Proprotor Short-Haul Aircraft—STOL and VTOL

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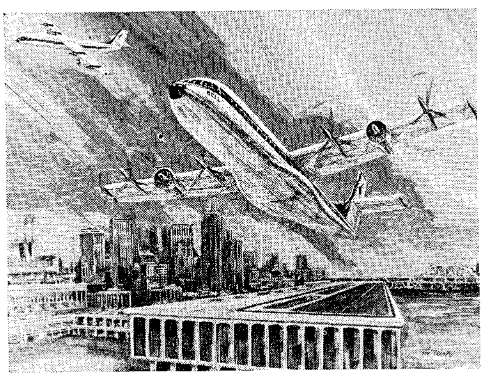
This Paper examines the characteristics of a series of aircraft for the short-haul market. The low disk-loading propeller/rotor is applied to a propeller-STOL (short takeoff and landing) transport, a fan jet-STOL transport, a tilt rotor-VTOL (vertical takeoff and landing) transport, and a fan jet-VTOL transport. The resulting aircraft concepts have an efficient low-speed, lift-propulsion system, and can operate with low noise and air pollution from metropolitan V/STOL airports. This paper concentrates on the first two STOL configurations. For low and medium disk-loading STOL aircraft, the gimbal propeller has important operational advantages compared to the rigid propeller. At takeoff, longitudinal cyclic pitch can be used to produce an upward force to reduce tail download requirements. For takeoff and landing in severe crosswinds, significant side force can be produced by means of lateral cyclic pitch. In cruise, the gimbal propellers give a significantly better ride than rigid propellers. In the approach, longitudinal cyclic pitch can control glide-slope height precisely. A STOL transport with a cruise speed of 400–500 knots (wing loading near 75 psf) could use the deflected slip-stream concept and medium disk-loading (30 psf), folding propeller/rotors (Frontispiece). Propulsion-system power requirements in both the cruise and low-speed mode would be supplied by convertible fan-shaft engines. This Paper shows the power balance between a twin fan-jet cruise requirement of 475 kt and an engine-out critical maneuver requirement at 60 knots.



Frontispiece Folding propeller fan jet STOL aircraft.

Nomenclature

A_w = wing area, flaps retracted, ft^2
c_w = wing chord, flaps retracted, ft
D = propeller diameter, ft
q = dynamic pressure, freestream, psf
C_X = longitudinal force coefficient, wind axes = (drag—thrust)/$A_w q$
C_z = total lift-force coefficient, wind axes = total lift/$A_w q$

Introduction

PRESENT congestion at major jetports can be alleviated by the provision of a separate air transportation system for short-haul travelers. For systems from city center to city center, this means terminals in densely populated areas and a stringent set of requirements for minimum land area, minimum air pollution and noise annoyance. The land area restraints call for STOL and VTOL aircraft. The trend, however, is for these aircraft to use much higher levels of installed engine power than conventional aircraft. This brings them into conflict with the noise and air pollution restraints. To use as little land as possible yet keep pollution and annoyance as low as possible, the efficiency of the low-speed, lift-propulsion system of VTOL/STOL aircraft must be maximized.

In the United States, passengers traveling distances of 100–400 miles comprise 40% of the total passenger volume and are estimated to reach 100 million annually around 1975.[1] The provision of a separate air transportation system for this short-haul market is predicted to reduce congestion at present jetports, thereby saving money for the airlines and saving time for the passengers. It is considered that STOL and VTOL aircraft will eventually fly complimentary missions in the short-haul market. The STOL aircraft will fly between metroports where 2000 ft of runway is available. These metroports will be fed by various combinations of ground, marine, amphibian, and air transport (helicopters) from city center and suburban terminals. High-speed VTOL aircraft such as tilt proprotor and folding proprotor aircraft will be a natural addition to link a metroport in one city with a high-volume, restricted ground area terminal in another city. In addition, where ground space is not available for a 2000-ft runway, direct VTOL service can eventually be provided between a high-volume suburban terminal in one city and a suburban terminal in another city.

Application of Rotary-Wing Technology to Short-Haul Aircraft

Shaft-driven, rotary-wing technology has had a wide application because it is the most efficient system to generate thrust at low speeds for relatively low weight and power expenditure. In the VTOL area, the tilting proprotor concept was explored by the Bell XV-3 in 1958–1960, the application to a tilt rotor VTOL transport was discussed by Wernicke and Edenborough,[2] and the application to a folding proprotor VTOL was discussed by DeTore and Gaffey.[3] It is considered that this technology also has an important application to the STOL field. As shown in Fig. 1, the two categories of STOL and VTOL both have a low disk-loading configuration in which the propeller/rotors are used for both takeoff and landing, and cruise up to 250–400 knots. For higher speeds, they both have a medium disk-loading configuration in which

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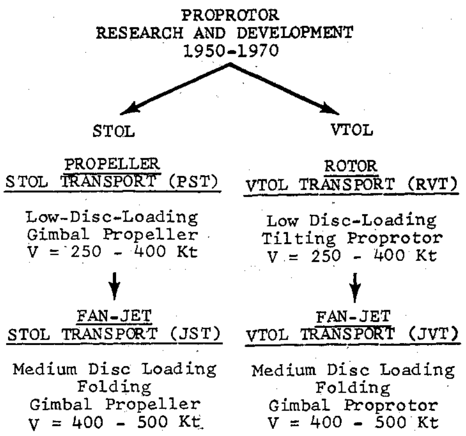


Fig. 1 Gimbal proprotor aircraft; chronology and application.

the propeller/rotors are used for takeoff, landing, and speeds up to 200 knots. For high-speed cruise they are stopped and folded, and fan-jet engines provide efficient propulsion at speeds of 400–500 knots. It is envisioned that eventually all four categories of aircraft could be flying complementary missions of a short-haul system.

Features of Gimbal-Propeller Rotor Systems

In the application of rotary-wing technology to STOL, the usual cost-effectiveness questions must be answered. The technology of the gimbal hub and cyclic blade-pitch control must be attractive from over-all considerations which include noise, system weight, performance, ride quality, control, and reliability.

Noise

The selection of a low-design propeller tip speed at takeoff (700–750 ft/sec) and the utilization of the highest possible lifting efficiency (low disk-loading propellers) should ensure acceptable noise characteristics. The widely suggested criteria of 95 PNdb at 500 ft is a reasonable design goal.

Rotor System Weight

Weight estimating methods at Bell were used to compare gimbal-hub and rigid-hub system weights. As shown in Fig. 2, the gimbal-hub system is estimated to weigh less in the disk-loading range from 5–30 psf. This is basically because of the gimbal system relieving the rotor shaft of large hub moments.

Ride Quality

For flight in the propeller/rotor regime, the in-plane forces developed by the blades in rough air are a significant factor for ride-quality evaluation. The gimbal-hub system, which has blade-flapping freedom, has a smaller force response to an

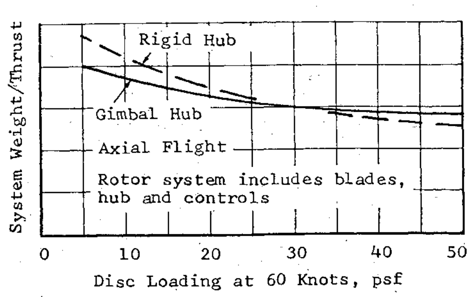


Fig. 2 Rotor system weight comparison.

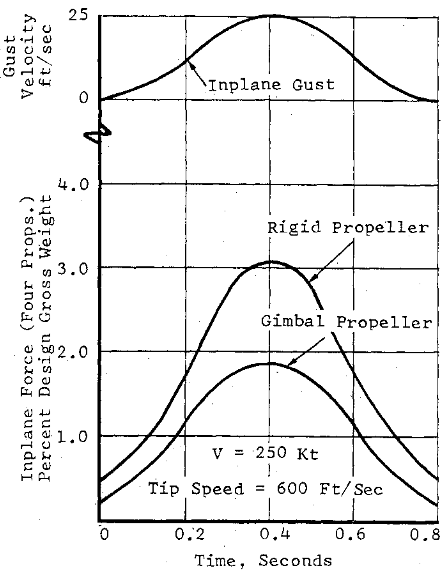


Fig. 3 Gust sensitivity comparison; typical cruise.

in-plane gust than a rigid-hub system, and thus would provide a softer ride for passengers. At a typical cruise condition, as shown in Fig. 3, the gimbal-hub system develops in-plane forces only 60% that of the rigid-hub system.

Control in Crosswind Landings

Metroports designed for STOL operations are currently planned with only one runway because of the anticipated ground area limitations near city centers. STOL aircraft will thus need to be designed with special crosswind capability. For typical 60-knot approach speeds, desired crosswind capability up to 35 knots has been specified.[4] This requires, for a typical STOL aircraft, a bank angle around 10° or a crab angle around 35°. The former is disliked by passengers and the latter by pilots, especially in IFR conditions. A crosswind landing gear is a possible solution, but in wet or icy conditions reverse thrust could not be applied until after the "decrab" sequence.

The combination of lateral cyclic blade-pitch and a gimbal hub was investigated and found to offer interesting potential. The application of lateral cyclic pitch to all four gimbal propellers of a STOL transport produces a side force for virtually no increase in required power, which enables an approach to be made with zero bank and zero crab. After touchdown, the reversed-thrust forces can also produce a side force (by reversed cyclic pitch) to maintain the aircraft on the runway centerline during deceleration.

An analysis of a crosswind approach for a 100,000-lb gimbal-propeller STOL aircraft is shown in Fig. 4. The aircraft is flying down a $7\frac{1}{2}°$ glideslope at 60 knots with a 30-knot crosswind from the left side. The two inboard propellers are developing the prime thrust (15% gross weight) as a result of differential prop-pitch selection (transparency mode). The outboard propellers are developing a nose-left moment to trim the fuselage-yaw moment, and this enables the rudder to reduce the fin force from 6500 lb to zero, in order to reduce the down-crosswind force. Lateral cyclic pitch has been applied to all four propellers, and this changes the in-plane force from a 5000-lb force down crosswind (which would have been produced by rigid propellers) to a 4000-lb force up crosswind. This force balances the fuselage side force. The left outboard propeller is operating with lateral cyclic pitch applied to maintain its resultant thrust vector axially; however, if desired, it could also produce a side force. Ailerons or spoilers balance the roll moment. Thus the total side force has been reduced from 15,500 lb to 4000 lb. The bank angle for a straight-in

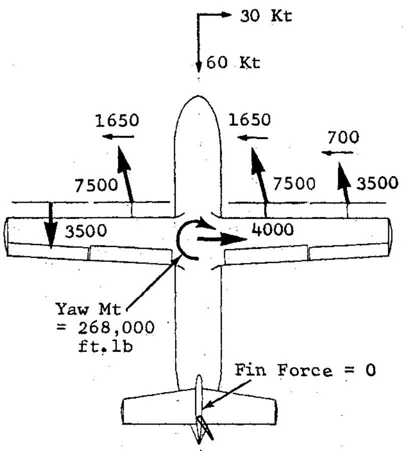


Fig. 4 Cross-wind approach; gross weight = 100,000 lb; 1) forces shown in pounds. 2) maximum thrust capability per propeller = 15,000 lb.

approach has been reduced from 9° to zero. At touchdown, as the collective pitch on all props is reversed, the lateral cyclic pitch is reversed (by mechanical coupling), and a side-force trim is maintained during deceleration. The differential thrust on the outboard propellers is also maintained by a mechanical coupling to retain a yaw-moment trim. The pilot thus has a powered yaw-moment and side-force control available during both the approach and ground maneuvers.

It should be noted that after setting up a particular cyclic trim, the aircraft can still be flown normally with bank or crab for greater crosswind capability if required. For a go-around, if all propellers were advanced to takeoff thrust with full lateral cyclic pitch, the aircraft would drift in that lateral direction but could be held straight by an opposite bank until the cyclic pitch control was returned to neutral.

A rigid propeller with cyclic pitch would not be as effective as the gimbal propeller, since it would primarily produce a moment rather than a side force.

Other STOL configurations, such as the augmentor wing, could have increased design crosswind capability by the provisions of side thrust; however, this would generally require additional ducting and probably bigger engines.

Fuselage Rotation at Takeoff

The use of longitudinal cyclic pitch on all four propellers has the potential to produce an upload and a nose-up fuselage pitching moment to shorten the ground roll and/or increase the payload. Experimental verification is required of this and wing effects, in and out of ground effect.

Glide-Slope Height Control

The prime height control in a typical STOL aircraft in approach mode is achieved by power modulation. A precise height control system can be provided by the use of longitudinal cyclic pitch on the inner two propellers. In approach mode, these would be operating with a reasonably large thrust vector because of outboard propeller transparency,[5] and so tilting the vector by cyclic pitch would provide a change in the vertical force vector.

Maintainability and Reliability

The gimbal-hub system has been in production on the Bell Model 47 for over 25 years. The gimbal hub is checked every 1200 hr, generally reinstalled, and it usually achieves a life of at least 5000 hr. Thus for a gimbal-propeller system operating primarily in axial flow and in cleaner air, a TBO time of 5000–10,000 hr would be anticipated. For a folding propeller/rotor system, used for approximately 25% of the flight time, a TBO time of 20,000 flight hours would be a reasonable target.

Performance Characteristics of Deflected Slip-Stream STOL Aircraft

To maximize productivity of STOL aircraft, emphasis must be placed on the low-speed, lift propulsion system. Span loading should be as low as possible, but consistent with cruise requirements for maximizing L/D. The propulsive efficiency of the low-speed propulsive system should be as high as possible to minimize noise and to provide balanced power conditions between low-speed and cruise requirements. For a deflected slip-stream STOL aircraft at takeoff, propulsive efficiency increases as the disk loading of the propeller system is reduced. The question is, for a given wing-span loading, what is the minimum disk loading which will provide the required incremental powered lift for the low-speed critical maneuver condition?

The extensive wind-tunnel research conducted by M. P. Fink et al. of NASA-Langley[6–9] since 1964 provided a data base to determine basic wing-propeller lift characteristics. Results for a typical deflected slip-stream lift system in takeoff mode at 60 knots are shown in Fig. 5. This system comprises 1) single Fowler flap, 40% chord extension, deflection = 40°; 2) leading-edge slat, 19% chord, deflection = 20°; 3) wing span not greater than 1.3 × propeller diameter × number of props; 4) wing thickness, 18%.

A significant trend is that of the increase in wing-lift coefficient attained as wing-chord/propeller-diameter ratio was reduced. In other words, for a particular diameter propeller and a particular disk loading, the higher the wing aspect-ratio, the higher the maximum achievable lift coefficient. This trend was also reported by Smelt and Davies[10] in 1937. A further discussion and comparison with analytical predictions is presented by the author.[11]

It is interesting to note that there are two asymptotic trends appearing in Fig. 5. As the wing-chord/propeller-diameter ratio (c_W/D) becomes very large, the incremental slip-stream lift becomes a smaller fraction of the total lift, and thus all the disk-loading contours approach the basic maximum wing-lift coefficient (which in this case = 3.2). In the other direction, as the wing-chord/propeller-diameter ratio becomes smaller, the wing becomes more effectively buried in the propeller wake. The maximum wing-lift coefficient for a

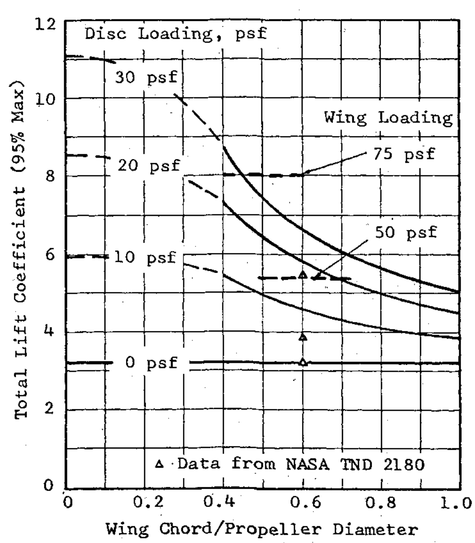


Fig. 5 Wing-propeller lift; takeoff configuration at V = 60 knots.

particular disk loading then asymptotically approaches the basic maximum wing-lift coefficient (3.2) multiplied by the ratio of slip-stream dynamic pressure to freestream dynamic pressure.

The basic wing and propeller proportions can thus be defined using Fig. 5. For a wing loading of 50 psf and a maneuver requirement of 1.3g with one engine inoperative, at 60 knots the maximum wing C_L required is 5.3. This C_L can be achieved by a c_W/D ratio = 0.4 at a disk loading of 10 psf or by other combinations ranging up to c_W/D ratio = 0.9 at a propeller disk loading of 30 psf. A productivity analysis defining the optimum vehicle in this range is presented in a later section of this paper. Similarly, for a higher wing loading of 75 psf, the maneuver C_L requirement at 60 knots is 8.0. This can be achieved by a c_W/D ratio = 0.4 at a disk loading of 25 psf or by other combinations ranging up to c_W/D = 0.6 at a disk loading of 50 psf. The cruise speed and engine-requirement characteristics of these aircraft are also presented in a later section. For a particular mission, the combination for maximum productivity can then be analyzed.

Typical Short-Haul Gimbal-Propeller/Rotor Aircraft

Typical aircraft resulting from the above low-speed lift analysis are shown in Figs. 6 and 7. In each case, a power balance was achieved between critical engine-out low-speed maneuver requirements and a cruise speed close to maximum vehicle productivity for the basic mission.

A gimbal-propeller STOL aircraft is shown in Fig. 6. The propellers provide low-speed lift augmentation and also cruise propulsion in the 250–350-knot speed range. A folding gimbal-propeller STOL aircraft is shown in Fig. 7. The propellers provide low-speed lift augmentation and propulsion up to 200 knots. The propeller system is powered by two convertible fan/shaft engines. At takeoff (at 60 knots), a typical disk loading on the four propellers and two fans is 30 psf. The wing is thus well buried in a slipstream of around

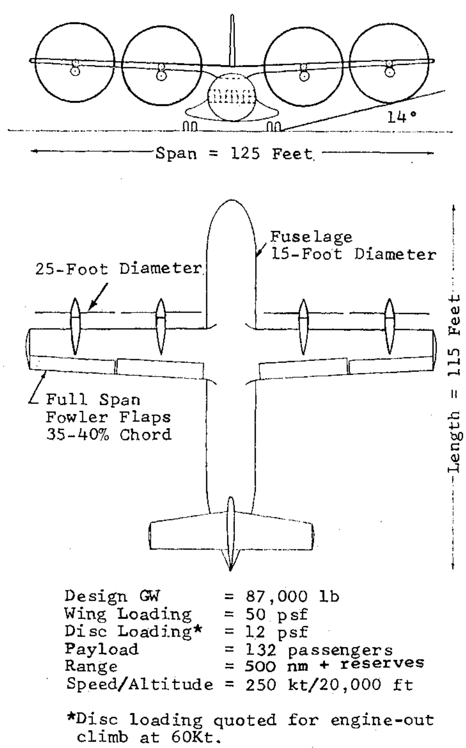


Fig. 6 Gimbal-propeller STOL (PST).

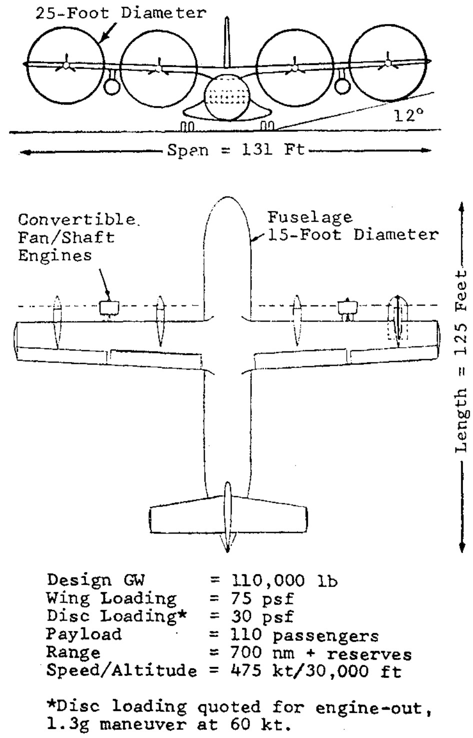


Fig. 7 Folding propeller jet STOL (JST).

115 knots velocity. During the 200-knot climb to cruise altitude, the interconnected propellers are declutched from the engines, stopped, and folded. The fan jets provide efficient cruise propulsion at 400–500 knots. The folded blades, with one above and two below the wing, are estimated to have a low cruise drag. Wind-tunnel testing of similar folding three-bladed rotors for VTOL programs has shown that cruise drag estimates can be based on exposed skin areas. For this STOL configuration, the two blades beneath the wing can be designed to fit streamlined fairings which will minimize exposed blade skin area.

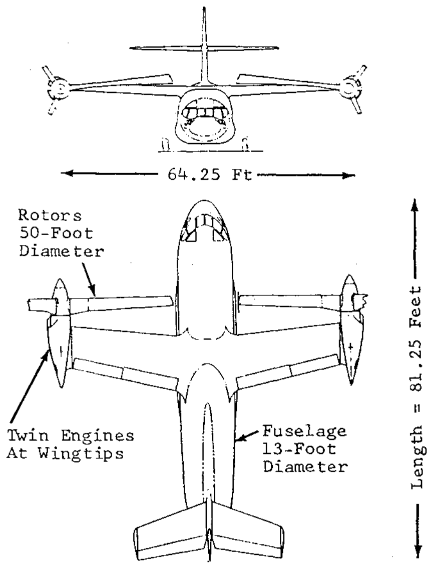
It is significant that the same technology can be applied to achieve VTOL. Figure 8 shows a typical gimbal-hub tilt proprotor VTOL aircraft with cruise capability of 350–400 knots. Figure 9 shows a fan jet-VTOL aircraft utilizing folding gimbal proprotors for efficient VTOL and fan jets for cruise at 400–500 knots.

The VTOL configurations have been well described,[2,3] and so the remainder of this paper will concentrate on the performance and productivity of the two STOL configurations.

Propeller-STOL Transport

The propeller-STOL transport aircraft (Fig. 6) utilizes four interconnected propellers. Most control features and relationships are similar to a typical STOL as described by Marks.[5] The differences, evolved from the lift analysis of Fig. 5, are in the use of low disk-loading gimbal propellers (12.0 psf at 60 knots) and in a high aspect-ratio wing (9.0).

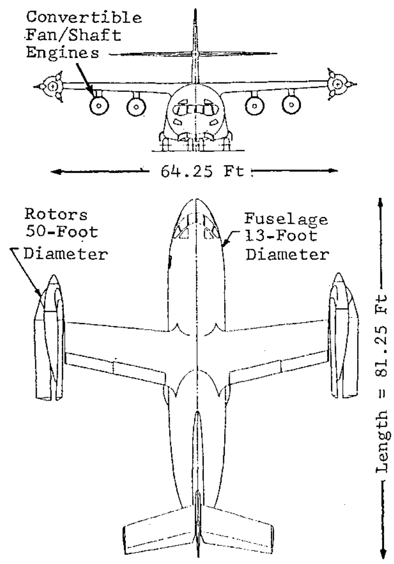
The combination of these provides a capability of 1.3g at 60 knots with one engine inoperative at sea level 95°F. The engine-out climb-gradient is 4.4°, which meets a typical STOL requirement.[4] The lifting efficiency in this climb condition is 14.3 lb/hp, which is higher than any other higher disk-loading solution with the same installed power. The balanced power cruise speed (all engines operating at 90% continuous power) resulting from this engine sizing is 255 knots at 20,000 ft (four-engine design), and 300 knots for a twin-engine design. These speeds are close to the optimum cruise speed for the



Design GW = 60,000 lb
Wing Loading = 85 psf
Disc Loading* = 15 psf
Payload = 68 passengers
Range = 500 nm + reserves
Speed/Altitude = 350 kt/30,000 ft

*Disc loading quoted for engine-out climb at 60 kt.

Fig. 8 Rotor VTOL transport (RVT).



Design GW = 82,500 lb
Wing Loading = 106 psf
Disc Loading* = 21 psf
Payload = 72 passengers
Range = 700 nm + reserves
Speed/Altitude = 400 kt/30,000 ft

*Disc loading quoted for engine-out climb at 60 kt.

Fig. 9 Folding-proprotor jet VTOL (JVT).

wing loading of 50 psf, and are adequate for short ranges of 100–250 miles.[4]

Thus this low disk-loading approach ensures minimum installed power and, in combination with low-propeller tip speeds, ensures low noise levels in the terminal areas. The diameter selection of low disk-loading propellers is limited by ground clearance which, in turn, is provided by fuselage diameter. The short-haul requirements for rapid passenger loading and unloading led to the selection of two aisles and six-abreast seating. This specified a fuselage diameter of 15 ft, and the selection of a high wing enabled propeller diameter to be as large as 25 ft.

The disk loading of these large propellers is 12.0 psf at takeoff (60 knots) and from weight considerations alone, as shown in Fig. 2, the gimbal-hub system is advantageous. The selection of the gimbal hub and the provision of cyclic pitch thus provides the control and operational features as discussed earlier.

The resulting STOL vehicle is predicted to offer the lowest possible aircraft operating cost in this weight class for ranges of 100–250 miles, and also to provide the pilot with significant new control capability. A productivity analysis was made within the range of propeller disk-loading from 10 psf to 30 psf, and the results are discussed next.

Productivity Analysis of Propeller STOL Aircraft

The aircraft productivity trend as a function of propeller disk loading was analyzed. This required the analysis of propulsive efficiencies, system weights, and balanced power cruise speeds.

The propulsive efficiency trend vs disk loading for takeoff and cruise is shown in Fig. 10. For a particular thrust, the blade area is fixed, and as the disk loading increases (diameter reducing), the induced power increases. The trend is stronger at takeoff than cruise, but in each case the lower the disk loading, the higher the propulsive efficiency.

The lifting efficiency analysis began with a disk loading of 12 psf and four 25-ft propellers at 60 knots at sea level, 95°F. This sized the wing span (125 ft) and the power required (6060 hp from three engines). Wing-chord to propeller-diameter ratio was then varied from 0.5–0.7 holding wing span and power constant. As the wing chord increased, the achievable wing-lift coefficient reduced (see Fig. 5), the wing area (and gross weight) increased, the aspect-ratio reduced, and total drag increased. Finally, when thrust available equalled total drag in 4.4° climb, the gross weight solution for that disk loading was obtained. For 12 psf disk loading, the wing-chord/propeller-diameter ratio was 0.57 and gross weight was 87,000 lb (Point Design I). The lifting efficiency was thus 14.3 lb/hp.

This method was repeated for disk loadings of 18.3 psf and 22.5 psf, holding wing span and installed power constant. At these higher disk loadings, the propeller diameter and thrust were smaller, and a smaller fraction of the wing span was immersed in the propeller wake. The gross weight solutions

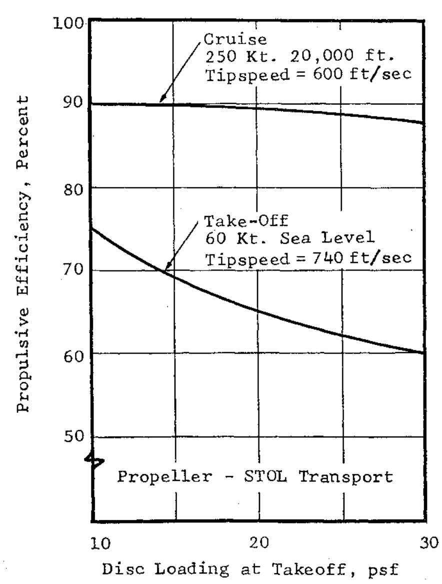


Fig. 10 Propulsive efficiency vs disk loading.

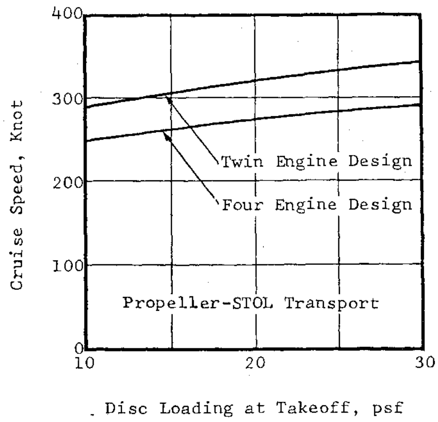


Fig. 11 Balanced power cruise speeds, alt = 20,000 ft.

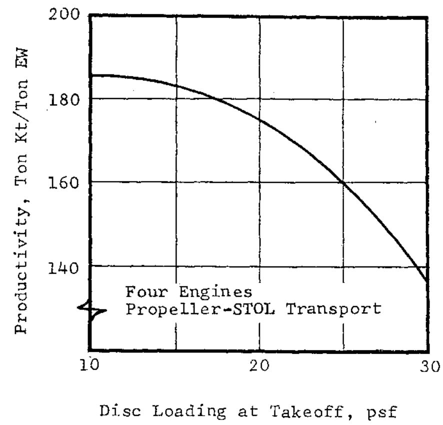


Fig. 12 Productivity variation with disk loading.

were 79,000 lb (Point Design II) and 72,200 lb (Point Design III), respectively. For each solution, the drag was checked to ensure that a 1.3g sustained maneuver could be achieved with one engine inoperative.

Thus the lifting efficiency increased as disk-loading decreased. For Point Design I at a disk loading of 12 psf, the lifting efficiency of 14.3 lb/hp can be compared to the higher disk-loading STOL aircraft[5] which had a lifting efficiency around 10 lb/hp under the same conditions. This increase in lifting efficiency was thus achieved by the optimization of disk loading and wing-aspect ratio.

The three point-designs were then analyzed to determine the trend of the empty weight ratios with disk loading. Bell weight estimating methods were used. As the disk loading reduced, for a constant power rating, the design torque increased and the propeller and transmission system weight increased. However, because of the gross weight increasing at a faster rate, the empty weight fraction actually reduced. The empty weight fraction for the low disk-loading Point Design I STOL aircraft, for a 1973–1975 design period, was estimated to be in the band 0.50–0.55.

Balanced power cruise speeds were then determined using the power as dictated by takeoff requirements. These are shown in Fig. 11 for both four-engine and twin-engine designs.

Pay-load capability was then determined for a typical STOL mission.[4] The mission range was 500 naut miles with reserves. The productivity, referring to empty weight, is shown in Fig. 12 and shows that maximum productivity occurs in the range of disk loading from 10–15 psf. This also is a strong parameter to indicate a similar reduction in direct operating costs.

Folding Propeller Fan-Jet STOL Transport

For longer ranges than that of the propeller-STOL transport, higher speeds are desirable. The longer-range markets suggested for STOL include New York to Atlanta (760 miles), New York to Chicago (725 miles), and Los Angeles to San Francisco (350 miles). For ranges of 250–800 miles, cruise speeds of 400–500 knots are desirable to hold trips under 2 hr.

These cruise speeds require fan jets with bypass ratios of 6–10. Thus the folding propeller aircraft (Fig. 7) becomes a candidate. Other candidate configurations are the augmentor wing and the externally-blown flap as discussed by Wick and Kuhn.[12] In comparison with these, the folding-propeller configuration has a more efficient system to convert engine power into low-speed thrust. For a high-aspect ratio wing (11.6), Fig. 5 indicates that the necessary maneuver C_L of 8 can be achieved with a disk loading of 30 psf. This ensures a 1.3g capability with a wing loading of 75 psf at 60 knots. The weight of each system for the same performance and control should therefore be compared closely. A detailed comparison is beyond the scope of this paper, but a preliminary estimate indicated that the empty weight fraction of the folding propeller-STOL concept, for a 1973–1975 design period, would be in the band 0.55–0.60. On the same preliminary basis, the other two concepts are considered comparable. The equivalent CTOL (advanced technology twin fan jet) is estimated to be 0.45–0.50.

In the performance area, an over-all comparison of low-speed lift-thrust characteristics was made. The twin fan jets of the folding propeller-STOL aircraft of Fig. 7 were sized for cruise at 475 knots at 30,000 ft. The cruise L/D was 8.1, wing loading was 75 psf, and design gross weight was 110,000 lb. Using convertible fan/shaft engine data, the engine output at low speeds was determined. The installed static thrust/gross-weight ratio with both fan jets operating (propellers folded) was 0.58 (sea level, standard day). The shaft horsepower available at sea level 95°F was 19,100 hp/engine (30-min rating). With the power of one engine applied to four 25-ft-diam propellers, the thrust/weight ratio at 60 knots was 0.54 and disk loading was 30 psf, thus meeting the low-speed maneuver requirement.

Low-speed lift-thrust characteristics with one engine inoperative were then determined for propeller systems of various efficiencies (disk loading was varied). The disk area of the propellers can thus be considered as the exit area of a low-speed propulsive device. Engine power, wing span, and wing aspect-ratio were held fixed.

The exit area of the propulsive device was considered to be uniformly distributed over the wing span. As disk loading increased from 30 psf the propulsive efficiency fell and, for a fixed power, the propulsive exit area reduced. Figure 5 provided a data trend to determine maximum wing C_L, which also fell with propulsive efficiency. The drag was calculated by simple momentum methods which allowed for the wing-profile drag and over-all wake deflection. Trends are shown in Fig. 13. Results indicate that for a propeller propulsive efficiency of 60% at 60 knots (disk loading = 30 psf), a C_z of 8 can be achieved for the 1.3g maneuver, and a positive thrust margin exists. This can be used for a horizontal acceleration of around 0.15g or for a climb angle of around 7½°. The propulsive efficiency contour of 45–50% corresponds generally to the augmentor wing as described by Kuhn,[13] and the 20% contour corresponds to the externally-blown flap as described by Wick and Kuhn.[12] These trends predict that the augmentor wing and the externally-blown flap concept cannot achieve the required low-speed performance with a twin-engine design and one engine inoperative. They thus require four engines with attendent higher operating costs. Or alternatively at the same level of installed power the folding propeller-STOL concept is able to lift a higher gross weight and probably a higher payload.

This folding propeller concept has some unusual characteristics. Firstly, it can be designed to meet the 1.3g maneuver

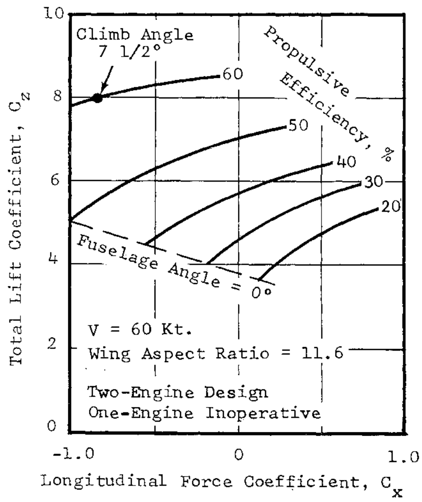


Fig. 13 Fan-jet STOL aircraft lift-thrust characteristics takeoff configurations.

requirement at 60 knots with one engine out as described above. Secondly, it can probably also be designed to achieve 1g flight (straight and level) at 60 knots with any one propeller inoperable and feathered. In this case, the fan on the dead propeller side would be increased in thrust to trim out the yaw moment. Thirdly, a fan failure at takeoff (fan feathered to flat pitch and still rotating) would not present a large problem, since the propellers would be developing the prime takeoff thrust. Fourthly, the aircraft would have extremely high performance with all four propellers and both fans operating. The lift at the beginning of the takeoff roll could be as high as 55% of gross weight, and lift-off could occur after ground rolls of less than 200 ft.

For the folding propeller STOL, if higher cruise speeds or lower aspect-ratio wings are required, the design disk loading can be increased. Figure 14 shows that if the disk loading is increased to 50 psf at 60 knots, the balanced power cruise

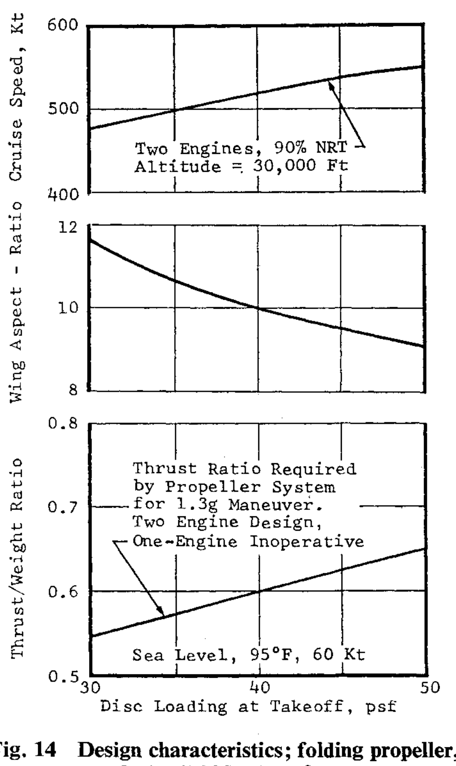


Fig. 14 Design characteristics; folding propeller, fanjet-STOL aircraft.

speed for a twin fan jet design is 550 knots, and the wing-aspect ratio can be reduced to 8.9. A productivity analysis is required to define the optimum combination of wing aspect-ratio and propeller-disk loading.

Conclusions

1) The interconnected shaft-driven low-speed lift-propulsion system based on four gimbal propeller/rotors has potential for STOL aircraft with cruise speeds of 250–500 knots from the viewpoints of performance and control. 2) The same technology can be used to add VTOL aircraft to the short-haul system. 3) The high propulsive efficiency at low speeds ensures minimum noise and pollution in the terminal area for any subsonic aircraft. 4) The trend towards low disk-loading rotor systems and high aspect-ratio wings requires careful attention to structural dynamics to ensure aeroelastic stability. Both trends, however, are in the correct direction for increased aircraft productivity.

Recommendations

1) Research and development of low disk-loading propeller STOL aircraft and folding propeller jet-STOL aircraft should proceed competitively with other candidate concepts for the short-haul market. 2) The over-all metroflight system, including the ground system, must be considered at the aircraft design stage to ensure a significant improvement in service for the short-haul traveler.

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