Design Considerations for a V/STOL Technology Airplane

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A high speed two-engine three-fan V/STOL airplane was designed to demonstrate and develop the technology for operational V/STOL aircraft having safe engine-out characteristics. Engine-out requirements, integration of propulsion and aerodynamic controls, and propulsion installation are the major factors affecting the configuration. Use of variable pitch fans enchances the control system providing a responsive and versatile airplane.

Introduction

A lift-fan airplane for research and demonstration of V/STOL technology was designed under contract to the NASA-Ames Reseach Center. The airplane is based on an operational multi-mission airplane designed for potential Navy use. The performance requirements include efficient loiter and cruise capability and high subsonic maximum speed. Maintenance and logistics considerations favor a twin engined arrangement. It will be used to examine handling requirements and develop operational techniques for the entire flight envelop of the operational airplane. The operational airplane is presented as the basis for the technology airplane. Engine-out requirements, aeropropulsion integration, and propulsion system installation are the major factors affecting the configuration. The Boeing design uses three variable pitch fans driven mechanically by two turboshaft engines. The Detroit Diesel Allison, Division of General Motors, and the Hamilton-Standard Division of United Technologies have worked closely with Boeing in this design.

Multi-Mission Lift-Fan V/STOL

The general arrangement of the airplane with the principal propulsion system components emphasized is shown in Fig. 1. The configuration is similar to that of most business jets with aft body mounted engines, a low wing, and a 'T' tail. The engines nacelles are somewhat larger than usual due to the large diameter of the low pressure ratio, high static thrust lift-cruise fans. An identical fan is located horizontally in the nose. The cross shafting between the two lift-cruise fans and the nose fan drive shaft and interconnecting 'T' box are apparent. The nose fan is disconnected by means of a clutch at the 'T' box during wing born flight. The lift/cruise engine/fan units rotate to provide thrust vectoring for V/STOL operation.

The total installed power is determined by the requirement for single engine operation. The minimum weight (achieved by jettisoning disposable payload) is equal to the single engine emergency thrust.

V/STOL Controls

During V/STOL operation, all three fans run at the same speed. Roll and pitch control moments are generated by increasing and decreasing the thrust from side to side for roll, and fore and aft for pitch. The roll and pitch thrust variation results from changes in blade pitch angle which transfer power among the fans without changing the turboshaft engine operating point. Yaw control is accomplished by tilting the thrust vectors in a spanwise direction, with the nose fan and the lift/cruise fan thrust tilting in opposite directions. The yaw control is actuated by vanes in the fan exhaust.

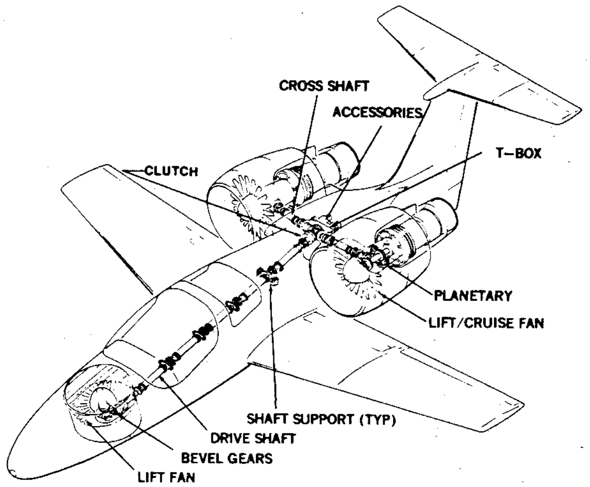

Fig. 1 Model 104-133 V/STOL aircraft.

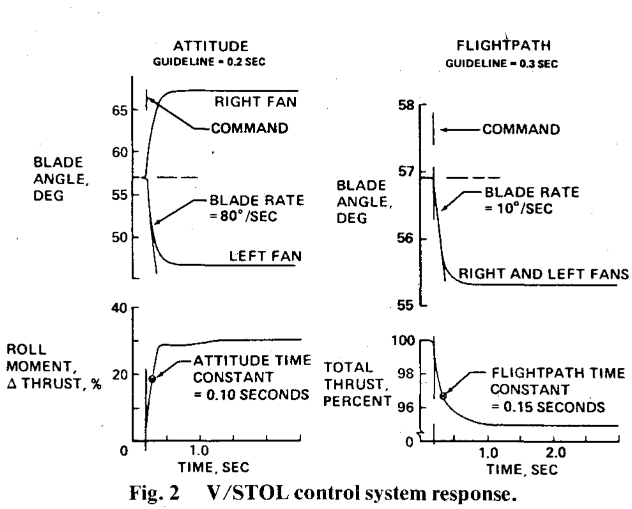

Fig. 2 V/STOL control system response.

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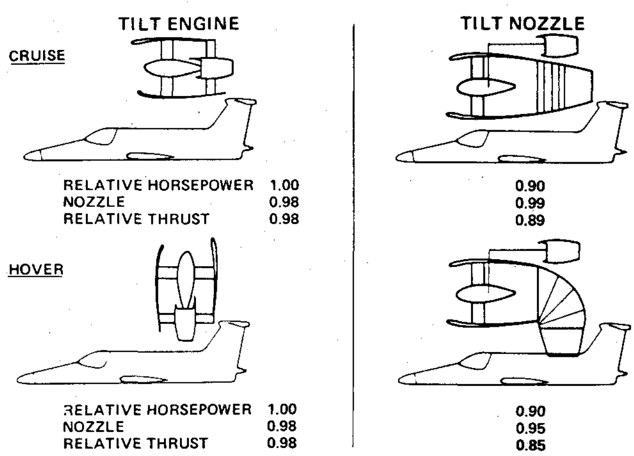

Fig. 3 Propulsion arrangements for thrust vectoring.

The response to attitude and flight-path commands are shown in Fig. 2. The maximum required moment has a time constant of 0.1 sec. Flight path control is exemplified by a fly-down command. The thrust is reduced 5% with a time constant of 0.15 sec.

Thrust Vectoring

Several alternate schemes for vectoring the lift cruise fan thrust were considered. Rotating the nacelles provides about 15% more vertical thrust at the lift/cruise fan than would otherwise be possible with the same engine. The thrust available with an engine out is the critical design condition. The comparison of a rotating nacelle and thrust deflecting nozzle is shown in Fig. 3.

In the rotating nacelle, the engine is supercharged by the fan for about 10% more power. The nozzle efficiency is about 98%. Using the emergency condition as a reference, the thrust is about 98% of the ideal.

For the nozzle deflection system, the engine is separate from the fan. This is necessary to keep the point of action of the vertical thrust vector near the wing trailing edge without moving the inlet ahead of the wing. The weight and complexity of two extra gear boxes are required by this separation. The supercharging action of the fan is lost, resulting in about 10% less power than would have been available with supercharging. In addition, a nozzle efficiency, including duct bend losses, approaching 95% may be possible. Thus, the thrust available is 85% of the ideal with supercharging.

In exchange for all these advantages (four instead of six gear boxes, an aerodynamic clean configuration, and 15% more emergency thrust) we must operate the lift/cruise inlet at high angles of attack during takeoff and landing transition. The critical design conditions of nacelle angle of attack, velocity, and power setting are shown in Table 1. These are the extremes that will be encountered with a broad V/STOL flight corridor. Wind tunnel data indicate that operation at these conditions is possible with a variable geometry inlet. Recent results using carefully tailored fixed geometry inlets have also been encouraging.

Comparison of Shaft and Gas Interconnect

There are three major differences between variable pitch shaft interconnected systems and tip turbine gas connected systems. The first relates to thrust response for control of attitude and translation.The second, to the size of the power source, and the third compares the response to an engine failure. Control is achieved by power transfer among fans. For the gas system, power transfer is by flow control. The thrust response depends on a change in fan rotational speed. Thrust response can be "quickened" by using vanes or thrust spoilers to provide an initial rapid response. The apparent time constant can be significantly reduced, although the system is complicated by the required lead and washout circuitry.

Table 1 Lift/cruise fan inlet design conditions

Flight mode	Airspeed, KN	Power setting, percent	Inlet angle, deg ~ Ω
STO			
lift off	75	100	70
approach to	75	50	90
VL	125	30	60

Table 2 Technology demonstration hover control power, model 1041-134

Control function	Design guideline requirement	System capability
roll	0.90 rad/sec^2	1.80 rad/sec^2
pitch	0.50 rad/sec^2	1.40 rad/sec^2
yaw	0.30 rad/sec^2	0.50 rad/sec^2
height	0.05 g	0.22 g

For the vaiable pitch system, power transfer is achieved by increasing the pitch of the upgoing fan and reducing it on the opposite fan. Control response is extremely rapid, limited only by blade pitch rate. The control system can be designed without lead and washout circuitry. The rapid response time is illustrated in Fig. 2.

The two systems differ in the size of the power source required for a given thrust level. The tip turbine fan is limited in the use of the gas power by turbine entry scroll temperature limits. Current technology limits this temperature to about 1375°F. For the shaft interconnect, the power turbine is arranged conventionally behind the compressor turbine, and all propulsion technology advances may be used. The power turbine entry temperatures currently available are about 1640°F, about 275°F higher than the scroll limits. For equal thrust, the power source for the tip turbine requires about 65% more mass flow, and the SFC is about 30% higher than the shaft interconnect system.

The response to an engine failure of the tip turbine system is fully active. The failure must be recognized and located. The proper valves must be actuated to reduce the power absorbed by the fans and to isolate the failed engine. The requirement for failure-sensing alone requires a major development.

For the variable pitch system, an overrunning clutch at each engine permits a failed engine to drop off the line. The governor adjusts the blade pitch to absorb the remaining power. No pilot action is required; it is a naturally automatic, or passive, system.

Technology Airplane

A technology aircraft, based on the multi-mission airplane, uses existing engines with the fans and transmission developed for the operational aircraft. As the engine growth is realized, the operational propulsion system will be available and qualified. The design of the technology airplane is accomplished by stripping the operational airplane and shrinking it wherever possible. The technology airplane has a more slender fuselage, a two-place instead of four-place cab, a substantially smaller wing area and span, no wing fold, and no military payload provisions. These differences result in an emergency landing weight compatible with the use of existing engines.

For the technology airplane, the V/STOL control system offers the ability to explore the flight regime in depth. Control power in excess of the guidelines is available so that a variable stability capability can be added to the aircraft. The use of a fly-by-wire and computer system makes this possible. A comparison of the guideline and available control is shown in Table 2. The time constants of the control system from Fig. 2 are short enough to permit examination, as part of the variable stability capability, of the effect of time constant increases on airplane operation in the V/STOL regime.

Summary

The V/STOL technology airplane, stemming from an operational design, will have the following attributes: 1) enough performance and control to permit extended flight research in the V/STOL mode; 2) capability of operating over the entire flight envelop of the operational airplane; and 3) development and qualification of the propulsion and transmission system for a future operational aircraft.

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