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The Shaft Driven Lift Fan Propulsion System for the Joint Strike Fighter

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Abstract

Analysis and testing are used to show the feasibility of an innovative shaft driven lift fan propulsion system for supersonic STOVL aircraft. Dual cycle operation of the cruise engine makes it possible to convert some of the jet thrust to shaft horsepower for driving the lift fan. Operation of the propulsion system is described and it is analytically shown that the designs of the engine, drive shaft, and clutch are within the state of the art. A demonstrator engine and lift fan were assembled from available components and operated for almost 200 hours in a full size airframe model. Testing proved the feasibility of changing the engine cycle to drive the lift fan, and of rapidly transferring thrust back and forth between the engine and lift fan to provide pitch control. The durability of the mechanical drive system and flight weight gearbox were also demonstrated.

Introduction

The next generation strike fighter will need to combine the short takeoff and vertical landing capabilities of the AV-8B Harrier with the supersonic performance of the F-16C Falcon, while providing greater range and increased survivability. This combination of vertical and supersonic performance requirements means that engine design, always an important part of any new airplane program, is a particularly significant factor in the development of a new strike fighter. The engine must provide enough vertical thrust for short takeoffs and vertical landings, but must not be so large that it increases supersonic drag or fuel consumption during cruise.

Figure 1 shows the maneuver and acceleration constraints on the thrust to weight ratio, T/W, and wing loading, W/S, of a representative strike fighter. The curves are obtained by setting thrust equal to drag for each of the performance goals. To minimize engine size, the maneuver goals drive the airframe design toward a large wing, while the acceleration time drives the design toward a small wing. There is an intermediate wing size that simultaneously satisfies all of the conventional performance goals, as shown in the Figure. Although this design point requires somewhat more thrust than a design that satisfies any single goal, both the short take off and vertical landing goals require even greater thrust.

Because the STOVL performance goals require more thrust than the combat goals, some form of thrust augmentation is necessary. Increasing vertical thrust by afterburning is not a satisfactory solution, due to the high temperatures and velocities of the lift jets generated by this approach. Increasing the size of the cruise engine to provide sufficient vertical thrust is not an optimal solution either, because the engine would then be larger than necessary for conventional flight. This would impose a weight penalty, because the inlets, nozzle, and airframe would also be larger than necessary. Also, when this oversized engine is throttled back for cruise, fuel consumption would be increased.

The method of functional analysis was used to systematically analyze the conflicting performance goals and devise a vertical lift system that would meet them. The requirement to perform STOVL strike and close air support missions was derived from top level military

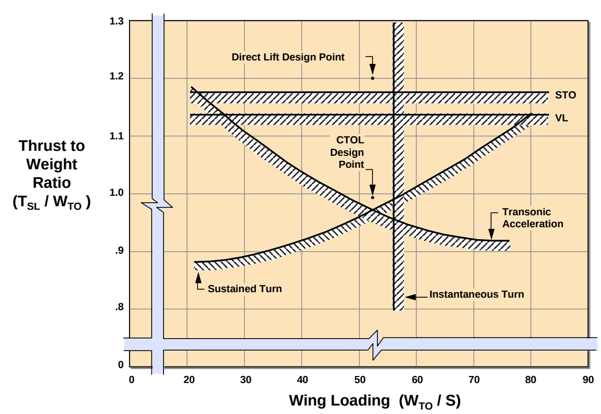

Figure 1: Performance Constraints on T/W and W/S

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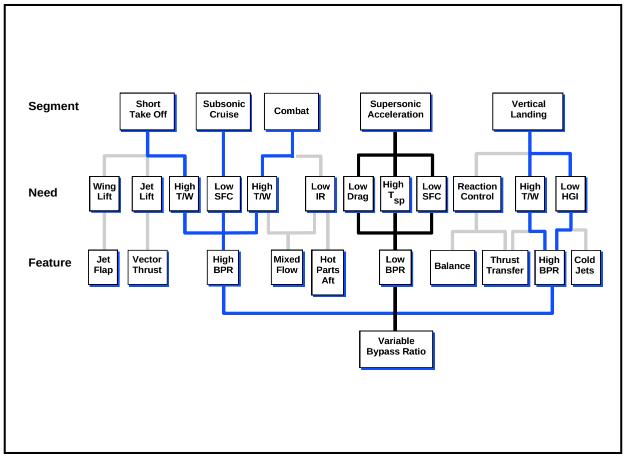

Figure 2: Analysis of Propulsion System Features

campaign strategies [1]. Each of the required missions was then subdivided into its mission segment tasks. Each segment task was further decomposed into needed performance capabilities, in order to reach a level where specific design features could be identified to meet the mission objectives.

A simplified version of this analysis for the propulsion system is shown in Figure 2. For example, the subsonic cruise mission segment requires low specific fuel consumption, which requires a high bypass ratio engine. The actual fan diameter and pressure ratio would be determined at the next level of decomposition. At the level shown, the Figure highlights the essential design problem: the STOVL, cruise, and combat segments require high bypass ratios, while the supersonic segment requires a low bypass ratio. The ideal solution would be a variable cycle propulsion system, with a high bypass ratio for the STOVL and subsonic mission segments and a low bypass ratio for the supersonic mission segments.

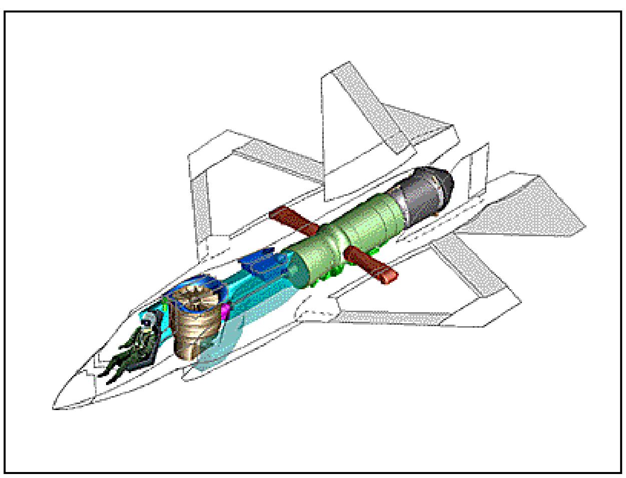

Figure 3: Shaft Driven Lift Fan Propulsion System

The purpose of this paper is to describe an innovative, dual cycle propulsion system that increases the bypass ratio of the cruise engine for short take off and vertical landing, without oversizing the engine or creating an unacceptable footprint. As shown in Figure 3, the effective bypass ratio is increased by installing a lift fan behind the cockpit. For STOVL operations, the lift fan is connected to the cruise engine by engaging a clutch on a drive shaft extending from the front of the engine. The engine operating point is simultaneously changed to convert some of the jet thrust to shaft horsepower. For cruise flight, the lift fan is disconnected and the engine operating point is changed to produce jet thrust, rather than shaft horsepower. The engine then operates as a conventional mixed flow turbofan.

The result is a dual cycle propulsion system with a much higher bypass ratio in the vertical flight mode than in the conventional flight mode. This system provides high levels of thrust augmentation with a cool, low pressure footprint, excess control power, and minimal effect on the design of the airframe. Since the cruise engine is optimized for conventional flight, the performance of the propulsion system is not penalized for its STOVL capability.

In this paper, the results of analysis and testing will be used to show the feasibility of this shaft driven lift fan propulsion system. In the next section, the dual cycle operation of the cruise engine will be described, and analysis will be used to show that the design of the engine, drive shaft, and clutch are within the state of the art. The results of propulsion system tests performed with a lift fan and demonstrator engine assembled from available components will be presented in the section after that. The Allison Advanced Development Company demonstrated the performance of the lift fan, gearbox, and shaft for the high power levels of a production propulsion system. The Pratt & Whitney engine company assembled a dual cycle F100-PW-229-plus engine from components of existing engines. It was operated in the conventional mode and then used to drive the Allison lift fan to demonstrate operation in the STOVL mode.

Dual Cycle Thermodynamics

The energy to drive the lift fan is extracted from the air that flows through the cruise engine. The change in the energy of the air as it passes through an engine operating in a conventional turbojet cycle is shown in Figure 4. Energy is added to the air as it passes through the fan and compressor, as seen in the Figure. The magnitude of the added energy is representative of the newest generation of engines. This energy appears as an increase in both the pressure and temperature of the air. Following compression, additional energy is added to the air by burning fuel in the combustor at constant pressure.

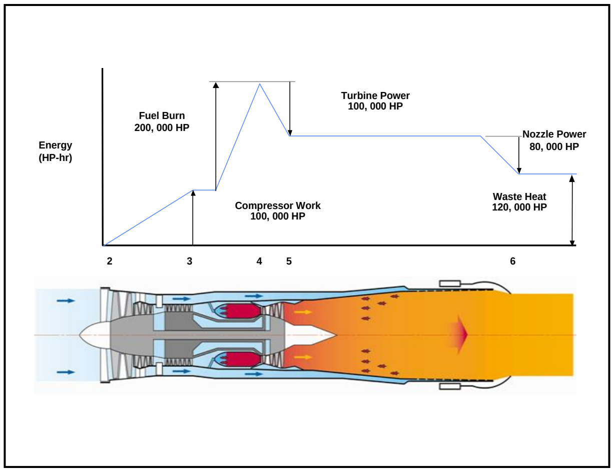

Figure 4: Energy Changes through a Turbojet Engine

Energy is then extracted from the hot, high pressure gas by the turbine section. Since the turbine drives the compressor, the amount of energy extracted by the turbine is the same as the amount added by the compressor. This energy loss is seen as a drop in the pressure and temperature of the gas. The energy remaining in the hot gas that leaves the turbine section is converted to thrust by expanding it through a nozzle. The temperature and pressure of the gas drop as it expands through the nozzle. Although the static pressure of the gas returns to atmospheric pressure, the temperature of the exhaust jet remains higher than the atmospheric temperature, so that this energy is lost as waste heat.

The thrust of the engine can be increased if the energy in the exhaust jet is transferred to a larger mass of air, rather than simply being expanded through the nozzle. The following simple analysis illustrates this phenomenon. If the thrust of the exhaust jet is $\dot{m}V$, then its kinetic energy flux is $\dot{m}V^2/2$. Transferring this quantity of energy to a larger mass of air reduces the velocity of the exhaust jet. This can be written,

$$\tfrac{1}{2}\,\dot{M}v^2 = \tfrac{1}{2}\,\dot{m}V^2$$

so that the jet velocities are inversely proportional to the square root of the jet mass flows,

$$\frac{v}{V} = \left[\frac{\dot{m}}{\dot{M}}\right]^{1/2}$$

The ratio of the thrust of the two jets is obtained by substituting this equation for the velocity ratio in the expression for the thrust ratio,

$$\frac{\dot{M}v}{\dot{m}V} = \left[\frac{\dot{M}}{\dot{m}}\right]^{1/2}$$

so that the jet thrust increases with the square root of the mass flow ratio.

To actually transfer the energy to a larger mass of air, another turbine stage is added to the engine. The energy extracted by this power turbine is used to drive an additional fan, as shown in Figure 5. The power turbine and fan are mechanically independent of the rotating components of the basic gas generator. Because energy is extracted from the hot primary flow, the thrust of the engine core exhaust flow is reduced. However, there is a net thrust increase for the complete turbofan system.

The shaft driven lift fan propulsion system increases thrust in a similar way; that is, energy is extracted from the hot turbine exhaust flow and transferred to a larger mass of air by the lift fan. However, the power to drive the lift fan is not obtained with a separate power turbine, but by changing the operating point of the turbine that drives the engine fan. This can be understood by examining the performance map of a typical turbine section, as shown in Figure 6. At any point on the map, the power produced by the turbine is given by,

$$\mathit{Turbine\ Power} = \dot{m}c_p T_{04}\left[1-(P_5/P_4)^{\frac{\gamma-1}{\gamma}}\right]$$

in which T_{04} is the stagnation temperature of the gas entering the turbine section, and P_5/P_4 is the pressure drop across the turbine section.

Increasing the fuel flow produces more turbine power by increasing T_{04}. The additional power accelerates the engine until the power absorbed by the compressor matches the power produced by the turbine, and the engine speed stabilizes. Because its speed is higher, the engine produces more thrust. The locus of steady state matching conditions defines the engine operating line, which is the diagonal running from the bottom left to the top right in

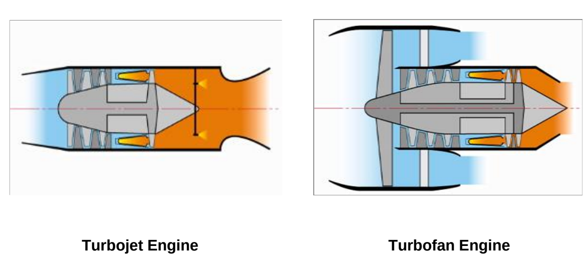

Figure 5: A Power Turbine Drives the Engine Fan

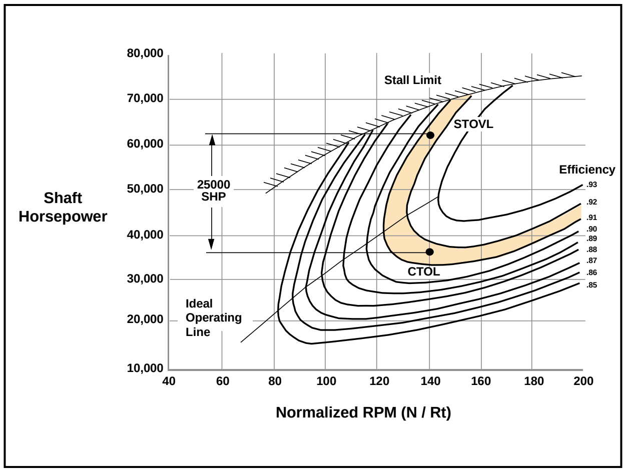

Figure 6: Turbine Performance Map

Figure 6. The engine and compressor are designed so that the turbine power and compressor power match near the point of maximum efficiency at every speed.

If the clutch connecting the engine to the lift fan is engaged at the same time as the fuel flow is increased, the additional power can be used to accelerate the lift fan, instead of the engine. By selecting the fuel flow to match the power produced by the turbine to the power required to drive the lift fan, the engine speed can be held constant. The process is similar to depressing the gas pedal in an automobile with a manual transmission. With the clutch disengaged, stepping on the gas causes the engine to accelerate. Engaging the clutch at the same time as you depress the gas pedal transfers the power to the drive wheels, so that the engine does not accelerate.

However, in a STOVL aircraft the requirement is to increase the *maximum* thrust of the engine. But at maximum thrust, the turbine inlet temperature, T_{04}, is already at the material limit of the turbine section. As a result, the gas temperature can not be increased to provide the energy to drive the lift fan. In the dual cycle engine, the additional power is obtained by increasing the pressure drop across the turbine section. As seen in Figure 7, the pressure rises through the compressor, remains constant through the combustor, then drops through the turbine section and nozzle, in two steps. This is shown by the solid line in the Figure.

Increasing the nozzle exit area reduces the pressure drop across the nozzle, causing a corresponding increase in the pressure drop across the turbine. For example, increasing the nozzle area so that $A_6 = A_5$, as shown by the dashed lines in Figure 7, causes the static pressure at station 5 to drop to atmospheric pressure. The larger pressure drop across the turbine produces more shaft horsepower, while reducing the thrust of the core flow. Engaging the clutch at the same time as the nozzle area is increased transfers the additional power to the lift fan, so that the speed of the engine does not increase. This is shown by the two points in Figure 6. The lower point is the conventional operating point and the upper point is used when the lift fan is engaged. Nearly 25,000 horsepower can be extracted before the turbine section reaches its stall limit. The thrust that can be produced with this much power depends on the diameter and pressure ratio of the lift fan. For example, with a fan diameter of 40 in to 50 in, the thrust is on the order of 15,000 to 20,000 pounds.

Because the net pressure drop from the turbine entry to the nozzle exit does not change, the static temperature of the exhaust jet is also unchanged. Therefore, extracting power from the gas stream does not change the waste heat, which is the excess static temperature of the exhaust jet. However, the total temperature of the jet is reduced. The equation for the change in turbine power is

$$\Delta SHP = \dot{m} c_p \Delta T_0$$

so that extracting 25,000 shaft horsepower reduces the total temperature of the jet approximately 250 degrees Fahrenheit in this engine.

The energy equation for the exhaust jet can be written in the form

$$T_0 = T + v^2 / 2c_p$$

Since the exhaust velocity is determined by the jet thrust and mass flow rate, $v = F/\dot{m}$, the energy equation for the exhaust jet can be written in terms of the nozzle thrust as,

$$T_0 = T + \frac{\left(F/\dot{m}\right)^2}{2c_p}$$

Therefore, the reduction in total temperature appears as a reduction in thrust at the nozzle exit. However, it

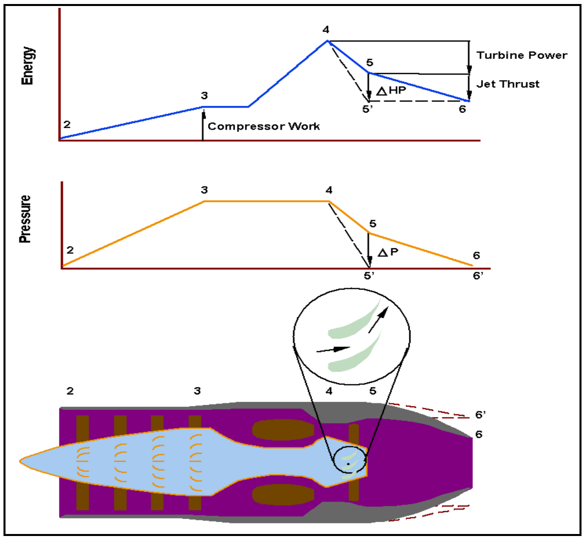

Figure 7: Nozzle Area Controls Turbine Power

reappears as a reduction in stagnation temperature when the jet impinges on the ground during vertical landings, and this reduces heating of the surface material.

The net effect of changing the turbine operating point is to transfer thrust from the engine exhaust jet at the back of the aircraft to the lift jet at the front of the aircraft. The relative magnitude of the energy transferred is illustrated in Figure 8. It is a fraction of the total energy available in the engine, and less than the power being extracted to drive the engine fan and compressor. Although the low pressure spool of the engine does have to be redesigned to handle the additional power, the energy levels are not extraordinary. The technology required to convert an existing military engine to drive a lift fan is comparable to converting the military engine to a high bypass ratio commercial engine. It is well within the state of the art.

The shaft driven lift fan propulsion system is a development of the Tandem Fan propulsion system [2] and the Hybrid Fan engine [3]. The Hybrid Fan engine is shown in Figure 9. Both of these engines combined a low bypass ratio cruise cycle with a high bypass ratio STOVL cycle. In the STOVL cycle, the flow from the engine fan was diverted from the engine core to nozzles at the front of the aircraft. Therefore, the engine fan became the lift fan. However, the operating point of the turbine was not changed to produce additional power to drive the lift fan. In addition, the loss of the supercharging effect of the engine fan on the core flow meant that these engines produced less thrust in the vertical mode than in the cruise mode. The tandem fan engines can be classified between the single cycle Pegasus engine and the dual cycle shaft driven lift fan propulsion system.

Mechanical Drive Components

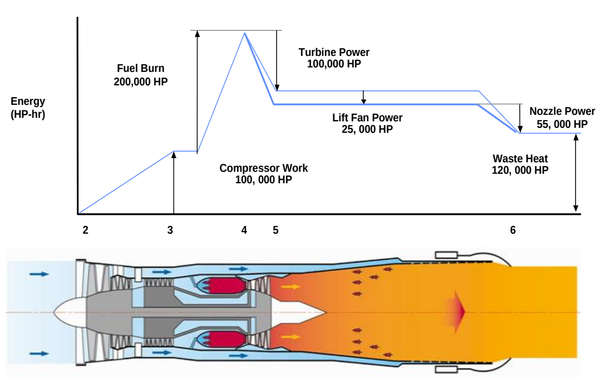

Figure 8: Energy from the Jet Drives the Lift Fan

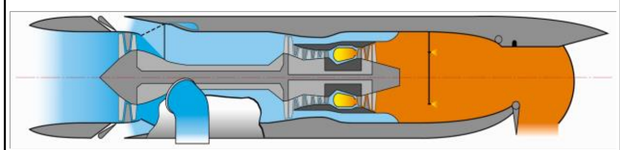

Figure 9: Hybrid Fan Engine

Power is the product of force times velocity. Therefore, the horsepower transmitted by a drive shaft is equal to the product of torque and angular velocity,

$$SHP = \tau \times \omega$$

The shaft must be designed to resist the torque. For a given horsepower, the torque decreases as the rotational velocity of the shaft increases,

$$\tau = \frac{SHP}{\omega}$$

The high rotational speeds typical of jet engines, around 10,000 rpm, make it possible to transmit large amounts of power with relatively small driveshafts. In terms of the maximum unit shear stress of the drive shaft material, σ, and the polar moment of inertia of the shaft, I_p, the torsion formula for round shafts gives for the diameter of the shaft,

$$d = \frac{2\sigma I_p}{\tau}$$

For hollow round shafts, the polar moment of inertia is

$$I_p = \frac{\pi d^4 \left(1 - f^4\right)}{32}$$

in which f is fraction of the shaft diameter that is hollow. The formula for the diameter of the shaft becomes,

$$d = \left[\frac{16 \times SHP}{\pi \omega \sigma \left(1 - f^4\right)}\right]^{1/3}$$

Figure 10 shows how the diameter of an aluminum shaft transmitting 25,000 horsepower varies with the speed of the engine. The lower limit is a solid core shaft and the upper limit is a thin wall shaft with a wall thickness equal

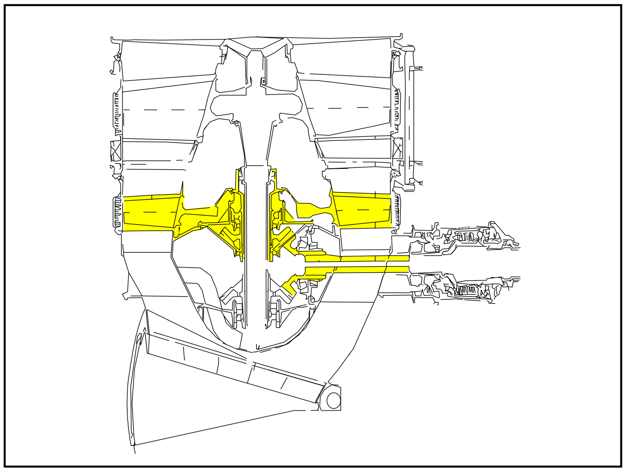

Figure 12: Two Stage Lift Fan with Gearbox

to 5% of the shaft diameter. The solid shaft is smaller, but the thin wall shaft is lighter. The design of a shaft is more complicated than this, because it depends on the number of support bearings and the natural frequencies of the shaft, but an aluminum shaft several inches in diameter can transmit the power required to drive the lift fan.

The clutch that connects the drive shaft to the lift fan has two functions. The first is to reduce the shock of engagement by slipping during the period of engagement. The second is to efficiently transmit the torque of the driveshaft to the lift fan, when the clutch is engaged. The simplest clutches use the friction between two surfaces to accomplish both functions. However, the number of disks and the size of the springs required to press them together in order to transmit 25,000 HP would result in a heavy clutch.

To reduce the size of the clutch, friction is only used to accelerate the lift fan from rest to the relatively low idle speed of the engine before take off, or during approach to the landing area. Less than full power is transmitted under these conditions, so that a small multi-disc friction clutch can be used to perform this engagement. Once the speed of the lift fan matches the engine speed, a mechanical lockup is engaged. This is used to transmit full power when the engine speed is increased for short takeoffs and vertical landings.

The horsepower absorbed by the clutch during the engagement period decreases as the engagement period increases**,**

$$HP = \frac{I\omega^2 / 2}{t}$$

in which the $I\omega^2 / 2$ is the rotational kinetic energy of the lift fan after it is connected to the engine, and t is the time of engagement. As seen in Figure 11, the knee of the curve is near 10 seconds at low engine speeds. This two step engagement strategy permits the design of a relatively lightweight clutch.

Propulsion System Demonstration

Although analysis had shown that the designs of a dual cycle engine, drive shaft, clutch and lift fan are within the state of the art, there were practical concerns regarding the development of such a propulsion system. For example, there were concerns about the weight and efficiency of the gearbox that drives the lift fan, and questions regarding the ability of the engine control system to synchronize the change in nozzle area with the operation of the lift fan, and the ability to rapidly transfer thrust from the engine to the lift fan for pitch control. To demonstrate the feasibility of the shaft driven lift fan propulsion system, the Allison, Pratt & Whitney, and Rolls Royce engine companies built and tested a demonstrator engine. To minimize the costs of this demonstration and show the relatively low risk associated with developing a dual cycle engine, the demonstrator engine and lift fan were assembled from existing engine components.

The production lift fan system is shown in Figure 12. It consists of a two stage counter rotating fan section, with variable inlet guide vanes to modulate the thrust of each stage at constant rotational speed. This arrangement of the fans permits the use of two driven gears, which reduces the load on each gear tooth in half. This keeps the power at a level similar to that currently being used on heavy lift helicopters. Spiral bevel gears will be used to accommodate the speed and torque requirements of the system. The nozzle consists of two telescoping hood segments to deflect the lift fan thrust aft during takeoff.

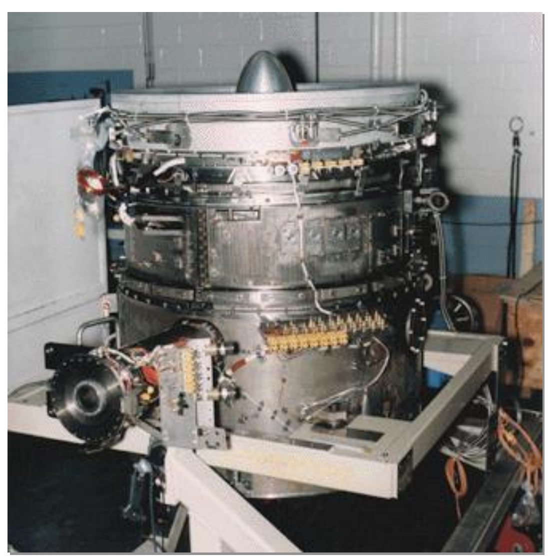

Figure 13: Single Stage Demonstrator Lift Fan

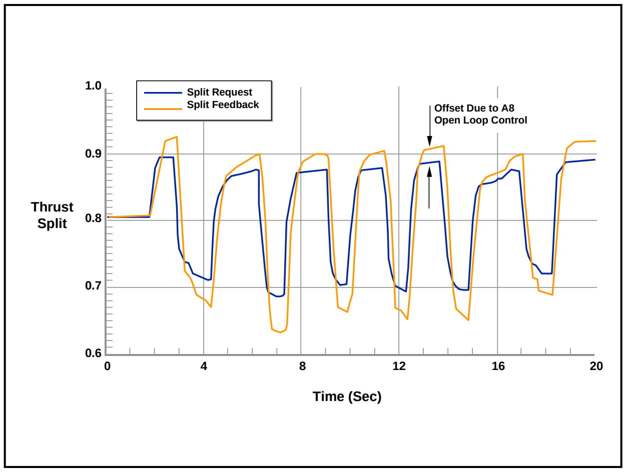

Figure 14: Response to Pitch Control Commands

The demonstrator lift fan shown in Figure 13 represents one stage of the production system. However, the single fan of the demonstrator system operates at the same power level as one stage of the production system. The first stage fan and inlet guide vanes from the Pratt & Whitney F119 engine were used for the lift fan. The Allison Advanced Development Company had gears manufactured using two different processes. The first set had teeth generated and hard finished on the same machine to provide high quality gears with a parallel depth tooth form. The second set were finish ground on a Weiner grinder so that a more sophisticated tooth contact pattern could be produced. Both designs were successfully manufactured. However, the hard finished gears were used in the demonstrator system, because they were the first set completed. Since the ground tooth gear set were also completed successfully, they are preferred for the operational aircraft.

Allison demonstrated the performance of the complete lift fan, gearbox, and drive shaft at the high power gear loading of the operational aircraft [4]. The power transfer efficiency of the gear set was measured. Vertical operation of the lubrication system and the oil cooling system were demonstrated, and the ability of the inlet guide vanes to modulate the fan thrust was shown. The distortion limits of the lift fan were also measured. The successful completion of these tests demonstrated the feasibility of building a lightweight lift fan and gearbox at the design power levels.

The Pratt & Whitney engine company combined the fan and core of a F100-PW-220 engine with the low pressure turbine from the more powerful F100-PW-229 engine to create the dual cycle PW-229 plus engine. The fan drum rotor was modified for attaching the shaft to drive the lift fan, and the fan duct was modified so that the bypass air could be diverted to the ducts that supply the roll control jets. The digital electronic engine control software was modified to control fuel flow and nozzle area on the STOVL operating line of the turbine map. Rolls Royce, Ltd. built the variable area thrust vectoring lift/cruise nozzle and the offtake ducts and nozzles for the roll control jets.

The engine was first run without the lift fan connected to demonstrate operation in the cruise mode. Then the lift fan was connected to demonstrate operation in the STOVL mode. The primary objectives of these tests were to prove the feasibility of changing the operating point of the turbine section to provide power for driving the lift fan, and the ability to rapidly transfer thrust from the cruise engine to the lift fan and back, in order to provide pitch control power. The dual cycle operation of the engine was successfully demonstrated by connecting the lift fan to the engine, and then increasing engine speed to full power along the STOVL operating line [4].

Pitch control is obtained by coordinating the area change on the cruise engine nozzle with the movement of the lift fan inlet guide vanes. At constant engine speed, increasing the nozzle area produces more turbine power and reduces the engine thrust. Opening the inlet guide vanes produces more lift fan thrust. If the movement is coordinated, thrust is transferred from the aft nozzle to the lift fan, while the total thrust remains constant. This provides a large pitching moment which can be used to control the aircraft in hover. Since thrust transfer is accomplished without changes in engine speed, high response rates are achieved. In addition, the pitch control loop is decoupled from the total thrust control loop which is used to command changes in sink rate.

Figure 14 shows the response of the propulsion system to a command to rapidly cycle the thrust between maximum nose up and maximum nose down moments. Six complete cycles were performed in 16 seconds. The response rate is excellent. The larger variation in the peak to peak thrust split is due to differences in the nozzle discharge coefficient between the small scale nozzles which were used to design the nozzle schedule and the full size nozzles. This illustrates the differences that can be expected when small scale data is used to design full size hardware. The control schedules could be corrected to eliminate the overshoot. However, this would not change the dynamic response, and therefore was not felt to be necessary.

This demonstration of the shaft driven lift fan propulsion system was highly successful. More than 40 hours of static testing were accomplished with no problems in the operation of the engine, mechanical drive system, or lift fan. The test proved the feasibility of changing the cycle of the cruise engine to provide power to drive the lift fan, and demonstrated the capability to rapidly transfer thrust back and forth from the cruise engine to the lift fan to provide pitch control. As a result of these tests, the propulsion system was installed in a full size airframe model and operated for another 160 hours to study jet effects in hover and transition [5].

Summary

The shaft driven lift fan provides a solution to many of the problems associated with the development of a supersonic STOVL strike fighter. It provides high levels of thrust augmentation, with a relatively cool, low pressure footprint. The aircraft is balanced in hover because thrust is transferred from the rear of the aircraft to the front, without increasing frontal area. Pitch and roll control power are also obtained by transferring thrust around the aircraft without changing total lift. Since the cruise engine is optimized for conventional flight, the performance of the engine is not penalized for STOVL capability. Removing the lift fan creates a conventional strike fighter with little penalty for commonality.

The feasibility and mechanical integrity of the shaft driven lift fan propulsion system has been successfully demonstrated. Analysis has shown that up to 25,000 shaft horsepower can be extracted from the exhaust jet of a modern turbofan engine to drive a lift fan. Due to the high rotational speed of the engine, this power can be transmitted with a drive shaft less than 10 inches in diameter. A relatively lightweight clutch can be employed by engaging the lift fan at low engine speeds, and using mechanical lockup to transmit the full engine power at high speeds.

Practical concerns regarding the ability of the engine control system to synchronize the operation of the lift fan and cruise engine were addressed by testing a demonstrator propulsion system. The Allison Advanced Development Company demonstrated the performance of the fan, gearbox, and shaft under the high power gear loading of the production system. The Pratt & Whitney engine company assembled a dual cycle F110-PW-229 plus engine from existing components, and Rolls Royce provided a variable area thrust vectoring nozzle. Testing of the assembled components proved the feasibility of changing the engine cycle to produce jet thrust or shaft horsepower, and of quickly transferring enough thrust to control the aircraft in hover. A total of 200 hours of trouble free operation were achieved during testing of the propulsion system

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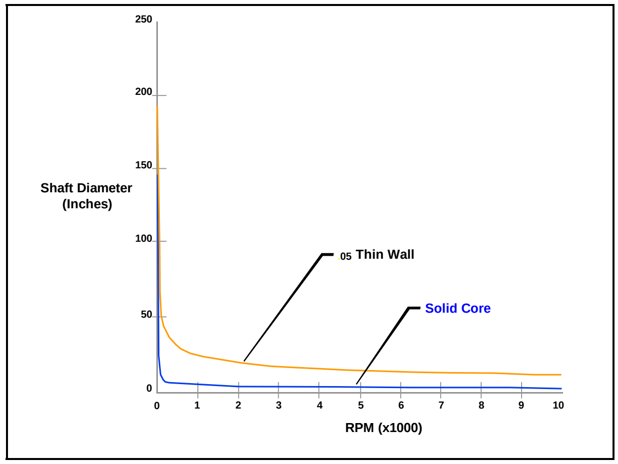

Figure 10: Driveshaft Diameter Decreases with RPM

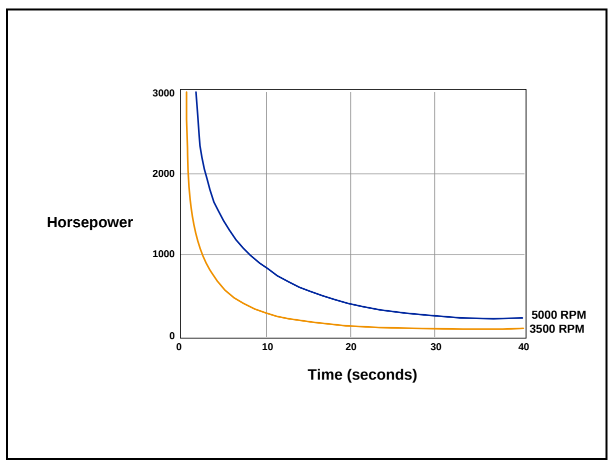

Figure 11: Clutch Size Decreases with Engagement Time