F-35 Air Vehicle Technology Overview

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D. F-35B STOVL Lift System

1. Background

For more than 50 years, fighter aircraft designers have vigorously pursued the speed and range of a conventional jet while achieving the basing flexibility of vertical takeoff and landing (VTOL). Numerous STOVL concepts have been developed over the decades, all with compromises that limited the effectiveness of the aircraft. The F-35B STOVL lift system successfully achieved a breakthrough that redefines the relationship between conventional thrust and vertical propulsive lift. Moreover, it achieves that with major increases in performance, efficiency, and safety. This elegant integration results in a relatively simple engine-driven LiftFan. It has an enabling engine powerful enough to achieve a lift-to-thrust ratio of approximately 1.5-to-1 (Fig. 16) – a significant increase over direct lift designs. The shaft-driven LiftFan provides high levels of thrust augmentation with a cool, low-pressure footprint, sufficient control power, and efficient packaging in the airframe design. Since the main engine is primarily optimized for conventional flight, the propulsion system performance is not compromised for its vertical lift capability. The LiftFan augments vertical flight similarly to the way an afterburner augments high-speed performance [31]. The lift fan provides an additional ingenious benefit: the (relatively cool) thrust exhaust protects the main engine inlet and forward portions of the aircraft from hot gas re-ingestion or damage.

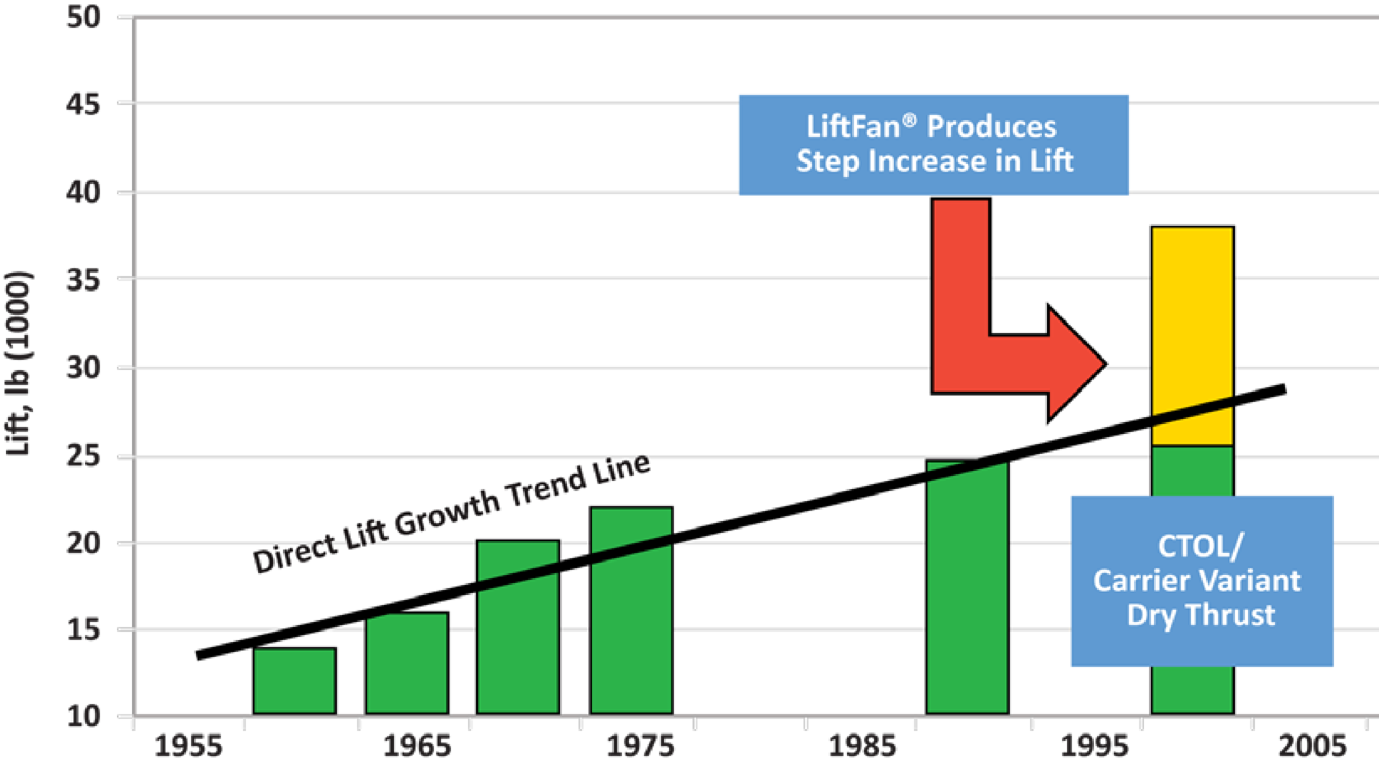

Fig. 16 Revolutionary step increase in vertical lift.

In addition to achieving powerful lift thrust, a STOVL aircraft must achieve sufficient control power in each axis to successfully transition through the wingborne, semi-jetborne, and jetborne flight phases. The F-35B STOVL lift system accomplishes this through several key components (Fig. 17):

1) LiftFan clutch and driveshaft: to selectively transfer power from the main engine to the LiftFan;
2) Variable area vane box nozzle (VAVBN): to control the LiftFan exit area and fore-aft thrust vectoring;
3) Roll post nozzles: to redirect main engine fan air through under-wing nozzles for roll control; and
4) 3BSM: to vector the main engine nozzle fore-aft and laterally for yaw control.

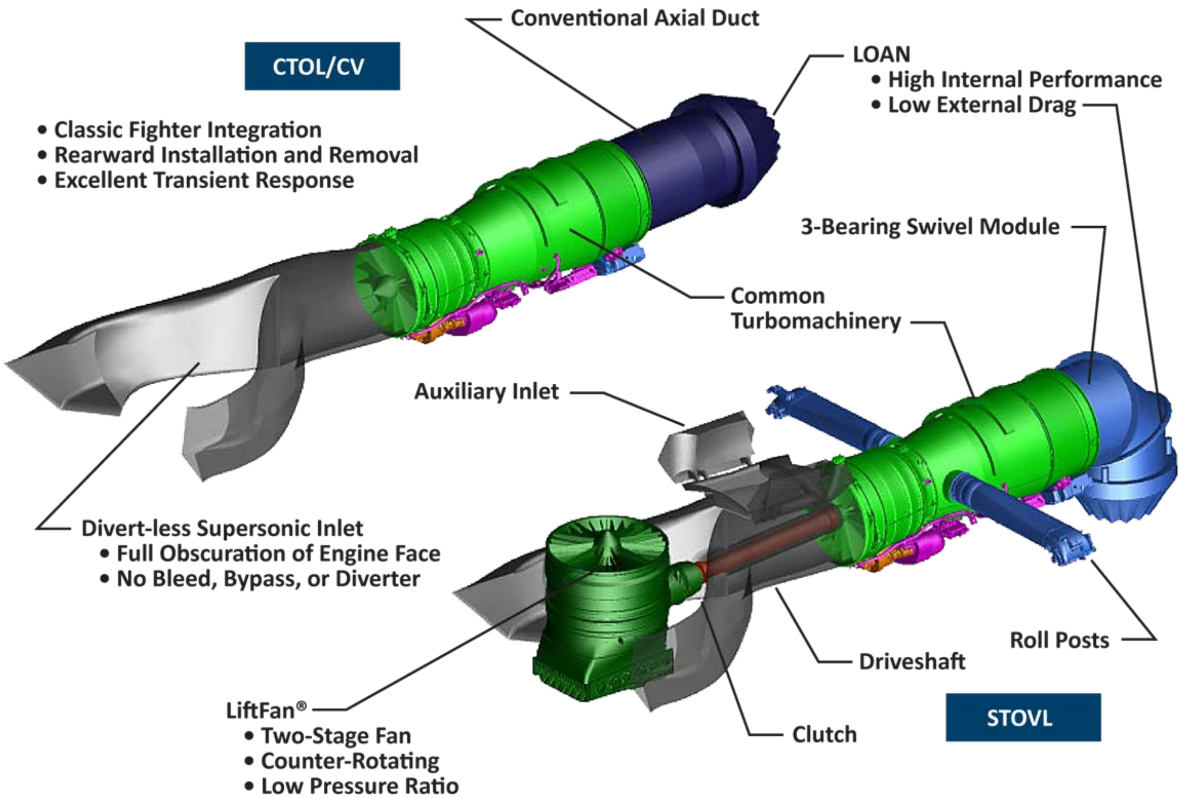

Fig. 17 Comparison of F-35 conventional and F-35B STOVL lift systems.

2. LiftFan Development

The F-35 LiftFan system is the overarching characteristic of the F-35B STOVL variant. It underwent years of technology development and maturation by Lockheed Martin and F-35 propulsion contractors Pratt & Whitney and Rolls-Royce. Initial work began in the late 1980s with STOVL JSF studies sponsored by the Defense Advanced Research Projects Agency. Lockheed Martin, General Dynamics, Boeing St. Louis (then McDonnell Douglas), and Boeing all developed concepts with different technologies for generating vertical lift [34]. These studies led to the ASTOVL competition that Lockheed Martin won with the shaft-driven LiftFan propulsive concept. This effort eventually evolved into the JSF concept demonstration phase resulting in the X-35B flight demonstration.

Rolls-Royce's LiftFan is a novel, counter-rotating concept with a bladed disk (blisk), two sets of stationary vanes, and a set of variable inlet guide vanes (VIGVs). The VIGVs provide the thrust variation from maximum to idle necessary for the VTOL application. The gearbox distributes 29,000 horsepower to the LiftFan rotor stages. The load capacity and envelope characteristics were key to providing an industry-first 30-1 horsepower-to-weight ratio. The previous norm (in earlier aircraft) was a ratio of no more than 15-to-1, which was then doubled.

The gearbox is integral to the LiftFan unit and employs counter-rotating output shafts to simplify geometry and reduce gear and bearing loads. VIGVs on the first fan stage provide thrust modulation. Lubrication for the LiftFan bearings and gearbox is provided by the LiftFan lubrication system, which is independent from the main engine lubrication system. The Rolls-Royce LiftFan is designed to operate throughout the entire speed range of the main engine.

One of the key challenges in transitioning the concept development to production was in the LiftFan's aeromechanical rotor modes. These caused operating restrictions (time at certain LiftFan speeds) on the X-35B. The spatial pressure distortions in the inlet flow field excited resonance modes in the LiftFan turbomachinery, becoming a high-cycle fatigue or aeromechanics concern. This was addressed in the F-35B by redesigning the upper LiftFan door configuration to reduce flow angularity and distortion. It was also addressed by redesigning the LiftFan rotor (hollow blades, blisk) that attenuated the modal responses.

3. LiftFan Clutch Development

Shaft/clutching functionality was achieved with both hardware and software functionality. Pioneering shaft, clutch, and gearbox designs permitted the development of a lightweight, high-speed (8000 rpm) drive train. A unique closed-loop clutching system provides precise control resulting in smooth, reliable power transmission to the LiftFan. This innovative clutch design, leveraging aircraft brake technology, produced a dry clutch plate arrangement. This achieved the required rapid engagement performance time, while providing durability that exceeded program requirements. The clutch is mounted to the LiftFan, with the input directly coupled through the main drive shaft and couplings to the main engine low-pressure rotor shaft. The clutch consists of a pack of dry disk plates. When driven together by aircraft-powered hydraulic actuation, the pack couples the main engine low-pressure rotor via the drive shaft to the LiftFan. Lubrication for the clutch bearings is provided by the LiftFan's lubrication system. The driveshaft couplings can flex to take up misalignment between the main engine and the clutch.

The LiftFan clutch allows the engagement and disengagement of the LiftFan from the main engine. It achieves this through two devices, each providing a torque path from input to output. During engagement, speed synchronization and acceleration of the fan rotors at low power is achieved by applying pressure to a pack of five carbon-carbon plates, operating dry. Subsequent engagement of a locking spline is required for high power transmission. Engaging the splined lock requires synchronizing the clutch input and output shaft speeds within a few rpm. An indexing mechanism insures against a failure to engage due to mating splines contacting end to end. During disengagement, the clutch plate pack unloads the splines to enable them to be retracted.

One of the key challenges experienced during the X-35 development was obtaining smooth clutch engagement with minimal transition time. Early clutch control design encountered a chatter phenomenon as the clutch plates came in contact. Through innovative closed-loop control modes, a combination of clutch clamping force and longitudinal position feedback solved the chatter problem, permitting smooth and precise engagements. Continued maturation during the F-35 program intended to complete the conversion in the minimum time (operational flexibility) and obtain a full-life clutch (minimized maintenance interval). The F-35 clutch can complete an engagement cycle within nine seconds from command to engage. With improved clutch plate material, the system will accommodate more than 1500 engagements.

4. Variable Area Vane Box Nozzle Development

Prior to the F-35 development phase, the X-35 LiftFan nozzle vectoring was accomplished via a three-hooded telescoping nozzle. Although very precise in directing the LiftFan thrust vector, it was heavy, required a lot of volume, and was difficult to integrate into the aircraft signature. This prompted the pursuit of a more compact design through a series of parallel vanes that could be hidden behind lower fuselage doors. The development of the F-35 VAVBN capitalized on five years of prior efforts by Rolls-Royce on vane box nozzles. These had been developed for earlier lift engine concepts that were considered in the JAST program [35]. It was tested in a 27-percent-scale demonstration (Image 5).

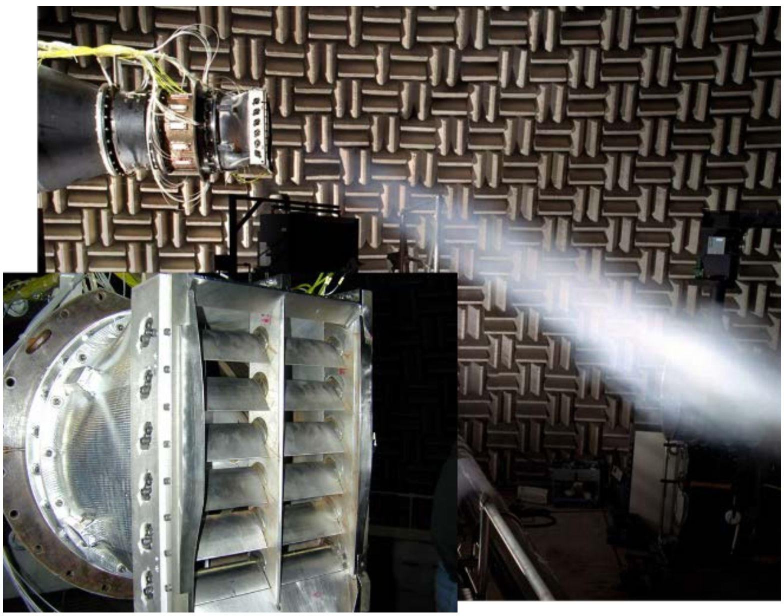

Image 5 Twenty-seven-percent-scale F-35B STOVL VAVBN test, with (inset) VAVBN closeup.

Many nozzle design variables were studied that included duct geometry, the number, spacing, and profiles of the movable vanes. Additional design parameters that influenced nozzle integration with the LiftFan included the gearbox profile, the location of six support struts, and the size and location of the vane actuator mechanism. Studies were also conducted to evaluate the tradeoffs of performance, vane actuation, and airframe integration. From these it became apparent that the vane box configuration with six highly cambered vanes with a low thickness-to-chord ratio was most promising. In addition to supporting flow path pressure, vane aerodynamics, and actuation loads, the nozzle box is designed to contribute to the airframe structural stiffness. The nozzle vane box is airframe-mounted, with the vane box sidewalls serving as aircraft structure keel members.

The VAVBN (Image 6) provides directional control of the LiftFan thrust vector and an additional effector to the VIGVs for turndown. *Turndown* refers to the commanded position of the lift fan inlet guide vanes used to control lift fan thrust. Three VAVBN vanes are driven by dual-tandem, linear, hydraulic actuators. Drive is transferred to the other three vanes through bar linkages. With this system, nozzle thrust may be directed in an arc of 41.75-104 degrees (fore/aft aircraft coordinate system), at a rate of 40 degrees per second. Independent control of the three VAVBN actuators provides the capability to vary the nozzle throat area independent of the vector angle. VIGV and VAVBN area variation are both used to control LiftFan performance, manage the LiftFan stall margin, and minimize thrust-thrust split coupling effects. Thrust split is defined as the ratio of main engine thrust over lift fan thrust, typically used to represent the propulsion system pitching moment applied to the aircraft.

Image 6 F-35 VAVBN as seen from below.

5. Roll Post Nozzle Development

The F-35B STOVL lift system uses roll nozzles in each wing to provide roll control in powered-lift operation. The roll nozzle controls thrust by varying the nozzle area using two hinged flaps. Unlike the reaction control systems on legacy vertical and/or short takeoff and landing (V/STOL) aircraft, the F-35 roll posts produce about 10 percent of the vertical thrust through redirected engine fan air. The port and starboard side roll post systems are part-number common and interchangeable, providing improved maintenance flexibility. Actuation for the nozzle flaps is provided by a twin-motor, hydraulic, rotary actuator. External, hydraulically actuated aircraft doors on the underside of the wing are opened in powered-lift operation to provide an exit aperture for roll post thrust.

A key challenge in transitioning to the F-35B was providing adequate roll control authority and rate for store asymmetries and fuel imbalance. The roll post nozzles were positioned as far outboard as the internal wing structure would allow to maximize the moment arm. Main engine fan air to the roll posts was increased to the extent possible while maintaining adequate flow to cool the exhaust liner. Architectural changes in full-authority digital engine control were made to minimize the time delay from roll moment command to roll nozzle actuator response.

6. 3BSM Development

The original design for the primary nozzle on the ASTOVL was a two-dimensional single expansion ramp nozzle. In this design, one nozzle flap is longer than the other. The nozzle vectors the primary thrust by deflecting the upper flap through at least 90 degrees. To control the nozzle exit area in hover, the lower flap was designed as a sliding panel that would retract as needed to adjust the backpressure on the engine. This was a critical control needed to make the shaft-driven LiftFan turbine work.

As Lockheed Martin began construction and tests of the nozzle, the shortcomings of the design became more apparent. The abilities to turn the flow through 90 degrees under high loads and control the nozzle exit area would have resulted in a very heavy design. This resulted in the pursuit of a lighter design that traced its roots to an early 1970s nozzle design from the proposed Convair Model 200 V/STOL fighter aircraft concept. A three-bearing swivel nozzle was developed by Pratt & Whitney and became part of the Convair Model 200 design that never continued into development. Following joint studies by Pratt & Whitney and Lockheed Martin, the 3BSM concept was integrated into the X-35B design and shown to be lighter. It also provided a very efficient means for turning the aft thrust post with minimal losses [36].

The F-35B 3BSM consists of a STOVL LOAN and a three-bearing swivel mechanism. The mechanism can deflect the exhaust flow through 95 degrees in the pitch axis and ±12.25 degrees in the yaw axis as a function of pitch angle. The 3BSM can vector up to 23,900 pounds of thrust at the maximum rearward thrust split. The 3BSM forward (No. 1) bearing is powered by twin fueldraulic actuator motors through a gearbox and drive train. The middle (No. 2) bearing is likewise powered by a twin fueldraulic actuator motor and gearbox/drive train system. A transfer gearbox links the middle and aft (No. 3) bearings with an efficient, compact, epicycle gear train. The twin actuator motors on the No. 1 and Nos. 2 and 3 bearings, respectively, are designed with a fail-degraded capability (full torque, half rate). This is one of the key differences between this design and that of the X-35B. In the X-35B, the Nos. 2 and 3 bearings were braked following a first failure, with no ability to continue vectoring the aft thrust post. This did not satisfy operational requirements requiring an ability to perform a shipboard vertical landing following a first failure. The dual redundancy on the fueldraulic motors enabled that fault tolerance on the F-35B.

7. *Technology Demonstration Program and Transition to the JSF Program*

The X-35B STOVL lift system completed more than 1200 hours of ground testing, culminating in the successful concept flight demonstration in August 2001. The aircraft accomplished this impressive performance under demanding hot, high-desert conditions and substantiated the robust performance capabilities of the shaft-driven LiftFan concept. Particularly impressive were the precise aircraft dynamics enabled by the responsive and accurate control of the STOVL lift system. Thirty-nine flights were conducted on the X-35B, including 22 hovers, 17 vertical takeoffs, 18 short takeoffs, 57 STOVL mode transitions, 27 vertical landings, 116 conversions (95 ground, 21 inflight), 63 clutch engagements, and 21.5 flight hours. This performance far surpassed the vertical operation goals and demonstrated sufficient maturity to proceed to production aircraft development.

The transition to a production F-35B principally centered on evaluating the STOVL lift system design changes and demonstrating a full-life propulsion system. More insights into the transition and full system development for the production F-35 system can be found in Ref. [38].

IV. Conclusion

The F-35 combines numerous technologies that have significantly advanced the state of the art in combat aircraft. This is particularly pronounced in the areas of integrated air vehicle subsystems and propulsion systems. The resultant aircraft provides exceptional performance with unparalleled capabilities, enabled by the air vehicle and propulsion systems.

The integrated air vehicle subsystems architecture selected for incorporation was based on a continuum of progressively refined development projects. Each of these further refined the concepts and validated the approach. The SUIT and MEA studies from the early 1990s gave the JSF contractor teams confidence in the concepts. The J/IST studies then provided the final proof of the viability of the designs. They also validated the conclusion that the overall air vehicle takeoff gross weight and cost could be reduced by 2 to 3 percent. The T/EMM system development project in J/IST contributed to the development of the turbomachine, fan duct heat exchangers, and other key elements used in the current F-35 PTMS. Without these elements, the chosen configuration might have been deemed too risky to pursue in the SDD program. Likewise, without the great successes of these development programs, many elements of the F-35's integrated systems, EHAS, and EPS would likely have been substituted with more conventional federated configurations. In such an instance, the benefits of the integrated systems might never have been realized. Instead, the resultant systems incorporated into the F-35 have been proven to provide excellent technical performance and reliability. They also provide a backbone for future systems growth through the expected long life of the F-35 program.

The F-35 propulsion systems incorporating the numerous technology upgrades have driven an unprecedented capability in performance. This has enabled the aircraft's unique performance capabilities, particularly in the F-35B STOVL variant. The final F-35 configuration incorporated a DSI, LO axisymmetric engine thrust nozzle, and unique STOVL propulsion system integrating the LiftFan and three-bearing swivel nozzle. These systems enabled the development of the F-35 variants, each providing exceptional performance and serving as the basis for long-term growth and capability improvements.