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Joint Strike Fighter Dual-Cycle Propulsion System

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The Joint Strike Fighter (JSF) is a family of aircraft that will be built in conventional, naval, and short-takeoff-and-vertical-landing (STOVL) variants. The key to the development of this family of aircraft is a new dual-cycle propulsion system, which is used to convert some of the jet thrust to shaft horsepower in order to power a lift fan in the STOVL variant. The theoretical basis for the dual-cycle operation of this engine will be presented. Some results of the engine test and development program conducted by Pratt and Whitney and Rolls Royce and the JSF STOVL flight-test program will also be discussed. Potential future applications of this dual-cycle propulsion concept to STOVL transport aircraft, compound rotorcraft, and for takeoff noise reduction will be described.

I. Introduction

THE F-35 Joint Strike Fighter will combine the supersonic performance of the F-16C Falcon with the short-takeoff-and-vertical-landing (STOVL) capabilities of the AV-8B Harrier, while providing greater range and increased survivability. There will be three variants: a conventional takeoff-and-landing variant for the U.S. Air Force, a short-takeoff-and-vertical-landing variant for the U.S. Marine Corps and United Kingdom, and a carrier-based variant for the U.S. Navy. These three variants are shown in Fig. 1. The naval variant has a somewhat larger wing, in order to reduce landing speeds for carrier operations. This also gives it somewhat greater range, both by reducing the induced drag and by providing additional volume for fuel.

The STOVL variant has a shorter canopy and a slight bulge behind the cockpit. These accommodate a lift fan installed in a bay between the inlet ducts. As shown in Fig. 2, the lift fan is driven by a drive shaft extending from the front of the cruise engine. This lift fan provides 18,000 lbs of thrust, almost half of the total lift in hover. A thrust-vectoring nozzle at the rear of the aircraft deflects the core thrust of the cruise engine, which provides another 17,000 lbs of thrust. A roll control nozzle in each of the wings is fed by fan air diverted from the cruise engine. These provide approximately 2500 lbs of thrust apiece. The two main lift nozzles and the two auxiliary roll control nozzles constitute a two plus two hover lift and control system.

The cruise engine is a conventional mixed-flow turbofan, providing more than 25,000 lbs of dry thrust. The lift fan is not connected to the engine during cruise. For STOVL operations, the engine operating point is changed so that its turbine section extracts additional energy from the exhaust jet and converts it to shaft horsepower. This power is delivered to the lift fan by engaging a clutch at the end of the drive shaft extending from the front of the engine.

The airplane is controlled in pitch by shifting power between the lift fan and the cruise engine nozzle. The cruise engine nozzle rotates from side to side in order to control the aircraft in yaw. To control the aircraft in roll, the area of the auxiliary nozzle on one side is opened, and the nozzle on the other side is closed. The total thrust remains constant while the thrust of the nozzle pairs are varied to provide control forces.

This novel shaft-driven lift fan propulsion system provides high levels of thrust for short takeoff and vertical landing, while reducing the temperature and velocity of the lift jets. Because the engine is optimized for mission performance, there is no STOVL penalty in fuel consumption during cruise. The added weight of the lift fan is less than that of alternative lift systems and also less than the weight added to the naval variant to make it carrier suitable. There are no constraints on the engine installation, so that the Air Force variant is very conventional, with inlets on the sides and the engine at the back.

The purpose of this paper is to describe the conception, functioning, and development of the shaft-driven lift fan propulsion system and to offer some speculations on future applications of this innovative engine concept. A combination of analysis, design, and flight-test information will be presented. In the next section, the dual-cycle operation of the propulsion system is described. Ground tests of a demonstrator engine are described in the section after that. The following section summarizes the flight demonstration of the STOVL variant of the Joint Strike Fighter (JSF). The last section includes some speculations on future applications of this new propulsion concept.

II. Principle of Operation

The Marines' requirement for a supersonic STOVL Strike Fighter meant that the propulsion system, always an important part of any new airplane program, was a particularly significant factor in the development of the Joint Strike Fighter. Short takeoffs and vertical landings require thrust-to-weight ratios greater than one. However, typical dry thrust-to-weight ratios of combat aircraft are on the order of only T/W ~0.75. Increasing the size of the engine to provide sufficient dry vertical thrust is not a satisfactory solution because the larger engine imposes weight and drag penalties. Also, when the oversized engine is throttled back for cruise, fuel consumption is significantly increased. Therefore, some method of thrust augmentation is necessary.

Increasing vertical thrust by afterburning is not a satisfactory solution either because of the high temperatures and velocities of the lift jets produced by this approach. As the following simple analysis shows, the most efficient way to increase thrust is to increase mass flow. By definition, thrust is the product of mass flow and velocity,

$$T = mv \tag{1}$$

in which m is the mass flux of the jet and v is the jet velocity. To increase the jet thrust at constant power, either the mass flux M can be increased,

$$T_M = Mv \tag{2}$$

or the velocity V can be increased:

$$T_V = mV \tag{3}$$

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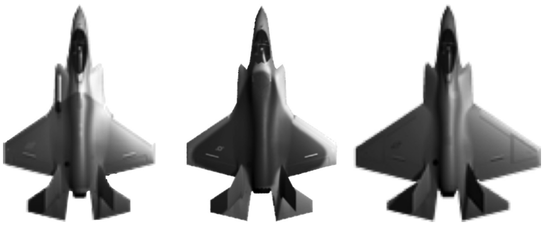

Fig. 1 JSF family of aircraft.

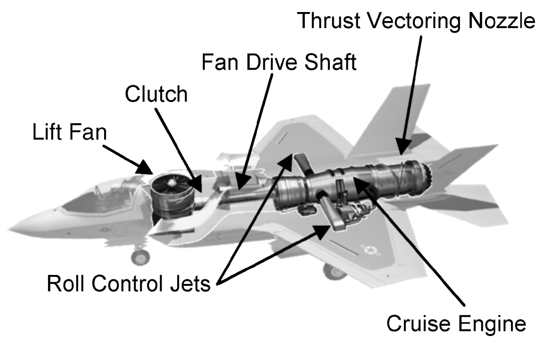

Fig. 2 Lift fan propulsion system.

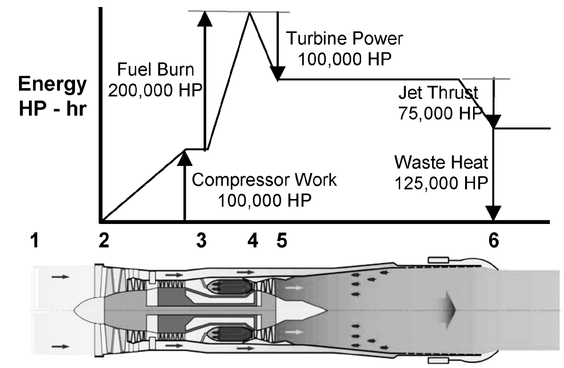

Fig. 3 Energy variations through a jet engine.

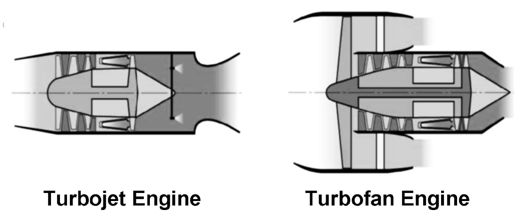

Fig. 4 Power turbine drives the engine fan.

The ratio of the thrust for these two cases is proportional to the ratio of the mass flows and inversely proportional to the ratio of the velocities,

$$T_M/T_V = (M/m)(v/V) \tag{4}$$

If the power $P = TV$ to produce each of the jets is the same, then

$$T_M v = P = T_V V \tag{5}$$

or, by substitution,

$$Mv^2 = P = mV^2 \tag{6}$$

Solving for the velocity ratio,

$$v/V = (m/M)^{\frac{1}{2}} \tag{7}$$

and substituting in Eq. (4) gives

$$T_M/T_V = (M/m)^{\frac{1}{2}} \tag{8}$$

so that thrust per horsepower increases with the square root of the mass flow.

Connecting the lift fan to the cruise engine in the STOVL variant of the F-35 roughly doubles the mass flow of the propulsion system and therefore increases the thrust by about 40%. However, a lift fan cannot be simply connected to the front of a turbofan engine. The lift fan would act as a brake, absorbing power and causing the engine to slow down and stall. In the F-35 propulsion system, power to drive the lift fan is extracted from the exhaust jet of the cruise engine.

This process can be understood by considering the changes in the energy of the air passing through a conventional turbojet engine cycle, as illustrated in Fig. 3. The magnitude of the energies in this figure is representative of the newest generation of engines. Energy is added to the incoming air by the work of compression as the air passes through the fan and compressor sections of the engine. This energy appears as an increase in both the pressure and temperature of the air. Following compression, the burning of fuel in the combustor section further increases the energy by raising the temperature of the air at constant pressure.

Energy is then extracted from this hot, high-pressure gas by expanding it through the turbine section. Because the turbine drives the engine fan and compressor sections, the amount of energy extracted from the gas by the turbine section is the same as the amount added by the compressor section, neglecting losses caused by real fluids effects within the engine. This equality is ensured by the speed of the engine. If the turbine does not extract enough power, the engine slows down, reducing the work of the compressor. If the turbine extracts extra power, the engine speeds up until the compressor absorbs all of the power. Extracting this energy produces a drop in the pressure and temperature of the gas leaving the turbine section.

The energy remaining in the gas that leaves the turbine section is equal to the energy added by the combustion of the fuel, less losses caused by real fluid effects within the engine. This energy is then converted to thrust by expanding it through an exhaust nozzle. The temperature and pressure of the gas are further reduced as it expands through the nozzle. Although the static pressure of the gas returns to atmospheric pressure at the exit of the nozzle, the temperature of the exhaust jet remains higher than the atmospheric temperature, so that some energy is lost as waste heat. This loss is unavoidable, even in an ideal, frictionless engine.

To produce a turbofan or turboshaft engine, another turbine section is added to the basic gas generator. The energy extracted by this power turbine is used to drive an additional fan or propeller, as shown in Fig. 4. The power turbine and fan are connected to each other, but are mechanically independent of the rotating sections of the gas generator. Because additional energy is extracted from the exhaust gas, the thrust of the primary exhaust jet is reduced. In a turboshaft engine, the additional turbine section extracts all of the useful energy from the exhaust flow, so that the remaining jet thrust is negligible. However, the fan or propeller transfers this energy to a larger mass of air, so that there is a net thrust gain, as given by Eq. (8).

The innovative feature of the engine in the Joint Strike Fighter is the capability it has to be switched between turbofan and turboshaft cycles. In the STOVL variant, additional energy is extracted from the turbine exhaust gas, converted to shaft power, and then transferred to a larger mass of air by the lift fan. However, the power to drive the lift fan is not extracted with a separate power turbine, but by changing the operating point of the turbine that drives the engine fan.

This process is illustrated in Fig. 5, which shows the performance map of a typical turbine section. At any point on this map, the power produced by the turbine is given by the expression,

$$\text{Turbine Power} = nmC_pT_{04}\left[1 - (P_5/P_4)^{(g-1)/g}\right] \tag{9}$$

in which n is the turbine efficiency, g is the ratio of specific heats, $P_5/P_4 < 1$ gives the decrease in static pressure across the turbine

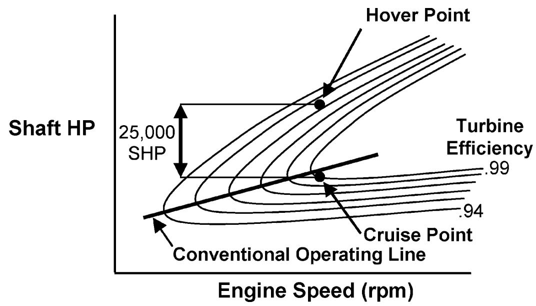

Fig. 5 Turbine performance map.

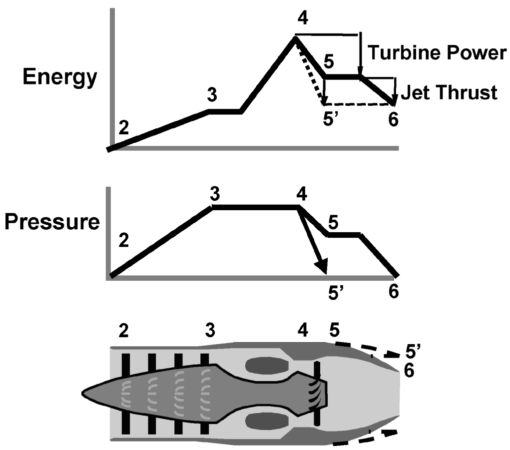

Fig. 6 Nozzle area controls turbine power.

section, and T_{04} is the stagnation temperature of the gas entering the turbine section.

The usual way of increasing engine thrust is by increasing the fuel flow to the engine, which increases T_{04}. The additional power to the turbine increases the speed of the engine until the power absorbed by the compressor matches the power produced by the turbine, and the engine speed stabilizes. Because the engine speed is higher, the mass flow increases, and the engine produces more thrust. The locus of steady-state matching conditions as a function of fuel flow defines the engine operating line, which is the diagonal running from the lower left to the upper right in Fig. 5. The turbine and compressor are designed so that the turbine power and compressor power are matched near the point of maximum efficiency at every speed.

However, in the STOVL variant of the F-35, the requirement is to increase the power of the turbine at the maximum engine speed. But, at the maximum speed the turbine inlet temperature T_{04} is at the material limit of the turbine blades, by design. As a result, the gas temperature cannot be further increased to provide additional power to drive the lift fan. Instead, in the F-35 the additional power is obtained by increasing the pressure drop $(P_4 - P_5) > 1$ across the turbine section.

The variation of static pressure through the engine is shown in Fig. 6. The pressure rises through the compressor, remains constant through the combustor, and then drops through the turbine section and nozzle, in two steps. This is shown by the solid line in the figure. At any engine speed, the static pressure at the turbine inlet is determined by the pressure rise across the compressor. However, the pressure at the turbine exit is controlled by the engine exhaust nozzle. Increasing the nozzle-exit area reduces the pressure drop across the nozzle $(P_5 - P_6)$, so that the pressure drop across the turbine $(P_4 - P_5)$ must increase to compensate.

This is described by the simple equation that the pressure drop across the turbine plus the pressure drop across the nozzle is equal to the total pressure drop, which is constant at any engine speed,

$$(P_4 - P_5) + (P_5 - P_6) = P_4 - P_6 \tag{10}$$

For example, increasing the nozzle-exit area so that $A_6 = A_5$ (as shown by the dashed line in Fig. 6) causes the static pressure at the turbine exit to drop to atmospheric pressure, so that $P_5 = P_6$. The entire pressure drop then occurs across the turbine, which produces more shaft horsepower, while reducing the thrust of the core flow. Another way to look at it is that the channels between the turbine vanes form an array of tangential nozzles that spin the turbine, as sketched in Fig. 6. Opening the engine nozzle decreases its thrust while increasing the thrust of the turbine nozzles. Therefore, as seen in Eq. (9), the performance of a turbofan engine can be modulated by adjusting the nozzle-exit area (changing P_5), as well as by varying T_{04}.

At constant engine speed, opening the nozzle-exit area reduces the thrust of the engine and produces more turbine power. Conversely, opening the lift fan inlet guide vanes produces more fan thrust. Engaging the clutch connecting the engine to the lift fan at the same time as the exhaust nozzle is opened transfers the additional power to the lift fan, instead of accelerating the engine. The process is similar to depressing the accelerator on an automobile with a manual transmission. When the clutch is disengaged, opening the throttle causes the engine to accelerate. But engaging the clutch at the same time as the throttle is opened transfers the power to the drive wheels, and the car accelerates instead.

The change in turbine power obtained by changing the nozzle-exit area is illustrated by the two different operating points in Fig. 5. The lower point is the conventional operating point, and the upper point is the STOVL operating point, used when the lift fan is engaged. In the F-35, almost 25,000 shaft horsepower can be extracted before the turbine section reaches its stall limit. The thrust that can be developed with this much power depends on the diameter and pressure ratio of the lift fan. For example, with fan diameters in the range of 40 to 50 in., the thrust is in the range of 15,000 to 20,000 lb.

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 Fig. 7. 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 in the conventional cycle. Although the low-pressure spool of the engine does have to be redesigned to handle the extra power, the power levels are not extraordinary. The technology required to convert an existing engine to drive a lift fan is comparable to converting an existing military engine to a high-bypass-ratio civil engine.

Pitch control is obtained by coordinating small, rapid area changes of the cruise engine nozzle with rapid movement of the lift fan inlet guide vanes. The effect is to transfer thrust from the aft nozzle to the lift fan, or the reverse, while the total thrust remains constant. This provides a large pitching moment. Because 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 vertical velocity.

The shaft-driven lift fan propulsion system is a development of the Tandem Fan engine[1] and the Hybrid Fan engine.[2] Both of these engines combined a low-bypass-ratio cruise cycle with a high-bypass-ratio STOVL cycle. A schematic of this type of engine is shown in Fig. 8. The engine fan is moved forward by extending the fan drive

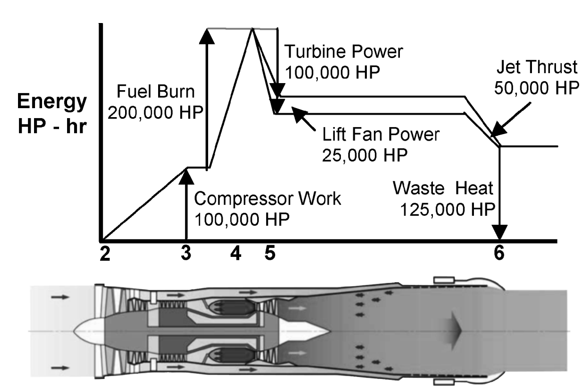

Fig. 7 Energy from the jet powers the lift fan.

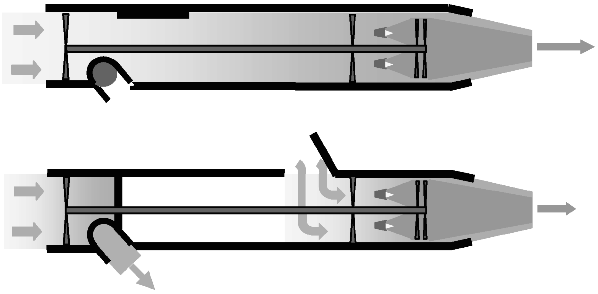

Fig. 8 Variable bypass tandem fan engine.

shaft and the engine case. In the STOVL cycle, the flow from the engine fan would have been diverted to nozzles at the front of the aircraft, so that the first stage of the engine fan would become a lift fan. An auxiliary inlet would be opened to provide air to the engine core.

However, the operating point of the turbine section would not have been changed to produce additional power to drive the lift fan. Furthermore, diverting the lift fan flow meant the loss of its supercharging effect on the core flow. Therefore, these engines would have produced slightly less thrust in the STOVL cycle than in the cruise cycle, despite the increased mass flow. The tandem fan engines can be classified between conventional single-cycle engines and the dual-cycle shaft-driven lift fan propulsion system.

III. Ground-Test Program

Analysis and simulation with an engine deck showed that a dual-cycle propulsion system was theoretically feasible. However, there were practical concerns regarding the development of such a propulsion system. For example, there were concerns about the weight and reliability of the 25,000-hp drive shaft and gearbox that drive the lift fan. There were also questions regarding the ability of the engine controls to synchronize the operation of the lift fan with the change in engine nozzle area, especially to rapidly transfer thrust back and forth from the engine to the lift fan for pitch control. To demonstrate the feasibility of the shaft-driven lift fan propulsion system, a demonstrator engine was built and tested. To minimize the costs of this demonstration, the demonstrator engine and lift fan were assembled from components of existing engines.

The production lift fan system consists of a two-stage counter-rotating fan section. This arrangement of the fans permits the use of two driven gears, which reduces the load on each driven gear in half. This keeps the power on each gear set at a level similar to that currently being used on heavy-lift helicopters. The demonstrator lift fan had only a single stage, but it was operated at the same power level as one stage of the production system. The first stage fan and inlet guide vanes from the Pratt and Whitney F119 engine were used for the demonstrator lift fan. The performance of the assembled lift fan, gearbox, and drive shaft were demonstrated at the same power levels as the operational aircraft.[3] These tests were performed at the Rolls Royce facility in Indianapolis, Indiana.

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 flight weight lift fan and gearbox at the required power levels.

To demonstrate that the operating point of a turbofan engine can be changed to extract additional power for driving a lift fan, the engine fan and core of the relatively low-bypass-ratio Pratt and Whitney F100-PW-220 engine was combined with the low-pressure turbine from the higher-bypass-ratio F100-PW-229 engine to create the dual-cycle PW-229-Plus demonstrator engine. The drum rotor of the engine fan was modified in order to attach the driveshaft for the lift fan, and the engine case was modified so that the bypass air could be diverted to the ducts that supply the roll control jets. A variable-area thrust-deflecting nozzle was mounted to the engine case. The digital electronic engine control software was modified to control fuel flow and nozzle area on the STOVL operating line of the turbine map.

Fig. 9 Large-scale Joint Strike Fighter model.

The engine was first run with the lift fan disconnected to demonstrate operation in the cruise mode. Then the lift fan was connected to demonstrate operation in the STOVL mode. This proved that the operating point of a turbine section could be changed to provide power to drive a lift fan. To show that the system could provide pitch control power, the ability to rapidly transfer thrust from the cruise engine to the lift fan and back was also demonstrated.

This demonstration of the shaft-driven lift fan propulsion system was highly successful. More than 40 h 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. These tests were performed at the Pratt and Whitney facility in West Palm Beach, Florida.

At the conclusion of these tests, the propulsion system was installed in a full-size airframe model and operated for another 160 h to study jet effects in hover and transition.[4] This model is shown in Fig. 9. The model was first suspended from the outdoor hover test facility at the NASA Ames Research Center. Measurements showed that the jet suckdown out of ground effect was less than 3% of the total lift and that the jet fountain and lift improvement devices limited suckdown at wheel height to less than 7%.

The pressures and temperatures of the jet flowfield around the aircraft model were also measured. At the same thrust levels as the Harrier, the jet footprint of the lift fan system was more benign. The cool forward jet from the lift fan blocked the hot engine exhaust gases from flowing forward into the engine inlets. No hot gas ingestion was observed in 30 min of hovering suspended 1 ft off the ground.

The model was then installed in the 80 × 120 ft low-speed wind-tunnel test section at the NASA Ames Research Center. Lift and drag measurements showed excellent short takeoff performance and a wide corridor for transition from hover to wing borne flight. It also showed sufficient control power for acceleration and deceleration during transition, as well as yaw control power for cross winds up to 30 kn. This program demonstrated the feasibility of the shaft-driven lift fan propulsion system and reduced risk to Technology Readiness Level 5.

IV. X-35 Flight-Test Program

The X-35 flight-test program had three primary goals: first, to demonstrate that it is possible to build highly common conventional, STOVL, and naval variants of a Joint Strike Fighter; second, to show that a STOVL aircraft can achieve supersonic speeds; and third, to demonstrate carrier suitable handling qualities and structural integrity of the naval variant. The first goal was achieved by

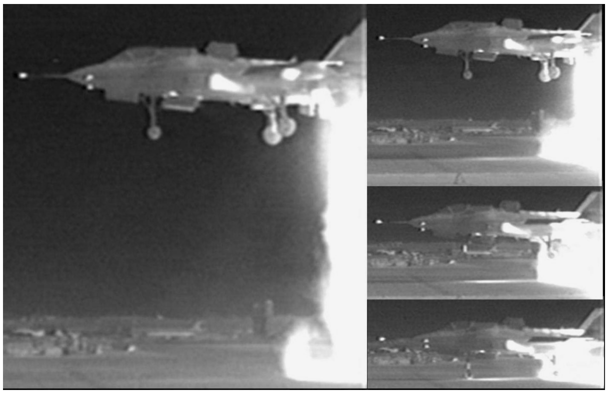

Fig. 10 Lift fan jet blocks hot gas ingestion.

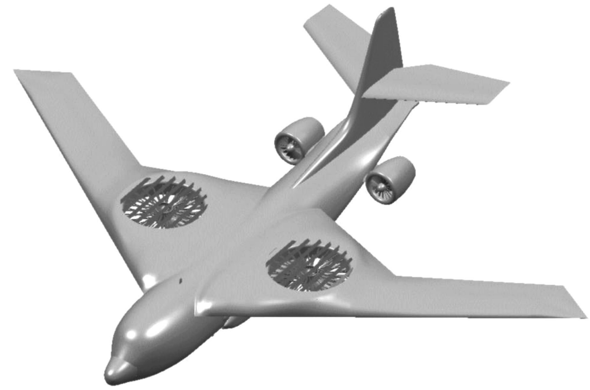

Fig. 11 Shaft-driven fan-in-wing transport.

building two separate airframes and demonstrating that they could be converted to any of the three variants. Because the conventional and STOVL variants of the JSF have the same wing planform, the first airframe was initially flown as the conventional variant and then converted to the STOVL variant. The second airframe was initially fabricated as the STOVL variant, but was modified and flown as the naval variant.

The first flight of the X-35A conventional variant was on 24 October 2000. Over the next 30 days it averaged a flight a day. It was flown not only by Lockheed Martin and BAE pilots, but also by U.S. Department of Defense and U.K. MOD pilots. It met or exceeded all of its flight-test objectives, demonstrating excellent handling qualities, and fighter-like performance, including maneuverability, agility, and supersonic speed. These tests were conducted at Edwards Air Force Base, California.

During December and January, this aircraft was converted into the STOVL X-35B variant by the installation of the lift fan and thrust-vectoring nozzle. After tethered testing of the installed engine, lift fan, and reaction control system during the spring, on 20 July 2001 the X-35B became the first aircraft in history to fly supersonically, hover, and land vertically. As seen in the infrared photographs of a vertical landing shown in Fig. 10, the jet from the lift fan provides a barrier that blocks ingestion of the hot engine exhaust gases.

The second aircraft, configured as the X-35C Naval variant, made its first flight on 16 December 2000. During 33 h of flight testing at Edwards Air Force Base, it successfully demonstrated the use of a side-stick controller in simulated carrier approaches. In February 2001 the X-35C was flown from Edwards Air Force Base, California, to the Patuxent River Naval Air Station, Maryland, becoming the first X-Plane in history to make a coast to coast flight across the United States.

Another 33 h of flight testing were completed at Patuxent River. The X-35C also achieved supersonic speeds and accomplished more than 250 field carrier landing practice demonstrations. These showed the carrier suitability of the naval variant. Flight testing of the three X-35 variants reduced risk of the JSF airframe and propulsion systems to Technology Readiness Level 6.

V. Future Applications of the JSF Engine Cycle

An obvious application for the Joint Strike Fighter propulsion system would be in the development of a STOVL transport aircraft. However, the F135 engine is optimized for use in supersonic aircraft, so that it has too much thrust for direct application to a subsonic transport aircraft. For example, four JSF propulsion systems would provide almost 160,000 lb of vertical lift, enough for the vertical landing of a C-130. On the other hand, just one of these engines has more thrust at idle power than the cruise drag of a C-130! Even with three engines shut down, it would be difficult to slow the aircraft to a hover.

Nevertheless, the concept of the shaft-driven lift fan might be used to develop a propulsion system in which a smaller engine drives a larger lift fan. This could provide as much vertical thrust, with a better match to the required cruise thrust. Such a large lift fan might be incorporated in the wing of the aircraft, as illustrated in Fig. 11. Because the power could be gradually transferred from the lift fan to the cruise engine, this aircraft would be easier to fly through conversion than previous fan in wing concepts.

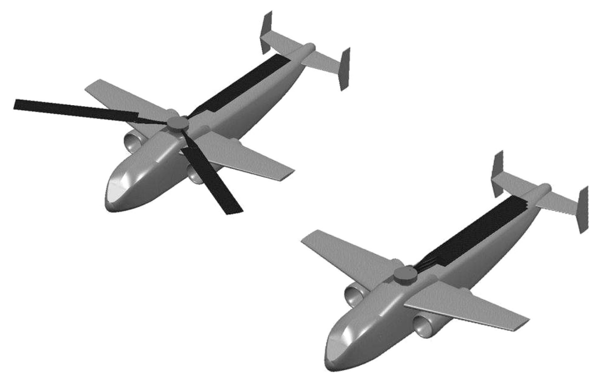

Fig. 12 Dual-cycle stowed rotor aircraft.

Similarly, the dual-cycle concept could be utilized to develop a compound rotorcraft. Instead of a lift fan, the driveshaft would be used to a power a helicopter rotor. The aircraft would have a small wing, as shown in Fig. 12. After vertical takeoff, power would be transferred to the exhaust jet, and the aircraft would accelerate. As the wing began to develop lift, the rotor would be unloaded. The weight of the aircraft would be gradually transferred to the wing. At high speeds, the rotor would be stopped and stowed. The process would be reversed to hover and land. Such an aircraft could hover as well as a helicopter, but fly significantly faster.

Takeoff noise has become a major constraint on airport expansion and limited use of the Concorde SST. A dual-cycle system incorporating an axial fan could be developed to boost takeoff thrust, while reducing jet noise. Such an engine might resemble the tandem fan engines. However, the front fan would be used to increase the bypass ratio on takeoff, but be feathered during cruise. Extracting power from the cruise jet during takeoff would reduce its velocity and noise, while driving the auxiliary fan would boost thrust.

There are other interesting possibilities. Removing the lift fan from the JSF airframe leaves a 50-ft^3 cavity with over 25,000 hp available to run a powerful radar, jammer, or other electronic equipment. The maximum dry thrust would be reduced by 30% or so to provide this power, but the remaining thrust would be adequate for subsonic cruise and could be restored or boosted with partial afterburning.

VI. Conclusions

The shaft-driven lift fan provides a solution to many of the problems associated with the development of a supersonic short-takeoff-and-vertical-landing (STOVL) strike fighter. It provides high levels of thrust augmentation, with a relatively cool, low-pressure footprint. The lift fan does not increase cross-sectional area, reducing wave drag. Because thrust is transferred from the rear of the aircraft to the front, the aircraft is balanced in hover. Pitch and roll control power are obtained by transferring thrust around the aircraft without changing total lift. Because the cruise engine is optimized for conventional flight, the performance of the aircraft is not penalized for its STOVL capability. Removing the lift fan creates a conventional strike fighter with little penalty for commonality. Although the Joint Strike Fighter lift fan propulsion system might be designed for supersonic aircraft, the dual-cycle concept can be applied to fan in wing or rotorcraft systems to provide similar advantages for subsonic transport aircraft.

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