To demonstrate, starting from a point 2000 ft above and about 2 miles from the airport, two landing approach profiles are shown in Fig. 11. One approach is for a constant descent angly, γ, of 10°, starting from an airspeed of 150 knots at 2000 ft and terminating at 0 knots at the landing pad. This approach requires a minimum average total deceleration of 0.26 g. Total deceleration is the sum of the equivalent deceleration required to descend along the flight path at constant velocity, tanγ, plus the actual deceleration along the flight path, $\dot{u}$, required to decrease airspeed. The time required for the approach on a 10° glide slope is 91 sec. The second approach consists of two segments, namely a constant 150 knot approach speed along a 14.8° descent path (tanγ = 0.26) plus a level flight deceleration to 0 knots (using $\dot{u}$ = 0.26). This second approach requires a total of 61 sec. Thus, the time required for these two approach profiles differs by 30 sec. Unfortunately, the landing approach profile corresponding to minimum time is impractical from the standpoint of safety and noise, and other operational considerations. However, the above example suggests that the minimum practical time for descent from a given point to the landing site will be achieved by decelerating the aircraft during the final phase of the approach while at the minimum descent angle permitted by operational considerations such as safety and noise.

Specific landing approach profiles for VTOL and STOL aircraft that were selected for evaluation are shown in Fig. 12. Rather than an absolute minimum time, a 10° descent angle was selected to provide near minimum time and still have adequate terrain clearance and reduced noise levels. An alternate VTOL flight path which terminates with a 200-ft vertical descent was included for comparison. The starting point 2000 ft above the runway was moved to a point 3 miles from the runway so that a level flight segment at 2000-ft altitude could be included to accommodate aircraft with low total deceleration capabilities. For the alternate VTOL approach, the time for the 200-ft vertical descent segment was assumed to be 30 sec. The sensitivity of total deceleration capability on time required for the approaches is shown on Fig. 13. A minimum deceleration boundary exists since a deceleration capability of at least 0.17 g is required just to achieve the 10° descent path at constant airspeed. The results indicate that the times required for the descent vary from about 1 to 3 min and that deceleration capability should be at least 0.25 g for STOL aircraft and at least 0.3 g for VTOL aircraft. The alternate VTOL approach terminating with a vertical descent requires about 25 addi-

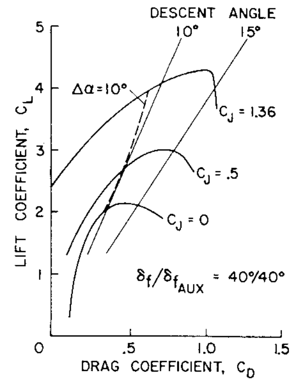

Fig. 14 Lift-drag polars for turbojet STOL model with externally blown flap.

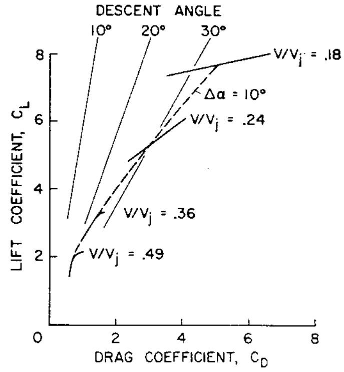

Fig. 15 Lift-drag polars for lift fan VTOL model with fan exit vanes deflected −20°.

tional sec for VTOL aircraft with 0.3 g deceleration capability. STOL aircraft required from about $1\frac{1}{2}$ min (for 0.2 g) to $\frac{1}{2}$ min (for 0.3 g) less time than VTOL aircraft. In most cases the air portion of the nonproductive time will be less for the STOL than for VTOL because the STOL does not have to slow down as much.

The total deceleration capabilities of particular VTOL and STOL aircraft differ greatly as illustrated in Figs. 14 and 15. Lift-drag polars for a turbojet STOL model that utilized externally blown flaps are shown in Fig. 14 for three thrust coefficients, Cj. The dashed line is for an angle-of-attack margin 10° from the angle of attack for maximum lift. The total deceleration capability of this STOL aircraft corresponds to about a 10° descent angle or about 0.17 g. Lift-drag polars for a lift fan VTOL model with fan exit vanes deflected 20° forward are presented in Fig. 15 for several flight velocity/fan exit velocity ratios. The total deceleration capability of this VTOL aircraft corresponds to an average of about 30° descent angle or 0.58 g, which is probably beyond passenger acceptance limits. If we compare the airborne portion of nonproductive time for these two aircraft types, we see that in spite of the difference in deceleration capability, the STOL time is only 24 sec longer than the VTOL time. Even so the deceleration capability of the turbojet-externally blown flap STOL concept (about 0.17 g) should be improved to minimize descent time. This statement also applies to the propeller STOL (deflected slipstream) concept and the turbojet-jet flap STOL concept. The deceleration capability of the propeller VTOL (tilt wing) concept (about 0.2 g) should also be improved. As indicated in Fig. 13, a tilt wing VTOL with 0.2-g deceleration requires about an additional $1\frac{1}{2}$ min for the descent compared to a lift fan VTOL concept using 0.3-g deceleration.

The effect of total deceleration capability on nonproductive time is illustrated in Fig. 16. The values of nonproductive time are based on the descent times from Fig. 13 and assumptions for times required for engine start and check-out, taxi, take-off, and landing ground roll as shown in Fig. 16. From this analysis it is concluded that nonproductive times for VTOL and STOL aircraft will be about the same. The DOC of VTOL and STOL aircraft should therefore be based on similar nonproductive times. This conclusion is somewhat sensitive to the actual values assumed for ground time, but it is unlikely that the nonproductive time difference between VTOL and STOL aircraft would exceed 3 min, which is much less than that assumed in some studies.

Concluding Remarks

Comparison of aircraft indicate that:

1) Rotor, propeller, lift fan, and lift jet VTOL concepts are competitive to the degree that research on all concepts must be continued before mission boundaries can be defined or concepts eliminated. The particular lift jet VTOL design of this study was the least promising type because of very high near field perceived noise levels. Rotor and propeller VTOL concepts are the most promising for 60 passenger aircraft operating over 100-mile stage lengths. Lift fan VTOL concepts are the most promising for 120 passenger aircraft operating over 500-mile stage lengths.

2) For a design field length of 2000 ft, propeller, lift fan, and turbojet STOL concepts are competitive in terms of design gross weight and direct operating cost. For a design field length of 1000 ft, the most promising STOL concepts are the propeller, lift fan, and turbojet types in that order. Furthermore STOL aircraft are much lighter and cheaper to operate than VTOL aircraft.

3) Major efforts must be expended to decrease near field and/or far field perceived noise levels generated by all VTOL and STOL aircraft. Public acceptance criteria and measured noise levels of representative VTOL aircraft are badly needed. Due to the rapid attenuation of high frequency noise with distance, the noise generated by lift fan VTOL aircraft may be as acceptable to a community as that generated by low disk loading VTOL aircraft.

Analysis of near-terminal operations indicates that:

1) Nonproductive time assumptions have a large impact on direct operating costs for short stage lengths. Therefore, a large research effort is needed to determine aircraft characteristics, navigational aids, pilot displays, operational techniques, and terminal facilities required to minimize lost time.

2) Analysis indicates that VTOL and STOL aircraft should be compared on the basis of nearly equal nonproductive times pending flight demonstrations.

3) Aircraft deceleration capability can have a pronounced effect on nonproductive time. For example, based on the 10° approach profile of this paper, the descent time of a tilt wing VTOL aircraft with 0.2-g total deceleration ($\tan\gamma + \dot{u}$) capability is about $1\frac{1}{2}$ min greater than the descent time of a lift fan VTOL aircraft using 0.3-g total deceleration.

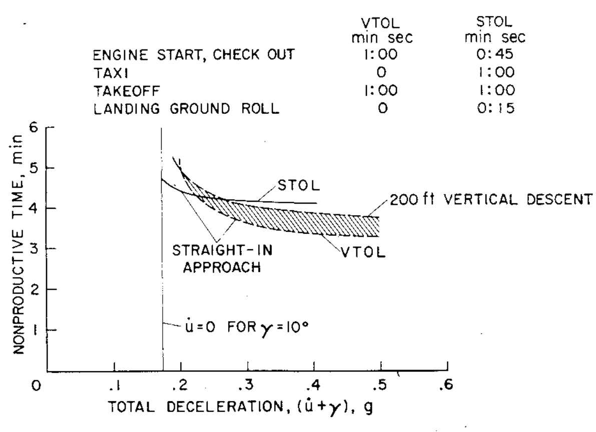

Fig. 16 Effect of total deceleration capability on nonproductive time.

References

[1] Fry, B. L. and Zabinsky, J. M., "Feasibility of V/STOL Concepts for Short-Haul Transport Aircraft" CR-743, 1967, NASA.

[2] Marsh, K. R., "Study on the Feasibility of V/STOL Concepts for Short-Haul Transport Aircraft," CR-670, 1967, NASA.

[3] "Study on the Feasibility of V/STOL Concepts for Short-Haul Transport Aircraft," CR-902, 1967, NASA.

[4] "Study of Aircraft in Short Haul Transportation Systems," CR-986, 1967, NASA.

[5] "Technical and Economic Evaluation of Aircraft for Intercity Short-Haul Transportation," Federal Aviation Agency-Air Defense System-74, Vol. I, II, and III, April 1966.

[6] "A System Analysis of Short-Haul Air Transportation," TR 65-1, Flight Transportation Laboratory, Massachusetts Institute of Technology, Aug. 1965.

JAN.-FEB. 1970 J. AIRCRAFT VOL. 7, NO. 1

Dynamic Stability of V/STOL Aircraft at Low Speeds

H. C. CURTISS JR.*
Princeton University, Princeton, N.J.

Various aspects of the longitudinal stability characteristics of propeller driven V/STOL aircraft at low speeds are described. Data on three tilt-wing configurations and a quad ducted propeller aircraft, from various experiments conducted with dynamic models, are presented and discussed. In the majority of flight conditions investigated, it was found that the measured transient motions could be satisfactorily approximated by linearized equations of motion. The stability derivatives determined from these experiments are presented, and the general trends of the stability derivatives in transition are examined. The linearized modes of motion typical of low-speed flight in transition are described. In certain of the low-speed flight conditions, nonlinearities are present, arising from the character of the static stability derivatives. These nonlinear motions are discussed. Stability derivatives from a single rotor and a tandem rotor helicopter are also presented for comparison purposes. It is noted that the helicopter has better stability characteristics in hovering flight than either the tilt-wing or quad duct vehicles. This is due to the fact that the helicopter has a smaller velocity stability and larger damping in pitch than the V/STOL vehicles of similar gross weight.

Nomenclature

c = mean aerodynamic chord, ft
g = acceleration due to gravity
I = moment of inertia in pitch
i_d = duct incidence ($i_d = 90°$ in hover)
i_T = thrust line incidence ($i_T = 90°$ in hover), equivalent to wing incidence or duct incidence
i_w = wing incidence ($i_w = 90°$ in hover)
L_0 = trim lift, lb
M = pitching moment, ft-lb, positive nose up
$M_u, M_w, M_q, M_{\dot{w}}, M_\alpha$ = stability derivatives, rate of change of pitching moment divided by moment of inertia with variable indicated in subscript
$M_\delta, M_\beta, M_{i_T}$ = control input terms, rate of change of pitching moment divided by inertia with control indicated in subscript
q = fuselage pitch rate ($\dot{\theta}$)
U = flight velocity, fps
U_0 = trim flight velocity, fps
u = horizontal perturbation velocity, stability axes, positive for forward motion of aircraft
w = vertical perturbation velocity, stability axes, positive for downward motion of aircraft
X = horizontal force, stability axes, positive forward
$X_u, X_w, X_q, Z_\alpha, Z_u, Z_w, Z_q$ = stability derivatives, rate of change of force divided by mass with variable indicated in subscript
$X_\delta, X_\beta, Z_{i_T}, Z_\delta, Z_\beta, Z_{i_T}$ = control input terms, rate of change of force divided by mass with control indicated in subscript
Z = vertical force, stability axes, positive downward
α = angle of attack ($\alpha \doteq w/U_0$), rad
α_{0L} = angle of zero lift, rad
β = propeller blade angle, rad
δ = longitudinal stick deflection
θ = fuselage pitch angle, positive nose up
σ = real part of characteristic root, per sec
ω = imaginary part of characteristic root, per sec
$(\dot{\ })$ = differentiation with respect to time

Presented as Paper 69-194 at the AIAA/AHS VTOL Research, Design, and Operations Meeting, Georgia Institute of Technology, Atlanta, Ga., February 17–19, 1969; submitted March 14, 1969; revision received August 7, 1969. The experimental research conducted at Princeton University was performed under the sponsorship of USAAVLABS Contracts DA 44-177-AMC-8(T) and DAAJ 02-67-C-0025 with financial support from the United States Air Force Flight Dynamics Laboratory and the U.S. Naval Air Systems Command.

* Associate Professor, Department of Aerospace and Mechanical Sciences. Member AIAA.

Introduction

All types of V/STOL aircraft have encountered various stability and control problems at low speeds. It is the objective of this paper to discuss in over-all terms some features of the longitudinal dynamic characteristics of two types of V/STOL aircraft, the tilt-wing and the quad duct configuration.

It is important to note two aspects of the experimental determination of the stability derivatives of V/STOL aircraft that are often overlooked. First, is the fact that forces and moments due to the propellers, as well as those arising from the interaction of the propeller flowfield with other parts of the aircraft, are of significance. Therefore, it is important to conduct experiments to determine the horizontal velocity (or advance ratio) derivatives (X_u, Z_u, M_u). This is in con-