Conceptual Design of a Lift Fan Plus Lift/Cruise Fighter Aircraft

G. C. Hill* and M. H. Waters†
NASA Ames Research Center, Moffett Field, Calif.

Results of a design synthesis and mission analysis of a supersonic VTOL fighter aircraft are presented. Propulsive lift is provided by a single turbotip-driven lift fan and the deflected thrust from a high-performance turbofan cruise engine fitted with an afterburner for supersonic flight. The inlet and thrust diverter in the main engine tailpipe are seen to be the principal design problems, due to mechanical complexity. V/STOL and supersonic design tradeoffs are addressed in lift fan sizing and placement, reaction and aerodynamic control sizing, fuselage volume requirements, and area ruling. The normal shock inlet design limits the top speed to a Mach number of approximately 2.0. Range and maneuverability, in terms of sustained turn rate, are used as figures of merit.

I. Introduction

THE United States Navy as well as several foreign governments have for some time been actively pursuing the development of a vertical takeoff and landing (VTOL) supersonic fighter aircraft. Several propulsion concepts have been proposed for this class of aircraft, including direct lift engines, vectored nozzle turbojets, the thrust augmentor wing, and several lift fans and cruise engine combinations. In this study, a candidate VTOL fighter design based on a turbotip-driven lift fan plus lift/cruise engine concept is analyzed to demonstrate propulsion system installation requirements and the mission performance that can be achieved with this configuration. No comparisons are made with other VTOL aircraft systems. The technology utilized is attainable for the 1976-1980 time period. The required engine and lift fan performance are extrapolated from hardware currently under test and development and several aerodynamically similar aircraft flying today.

Mission profiles, armament, weapon systems, and performance objectives were provided by the Naval Air Systems Command.[1] The requirements were taken as guidelines since the intent was not to design the optimum aircraft to meet these goals but rather to study a lift plus lift/cruise configuration with the appropriate mission requirements.

In synthesizing this aircraft and evaluating its performance, the High Performance Aircraft Synthesis Program (HiPerAc) developed at the Naval Air Development Center was utilized extensively. This program has been under development and in use at NADC for over 10 years and more recently at the Systems Studies Division, NASA Ames Research Center. Additional programs were developed in-house in the area of weights, aerodynamics, and lift fan performance to support the basic synthesis program.

II. Design

A. General

Figure 1 is a three-view sketch of the general layout of the lift fan plus lift/cruise fighter. It is a single-piloted, supersonic, fixed-wing fighter and ground attack aircraft with both vertical and short field capabilities. Adequate weight and volume allowance is made for the avionics equipment necessary to conduct limited bad weather operations, and provisions for air-to-air and air-to-ground weaponry have also been included.

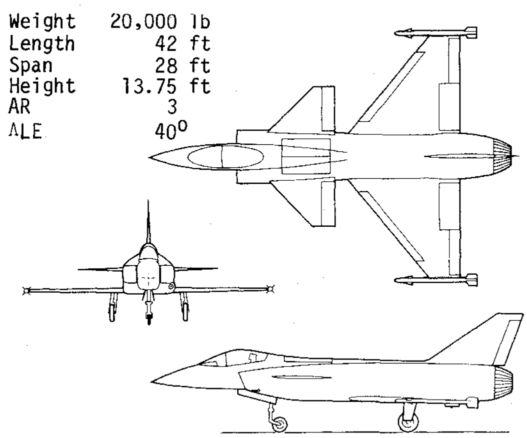

Fig. 1 Aircraft configuration.

B. Propulsion System Design

The integration of VTOL and supersonic flight has always plagued the aircraft designer because the VTOL requirement of balancing vertical thrust about the aircraft center of gravity creates volume requirements which are inconsistent with the fuselage area ruling necessary to minimize supersonic wavedrag. This problem is discussed in more detail later in this paper. The propulsion system design chosen for this study has a single turbofan engine fitted with a diverter system in the cruise engine tailpipe to provide thrust to a direct lift nozzle and also to drive the turbotip-driven lift fan. Two large transfer ducts carry the cruise engine exhaust gas from the bleed plenum to the lift fan scroll. The lift fan is situated under the shared inlet to help alleviate the poor thrust/volume ratio associated with lift fans for fighter-type aircraft. The arrangement of this design is shown in Figs. 2 and 3.

Several aspects of this design, both mechanical and aerodynamic, require development. For example, the diverter system in the tailpipe of the cruise engine and the mechanical coupling of the bleed plenum, the aft direct lift nozzle, and the lift fan transfer ducts present a design problem. Section A-A in Fig. 2 shows a sketch of an exhaust deflection system with a variable position plug nozzle. The mechanical details of several block-and-turn-type nozzle systems that could be used

Presented as Paper 74-969 at the AIAA 6th Aircraft Design, Flight Test and Operations Meeting, Los Angeles, Calif., August 12-14, submitted August 29, 1974; revision received January 23, 1974.

Index categories: Aircraft Configuration Design; VTOL Aircraft Design.

*Aerospace Engineer, Aeronautical Systems Branch. Member AIAA.

†Chief, Aeronautical Systems Branch.

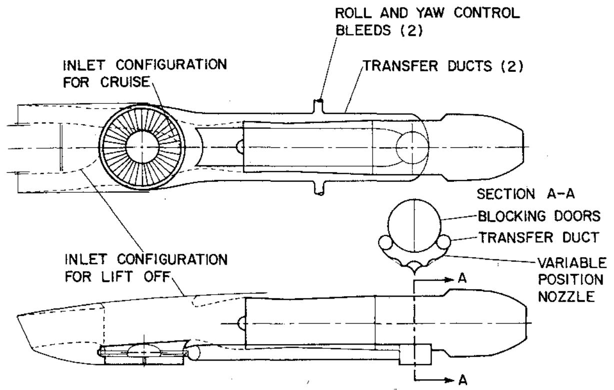

Fig. 2 Propulsion system configuration.

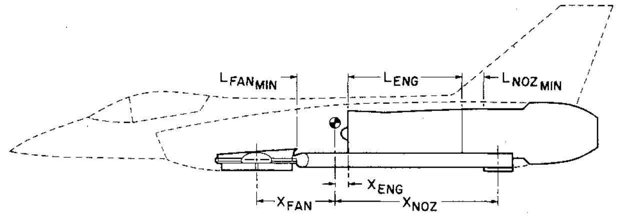

Fig. 3 Critical dimensions for propulsion system integration.

in this design can be found in Refs. 2 and 3. The variable position vectored nozzle controls the amount of air bypassed to the lift fan and thus controls the thrust split between the lift fan and the aft vectored nozzle. This could be used to maintain desired pitch attitude during hover.

The inlet design also presents both mechanical and aerodynamic problems. Mechanically, the vertical side walls of the center body and a horizontal plate at the bottom of the inlet must translate fore and aft to expose the lift fan during liftoff and to provide uniform diffusion during cruise. Also, doors open directly above the lift fan to provide the necessary increase in intake area during lift fan operation (see top view in Fig. 1). With the side walls retracted (liftoff inlet configuration in Fig. 2), the volume above the lift fan acts as a plenum for airflow to both the lift fan and the cruise engine. Aerodynamically, there is no known precedent for this shared inlet concept. Both distortion and pressure recovery could be problems. However, these problems can be minimized by proper sizing of the top doors; if necessary a bell-mouthed shape could be simulated with the top doors in the open position. Also, a generous lip ahead of the cruise engine inlet diffuser would minimize separation of the flow being turned at the top of the inlet. Engine control during transition from vertical to horizontal flight would have to be carefully managed but should be no different than for other VTOL aircraft concepts. The top doors would be left open until full horizontal flight at low speeds to insure maximum inlet pressure recovery for the cruise engine airflow.

An element of the propulsion system design (not shown in Fig. 2) that could be incorporated is an interburner ahead of the lift fan turbine. The advantage of an interburner is the reduced size of the lift fan tip turbine that results from the increased energy in the reheated gas. For such a design, the transfer ducts could be manifolded together into the interburner, which would then discharge this reheated gas into the lift fan turbine scroll.

Also shown in Fig 2 are the transfer ducts to the wing tips, which provide thrust for roll control. Small convergent nozzles are assumed to be installed at the wing tips. Both interburning and ejector thrust augmentation could be used to augment roll control thrust, but the reduced bleed requirement would be offset by the added complexity of these methods, and may introduce unacceptable weight and volume penalties.

Secondary missions use short takeoffs to increase the allowable gross weights over the basic VTOL mission for additional weapons and/or fuel loads. In achieving minimum takeoff distances, the canard and lift fan provide lift as well as trimming forces. The engine, operating at maximum nonafterburning power drives the lift fan and provides horizontal thrust. The amount of gas flow bypassed to the lift fan is set to insure pitch balance of liftoff and the resultant accelerating thrust then determines the required takeoff distance. Takeoff distances for this configuration are calculated in the mission analysis section, but the aircraft design does not reflect specific short takeoff and landing (STOL) performance requirements.

C. Propulsion System Sizing

The propulsion system sizing factors considered here are the fan bypass ratio, the fan pressure ratio, the temperature rise in the interburner, and the thrust rating of the cruise engine. The lift fan bypass ratio is defined as the gas flow bypassed forward of the lift fan ratioed to the gas flow vectored aft. The sum of these two gas flows and the flow ducted to the wing tips for roll control equal the total gas flow of the main engine. To provide for vertical liftoff, the propulsion system is sized for a maximum thrust 10% greater than the liftoff weight.

The turbofan cruise engine is based on the Pratt and Whitney F100/F401 engine cycle. Tailpipe pressure and temperature for the intermediate engine power setting (maximum nonafterburning rating) were maintained for liftoff and for transition to level flight.

Lift fan performance was based on a General Electric study,[4] although the design of the scroll and other peripherals were modified somewhat. A 180° scroll admission angle was assumed to minimize the lift fan width, and a short diffuser was assumed in calculating the thrust from the lift fan and the turbine exhaust.

Figure 3 demonstrates how the lift fan and aft nozzle thrust must be balanced around the aircraft center of gravity to maintain pitch control. For a given set of sizing parameters and a given center-of-gravity position, the locations of the lift fan and the aft nozzle with respect to the center of gravity are set to balance the pitching moments. The minimum distance of the lift fan is set by the inlet length required ahead of the engine; the minimum distance for the aft nozzle is set by the engine length. These distances should be minimum (as shown in Fig. 3) to have the least impact on weight, airframe volume near the cockpit, and transfer duct length.

The baseline propulsion system characteristics include a lift fan/pressure ratio of 1.3, no interburning between the cruise engine tailpipe and the lift fan, a constant cruise engine rating, and a roll thrust requirement of 1000 lb available at each wing tip (see Sec. II-D). With this baseline system, the bypass ratio to the lift fan was varied to change both the thrust split between the lift fan and the aft-vectored nozzle and the total amount of lift force generated. (The roll thrusters are not included in the total lift force since they are assumed to be acting on demand.)

Figure 4 demonstrates the effects of varying this bypass ratio. At a high bypass ratio, the high thrust of the lift fan requires that the aft nozzle be placed farther back to maintain pitch balance; at a low bypass ratio, the reverse is true – the lift fan must be moved forward. At a bypass ratio of 0.8, the system is balanced in pitch with both thrust points at their minimum positions. The lift fan diameter is seen to increase slightly at higher bypass ratios. This is the critical dimension that controls the maximum fuselage width, and the impact on the overall aircraft design is significant. Note that the total lifting force also increases with increased bypass ratio, which demonstrates the augmentation of thrust by the lift fan. The takeoff gross weight is defined as 90% of the lifting thrust available. Thus, the percentage of the gross weight that is

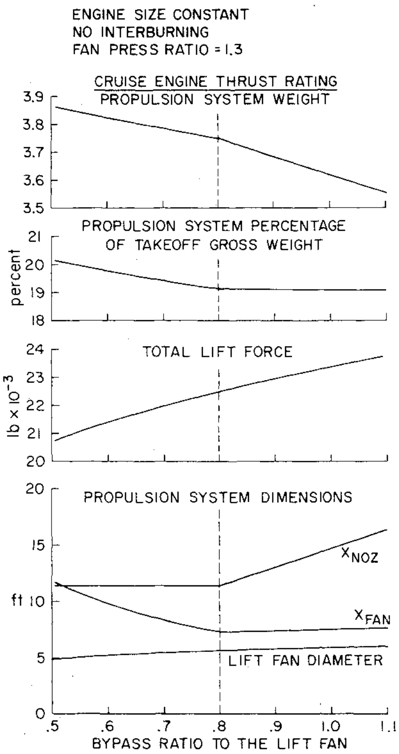

Fig. 4 Effect of lift-fan/bypass ratio on propulsion system sizing.

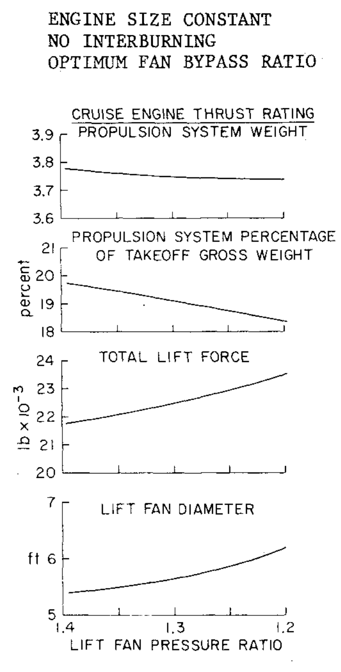

Fig. 5 Effect of design lift fan pressure ratio on propulsion system sizing.

propulsion system weight (cruise engine, lift fan, and transfer ducts to the fan and roll control thrusters) is lowest at the bypass ratio that minimizes the displacement of the vertical thrust points and remains constant at higher bypass ratios. Since the main engine thrust rating is fixed, the top curve in Fig. 4 essentially shows the increase in total propulsion system weight at increased bypass ratio. In all subsequent figures on propulsion system sizing, a bypass ratio was selected that results in pitch balance with both the lift fan and aft nozzle in the minimum locations depicted in Fig. 3.

The effect of lift fan/pressure ratio is shown in Fig. 5. Increasing the fan pressure ratio reduces both the fan diameter and the total lifting force available. Reducing the fan diameter is highly desirable from the point of view of installation in the aircraft, but the higher fan pressure ratio requires increased bypassed flow to drive the tip turbine, thereby degrading static thrust of the total system. The bypass varies from 0.68 to 0.9 for increases in the fan pressure ratio from 1.2 to 1.4. The total propulsion system weight is reduced slightly with an increased fan pressure ratio, as shown by the top curve in Fig. 5 (again the main engine thrust rating remains constant). However, the reduction in lifting capability dominates, and the weight fraction of the propulsion system increases at higher fan pressure ratios.

Providing a modest level of interburning ahead of the lift fan turbine is an alternative method of generating additional lifting thrust. The temperature in the main engine tailpipe is 1317°R. Interburning is provided between the tailpipe and the lift fan for temperatures to 1700°R (Fig. 6). Although this increases the complexity of the propulsion system, the total lifting thrust is increased significantly. The diameter of the lift fan increases slightly with interburning because of the larger turbine required for the hotter gas. Also, the weight of the propulsion system increases slightly (as shown by the top curve), but the increased lift capability dominates and the weight fraction of the propulsion system (and therefore the weight penalty of the VTOL system) is reduced with increased levels of interburning.

The remaining variable in the propulsion system sizing is the scaling of the main engine. The baseline value assumed is a rated gas flow of 265 lb/sec. Figure 7 shows a variation from 242.5 to 287.5 lb/sec. The optimum bypass ratio as defined previously remained essentially constant, and thus increasing the size of the main engine also increased the flow to the fan, which increased the diameter as shown. Predictably, the lifting force increases almost in proportion to the main engine gas flow. The thrust/weight ratio of the main engine was assumed to decrease slightly with increased size; the net result is a decrease in the ratio of main engine rated thrust to total propulsion system weight and an increase in the propulsion system weight fraction.

Under the Mission Analysis section presented later, the baseline system was assumed throughout. This baseline system includes a lift fan pressure ratio of 1.3, a fan bypass ratio of 0.8, a cruise engine rated gas flow of 265 lb/sec, and no interburning ahead of the lift fan. A more thorough preliminary design study would demonstrate the effect of various combinations of these propulsive system parameters

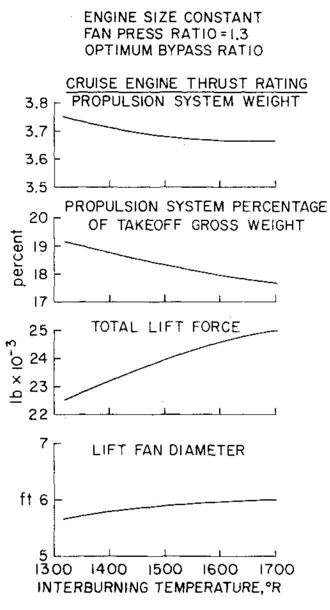

Fig. 6 Effect of interburning on propulsion system sizing.

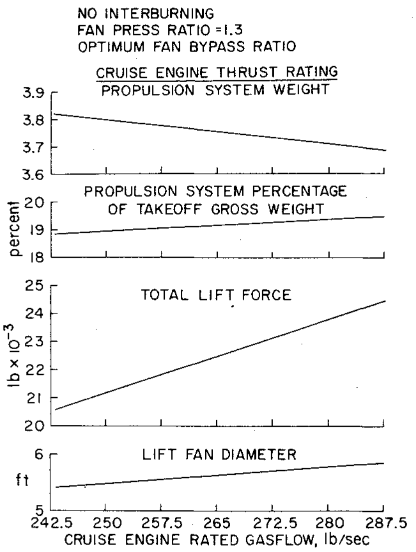

Fig. 7 Effect of cruise engine size on propulsion system sizing.

on mission performance in deriving an optimum system design. This was beyond the scope of the present study.

D. Control

For flight speeds below those for which normal aerodynamic surfaces are adequate, control is provided by regulating the transfer of gas flow to the lift fan, varying the nozzle area of either the lift fan or vectored thrust plug nozzle, and bleeding to reaction nozzles. Special attention was given to roll control since it will require thrust bleeding and therefore have the greatest effect on propulsion system sizing. An automated stability augmentor system will be required; however, for preliminary design, the details of response times, axis coupling, and damping were not considered; only the provision for generation of sufficient moment forces was allowed to impact in this preliminary design study.

Roll axis control is accomplished by bleeding hot gas from the lift fan transfer ducts to reaction nozzles mounted in the wing tips. A 1000-lb bleed requirement from the engine for roll control was used in the engine/lift fan sizing. This criterion was established from recent simulator studies on hovering flight of VTOL aircraft[5] conducted at NASA Ames Research Center.

Two types of wing tip nozzle systems were considered: the "equal-and-opposite" system shown in Fig. 8 and a "one-arm" method, which is similar, except that only the down wing is thrusted. The two systems are compared in Fig. 9, which plots roll moments vs the control force required at each wing tip and the total force (lift fan, nozzle, and wing tip control) required to maintain hovering flight (sum of the vertical thrust components equal to weight) for various angles of bank. The equal-and-opposite method was selected, although the total amount of thrust required is greater, due to the up wing thrust acting with the weight. The determining factor was minimizing the size of the flow transfer duct to each wing tip. This method allows the use of a single circular duct for each wing. An "always pointing down" nozzle at the wing tip was also considered, and it was found to have the same effect as the one-air method – a slight reduction in total thrust required. However, an increase in the size of the transfer ducts is also required.

In pitch, static balance was provided by utilizing the lift fan sizing and balance computer program. The aft plug nozzle, by controlling the lift fan/bypass ratio, provides the desired pitch control. If gas flow transfer causes excessive pitch response times, more immediate response could be generated through variation of the lift fan louvered nozzle throat area by manipulation of the louver angles.

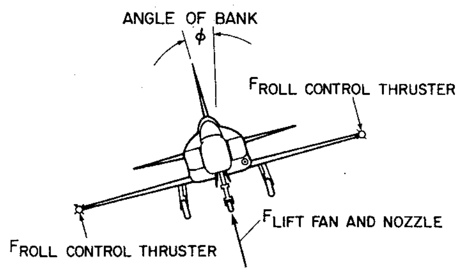

Fig. 8 Roll control forces.

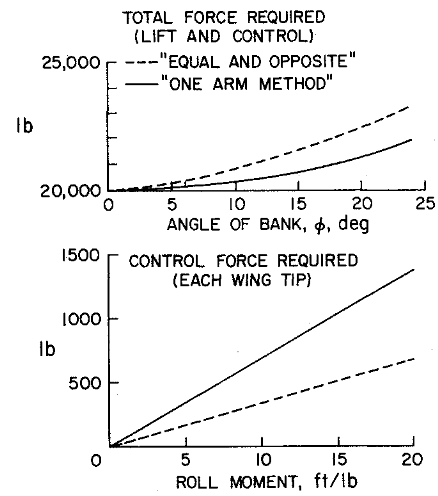

Fig. 9 Effect of roll control thruster methods.

DESIGN 20,000	EMPTY 11,858	STRUCTURE 5185	WING	1552
			TAIL	435
			BODY	1926
			LANDING GEAR	675
			SURFACE CONTROLS	597
		PROPULSION SYSTEM 3930	ENGINE	3040
			INSTALLATION	30
			INLETS	445
			FUEL SYSTEM	310
			OIL SYSTEM	30
			STARTING SYSTEM	55
			ENGINE CONTROL	20
		VTOL SYSTEM 870	LIFT FAN	611
			TRANSFER DUCTS	188
			ROLL CONTROL	71
		FIXED EQUIPMENT 1100	INSTRUMENTS	100
			HYD/PNU	105
			ELECTRICAL	355
			FURNISHINGS	225
			AIR COND	120
			ANTI ICING	10
			COMM/NAV	185
		WEAPON SYSTEMS 800	RADAR	
			NAVIGATION	
			FIRE CONTROL	
			COUNTER MEASURES	
			ARMAMENT PROVISIONS	
	USEFUL LOAD 8115	CREW & SUPPORT 225	CREW	190
			CREW EQUIPMENT	10
			OXYGEN	25
		40	OIL	40
		FUEL 5600	UNUSABLE FUEL	46
			INTERNAL FUEL	5554
			TIP TANK FUEL	0
		ARMAMENT 2250	GUN SYSTEM	
			AMMUNITION	
			MISSILES	
			PYLONS	
			RACKS	

Fig. 10 Aircraft weight statement.

Lift fan installations usually employ louver-type nozzles that fold flat for aerodynamic fairing when not in use. These swiveling vanes can also be used to deflect the fan flow from side to side to provide yaw control. A small amount of bleed might have to be provided for a bidirectional reaction-type nozzle in the tail, similar to those at the wing tips, to ensure adequate yaw angular accelerations.

E. Airframe

1) Weights

The weights table in Fig. 10 was computed from an inhouse synthesis subroutine. This preliminary design program averages several independent weight-estimating equations to predict the weight of the major structural components. The avionics and othe provisions directly related to mission and armament are separated and considered to be payload. This program has achieved good correlations in predicting the weights of nine contemporary fighter and attack aircraft, including the AV-8A Harrier.

The engine and lift fan propulsive unit weights were taken from the scaling and balancing program discussed previously. Allowances were made for common structures cutouts, and relieving loads unique to this configuration. Minimal assumptions were made for advanced materials.

2) Volumes

Despite the strong dependence on weight for VTOL and supersonic and transonic maneuvering performance, fuselage volume generally limits fighter performance because of drag penalties. The internal volume and arrangement were not analyzed in detail; instead, an area rule program was used to assure sufficient volume and to provide a minimum drag shape (shown graphically in Fig. 11). A total Sears-Haack area distribution for a given volume is plotted. The cross-sectional area distributions of external surfaces are subtracted, leaving the minimum wave-drag fuselage shape. This method is similar to that of Ref. 6. Within this area, the volumes of major components are then mapped. More detailed calculations of adjacency, smoothness, and minimizing drag penalties due to separation are beyond the scope of this study.

The aft wing configuration was selected primarily to allow better area ruling around the large volume required for the lift fan and inlet. The secondary advantage of the canards over an aft stabilizer is that they generate vortices which, if properly located, can augment lift during the STOL mode and during transonic maneuvering; further, they provide a lifting trimming surface in supersonic flight. However, they also generate downwash, which reduces wing lift and can cause stability problems.

3) Aerodynamics

The wing geometry is similar to the newest generation of highly maneuverable fighters. Wing loading is kept low to provide high turn rate capability, even though range optimization, especially for supersonic missions, would dictate higher wing loading and greater sweep. An additional constraint affecting the aspect ratio was limiting the wing span for handling considerations aboard small ships and avoiding the weight penalty of folding wings.

III. Mission Analysis

Guidelines for mission profiles, payloads, combat, and landing fuel were taken from Ref. 1. Ranges are treated parametrically here and do not reflect those of Ref. 1 that are classified. The inlet pressure recovery and zero-lift drag used in performance simulations are shown in Figs. 12 and 13, respectively. Engine performance was taken from the F100/F401 cycle computer program provided by Pratt and

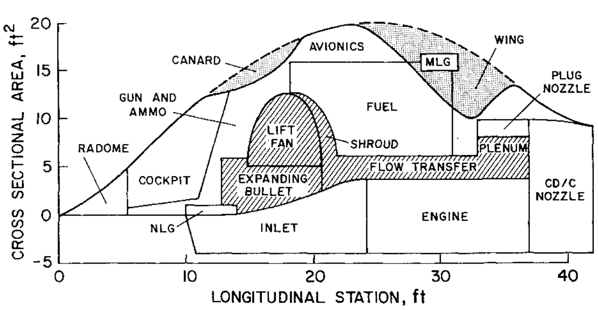

Fig. 11 Aircraft cross-sectional area distribution.

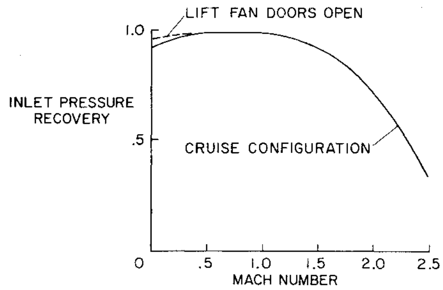

Fig. 12 Inlet pressure recovery schedule.

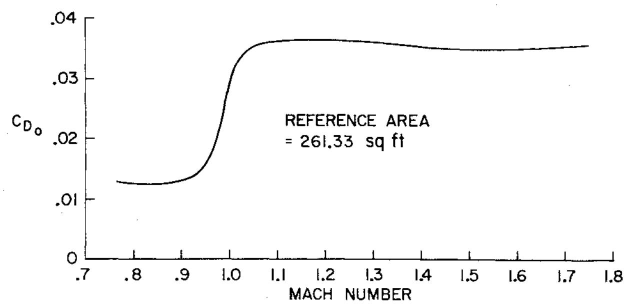

Fig. 13 Aircraft zero lift drag.

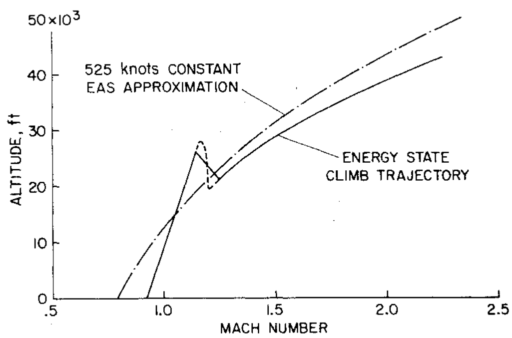

Fig. 14 Minimum energy climb trajectory for DLI mission.

Whitney. The method of Ref. 7 was used to calculated drag due to lift. This method reflected excellent correlations with wing-tunnel model tests on lightweight fighter configurations and reflects the advances in vortex lift aerodynamics at high angles of attack.

The most stringent of the design missions was the deck-launched intercept (DLI) mission, involving a vertical takeoff, a supersonic climb/cruise, a combat fuel penalty expressed in energy height, and a subsonic return leg. Ground rules specified either constant Mach number or constant equivalent airspeed (EAS) climbs. Figure 14 illustrates a minimum energy climb path calculated for this aircraft by the program of Ref. 8. A constant EAS of 525 knots was selected to approximate the minimum energy path for the climb/acceleration phase.

The DLI mission radii achievable for a range of fuel fractions are shown in Fig. 15. The supersonic outbound leg altitudes are determined by the 525 knot EAS at the selected Mach number, except for Mach 1.6 at 40,000 ft, where a higher altitude was used to increase range. The fuel penalty for combat, warmup, takeoff, and landing reserves is approximately half the available internal capacity. This configuration was not scaled up in this study to meet the range specifications of Ref. 1. This would require a considerably larger cruise engine, and it is probable that dual cruise engines would be more appropriate for an aircraft designed to meet the specified mission range.

Turn rate is also an important design consideration. Sustained turn rate is defined as the maximum angular change of direction that can be maintained without loss of altitude or

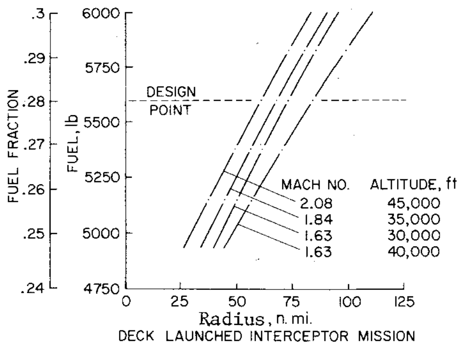

Fig. 15 DLI mission performance.

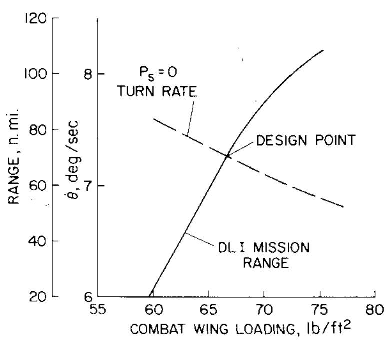

Fig. 16 Effect of wing loading on mission range and combat sustained turn rate.

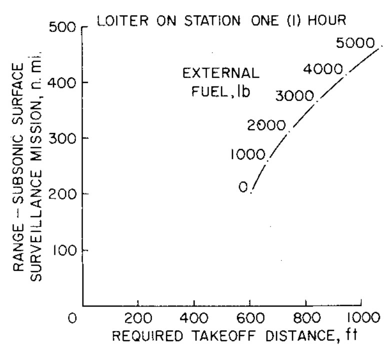

Fig. 17 Subsonic surface surveillance mission performance.

airspeed, i.e., specific excess energy (P_S) equal to zero. Unfortunately, the wing loading (W/S), the dominant factor in achieving high turn rates, varies inversely with range for the high-speed DLI mission (Fig. 16). This is a fundamental tradeoff in fighter aircraft design.

Another important mission is a subsonic surface surveillance mission which uses external fuel tanks for extended range. This mission uses a short-field takeoff to accommodate a greater payload, a minimum fuel climb and cruise outbound, a specified loiter on station, combat fuel penalty, and then an optimum speed and altitude return leg. Since the amount of external fuel and, therefore, the range are determined by the STOL takeoff distance, the range vs deck length is plotted in Fig. 17. The required ground roll distances exceed those allowed in Ref. 1 because of the low lift fan thrust setting allowable to balance pitching moments. This illustrates the absence of STOL considerations for the original concept.

IV. Conclusions

The objective of this study was to examine the application of the turbotip driven lift fan for a supersonic VTOL fighter mission. This configuration was not intended to meet the stated Navy mission specifications. The latter were selected only to provide an appropriate scenario for the analysis. It was found that the remote lift fan has advantages in location flexibility and as a variable thrust propulsion cycle. Also, advancement of lift fan technology to reduce lift fan weight and volume would be an advantageous technology to pursue.

Scaling this particular configuration to meet the Navy mission radius would result in unacceptable performance penalties. With the level of propulsion technology assumed here, a larger aircraft with a multiple engine/lift fan combination would be more appropriate.

It cannot be assumed that a VTOL aircraft will have adequate STOL performance. This aspect must be considered along with the VTOL requirements in the conceptual design phase. For the configuration developed in this study, adjustments to wing and center-of-gravity positions could most likely improve the STOL performance, but the effect of these changes on the design integration and handling performance would have to be considered.

The cruise engine selected for this study on the basis of an existing family is not optimum. An engine designed so that bypass air can be diverted to the lift fan directly would have weight and volume savings, since the transfer duct lengths would be reduced and the aft plenum eliminated. As a cruise engine, the selected gas generator is also oversized by VTOL requirements. A more optimum system might be achieved by reducing the size of the cruise engine and augmenting the lift fan performance through interburning.

Inlet flow and tailpipe thrust diverters are very critical to this concept in terms of performance and volume. These two areas provide the greatest opportunity for ingenuity in design, and they also represent the greatest lack of experimental study.

Although this aircraft design does not meet the Navy mission requirements, this study has demonstrated that this configuration has potential for a small VTOL fighter with ranges and payloads similar to that of the Harrier and with added supersonic capabilities.

References

[1] "Advanced V/STOL Propulsion Weapon System Performance Requirements," March 1972, Naval Air Systems Command.

[2] Migdal, D., "Effect of Exhaust Deflectors on the Design of Lift Plus Lift/Cruise V/STOL Aircraft," SAE Paper 730959, Oct. 1973.

[3] Gill, J. C., "Advanced Technology Thrust Vectoring Exhaust Systems," *Journal of Aircraft*, Vol. 11, Dec. 1974, pp. 764-770.

[4] Przedpelski, Z. J., "Lift Fan Technology Studies," General Electric Co., NASA CR-761, April 1967.

[5] Grief, R. K., Fry, E. B., Gerdes, R. M., and Gossett, T. D., "Effect of Stabilization on VTOL Aircraft in Hovering Flight," NASA TN D-6900, Aug. 1972.

[6] Jenson, S. C., "Design Synthesis of Twin-Engined Fighter Physical Characteristics for Parametric Studies," Rept. D6-20441TN, Feb. 1968, Boeing Co., Seattle, Wash.

[7] Nelms, W. P. and Axelson, J. A., "Preliminary Performance Estimates of a Highly Maneuverable Remotely Piloted Vehicle," NASA TN D-7551, Feb. 1974.

[8] Ardema, M. D., "Approximations in the Minimum Time-to-Climb Problem," NASA TM X-62, 292, Aug. 1973.