Vertical Take-off and Landing (VTOL)

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Abstract

The need to transport troops to and fro on the battlefront under stringent take-off and landing conditions necessitated the need for vertical take-off and landing (VTOL) capabilities in transport aircraft. The design principles and the features of VTOL aircraft were then extrapolated to modern turbojet engines with thrust vectoring capabilities to produce the V22 Osprey, Harrier jump jet and the F35 Lightning II. The demand for VTOL aircraft with attack capabilities is proven to be a tactical advantage. Be it turbo shaft or turbofans, the giants of the aerospace industry – Pratt and Whitney, Bell Aircraft Corporation, Boeing Rotorcraft systems, General Electric Aviation, and Rolls Royce have all had their own takes on designing engines for VTOL applications since late 1950s.

Nomenclature

SFC	Specific Fuel Consumption
VTOL	Vertical Take-off and Landing
V/STOL	Vertical/ Short take-off and Landing

Introduction

The design and development of VTOL aircraft began with the application of turbo shaft engines on a helicopter, which is the oldest and most reliable form of Rotorcraft. The sole purpose of helicopters was quick and easy transport of troops to the battlefront either from the base location or aircraft carriers. The helicopters were limited by speed, range and transport capabilities in the past. These constraints led to the development of turbofan engine powered supersonic VTOL aircraft with extensive attack capabilities to provide air support.

The design features and challenges overcome by Bell helicopters and Boeing Rotorcraft systems to build the V22 Osprey is analyzed in detail. The design and development of turbofan engines for the Harrier Jump jet and the much criticized Lockheed Martin F35 Lightning II is discussed in the sections to follow.

Need for Vertical Take-off and Landing

IT was obvious from the result of WWI that the aviation technology played a key role in determining the outcome of the war. The end of WWII played a major role in motivating the Allied Forces to feel the need for dominating the airspace in order to gain tactical advantage in the battlefield. The ability to quickly introduce soldiers at battlefronts and to retreat with minimum casualties provided a great advantage. This then led to the use of helicopters, which are the oldest form of VTOL aircraft in existence, as transport vehicles. The large yet efficient rotor blades of helicopters put a limitation on its speed, range, and altitude. The need to design a long range, high speed rotorcraft was paramount. This led to the development of V22 Osprey by a collaboration of Bell Aircraft Corporation and Boeing Rotorcraft systems in 1985.

Developed in the 1950s, with a total flight time of over 20 million hours, the Harrier Jump Jet is the first and the most successful VTOL aircraft in aviation history. The Harrier family formed an extensive attack force for the Royal Navy. The United States counterparts then began developing supersonic jets with short take-off and landing abilities and also vertical take-off technology in the recent past. The major players of this industry include McDonnell Douglas, Boeing aerospace, and Lockheed Martin among others.

Classification

The VTOL technology is mainly classified based on the nature of requirement such as transport and air strike. The transport class aircraft with VTOL technology are mostly rotorcraft like Helicopters, Gyrodynes, tilt rotors and tilt wings, which use advanced turbo shaft engines. Recent developments in the rotorcraft field is on cyclogyo and heliogyro designs which have always been futuristic and out of grasp since their first prototypes. On the other hand, the attack jets which use VTOL technology primarily contain light weight, efficient turbofans augmented with power lift fans to initiate take off. The design principles on a turbo shaft engine on such aircraft are discussed in the sections to follow.

Design considerations

The design principles and major constraints on engines powering a VTOL aircraft is classified based on the type of engine and its application in this section. This gives a chronological account of the developments in this technology. The VTOL technology gained popularity through various rotorcraft designs in the 1960’s and evolved as the aerospace industry nurtured. Several configurations of rotorcraft have been developed and tested successfully in the past, namely, Helicopters, Autogyros, Gyrodynes, Cyclogyros, and Heliogyros. The success of rotorcraft with VTOL technology was followed by powered lift designs using turbo fan engines with auxiliary/ augmented lift fans.

1. Helicopter:

The design features of a helicopter is better understood by a thorough insight on its requirements. The primary requirements being, Horizontal stability, Vertical stability, Precessional stall, tail rotor stability, and rotor flutter among few other. The first and foremost requirement is of a high thrust to weight ratio which helps develop the required lift force for vertical take-off. The need for landing gear is thus eliminated. The high angular velocity of the rotor blades causes several planar and non-planar instabilities in pitch, yaw and roll. This places a direct constraint on the design of the turbo shaft engine, which drives it. A typical rotor on a helicopter operates at 450 rpm. A torque counteracting mechanism is most important to stabilize the aircraft in flight. The horizontal and vertical stabilizers are mounted on the mast to maintain the pitch and yaw stability. Hovering is a specialty of helicopters. This puts a constraint on the range. A light weight structure is also an important feature in the design. The most common challenge in designing a helicopter is that of Vibrations and noise. The vibrations and noise are reduced through several active and passive techniques like harmonic control, structure control response, and blade control. The vertical drag on a helicopter is a primary factor in determining the engine specifications. Most rotorcraft manufacturers design high speed gearbox for turbo shaft engines with a clean nacelle design to avoid precessional drag and stall.

2. Gyrodyne:

Gyrodynes are also called compound helicopters which use the same technology as helicopters for vertical take-off and landing but have wings mounted with propellers on the fuselage to provide thrust. The design considerations are unique as the shaft power developed by the engine should drive the main rotor and two auxiliary propellers for thrust. Due to the unconventional design this type of a rotorcraft is unpopular for VTOL applications.

3. **Tiltrotor:**

The tilt rotor technology combines the advantages of the vertical take-off mechanism of a helicopter mounted on wings with a tilting mount for the rotors. This allows the rotor to be tilted beyond 90^0. The introduction of this surpasses the limitations of helicopter design. The convertiplane design of a tilt rotor engine requires that the engines be tilted vertical for take-off and landing conditions. This calls for the engine assembly to be functioning in a vertical configuration. This is one of the major constraints on the engine. The thrust to weight ratio is extremely demanding of the engine. The gyroscopic precession at very high rotor speeds imparts tremendous loads on the engine shaft. These aircraft are mostly used in for military transport applications requiring very high payload capacities. These are some of the main constraints on such aircraft.

4. **Powered lift:**

As the name suggests, a powered lift aircraft is mounted with an engine and a power lift fan to generate the thrust required for a stable take-off and landing. The inflight thrust requirements are met by an efficient turbofan engine with an afterburner design. The power lift fan with equal thrust capability is driven by bleeding power from the turbine. Auxiliary roll thrust mechanisms are used to stabilize the down force. During take-off the thrust from the jet is directed downwards to generate the lift force required. The nozzle configuration changes accordingly to accommodate for this requirement. The pneumatic controlled universal joints operating at extremely high temperatures of $2{,}000^0$C poses a major challenge in design for these aircraft. The propulsive power should still suffice a supersonic cruise and dash capabilities for such advanced jets.

Engine Specifications and applications:

Sikorsky UH-60 black hawk: GE T700 family

The Black Hawk or more commonly known as the Hawk is a United States army tactical transport helicopter. This was brought in service in 1974 and forms a fleet of 4,000 since. Being branded as one of the most advanced transport aircraft the design and engine specifications are of great interest. The Black hawk is powered by a General Electric T700 family engines with a unit cost of $900,000. The GE T700 is a direct drive turbo shaft engine with annular intake and a particle separator. The engine uses a combination of 5 axial compressor stages followed by a centrifugal compressor stage for high pressure stream requirements. It has a pressure ratio of 19 and a mass flow rate up to 6 kg/s. The engine has an inlet diameter of 16 inches and weighs about 250 kg. The two stage gas turbine has a max rotational speed of 44,700 rpm and a two stage power turbine driving the shaft through the gearbox. This engine has a specific fuel consumption of 0.47 which makes it very fuel efficient for long range transport. The GE T700 engine was tailor made for the UH-60 Black Hawk and the Apache Helicopter. The in ground thrust to weight ratio of the GE T700 engine is about 6.31 kW/kg, which suffices the thrust requirement. However the large rotor blades limits the maximum forward velocity to 400 km/h. The VTOL ability of a helicopter enables it to perform tasks that a fixed wing aircraft cannot. The Figures 1 and 2 show the UH-60 Black Hawk aircraft and the GE T700 engine.

Figure 1: Sikorsky UH-60 Black Hawk

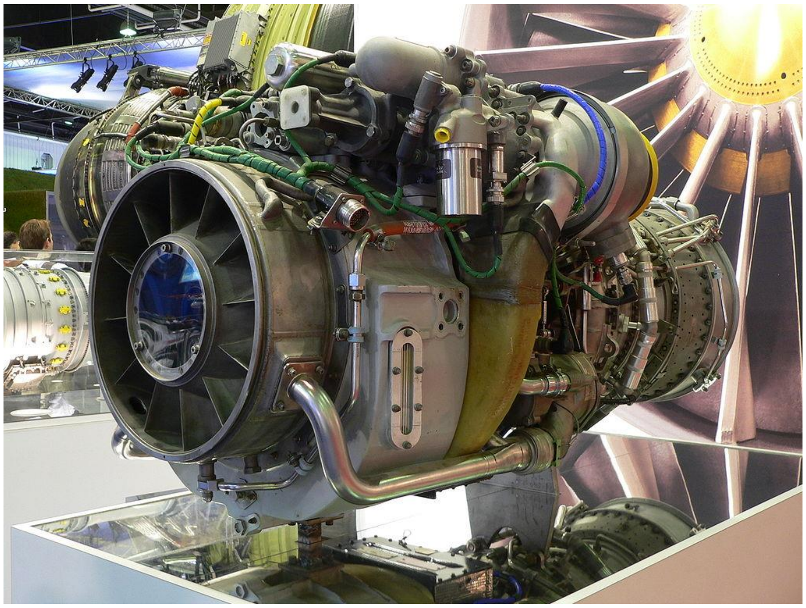

Figure 2: GE T700 engine

V22 Osprey – AE1107: Rolls Royce T406

The world's first successful tilt rotor aircraft which has been in development for 25 years costing around $35.6 billion reached production line in 1998 and first saw flight in 2007 in Iraq by the United States Marine Corps. The engine design is an amalgamation of turbo shaft and turboprop design. The major design considerations include that of the propeller/ rotor, tilt rotor mechanism, and the problem of precessional stall. The engine is mounted on the wing tips with a connecting drive shaft running through the fuselage allowing the aircraft to function normally even during one engine inoperative condition. The lift during take-off and landing is generated at full throttle setting of the engine in the rotor configuration just like a helicopter.

The thrust during cruise is achieved by tilting the rotor horizontal to keep it in a propeller configuration. The V22 osprey is powered by a Rolls Royce Allison T406 engine with a 14 stage axial compressor with variable inlet guide vanes for pressure ratio of 16.7 and an inlet mass flow rate of 16.1 kg/s. The engine uses a conventional annular combustor design. The turbine assembly consists of two stage single crystal bladed gas turbine followed by a two stage power turbine connecting the gearbox to the shaft assembly. It has a SFC of 0.426 SLS making it the most fuel efficient tilt rotor aircraft in history. The primary problem of tilt rotor mechanism was solved by replacing the tilt gear with the entire engine assembly rotation. This imposed on the engine other constraints like vertical operation and stability. The gyroscopic precessional load was problem was solved by connecting a drive shaft on stronger material, which alone handled the load. These are some of the many design considerations of the V22 Osprey.

The tilt rotor design enables the V22 osprey with a longer range, higher speed, higher altitude and better payload capacity. This is mainly because of the advancements in composite material technology which accounts for 43% mass reduction of the fuselage. However it comes with a few drawbacks like limited airplane mode speed and lower stall speeds. The new variants of V22 Osprey also provide light combat air support. Figures 3 and 4 show the V22 osprey and the RR Allison T406 engine.

Figure 3: Bell Boeing V22 Osprey AE1107

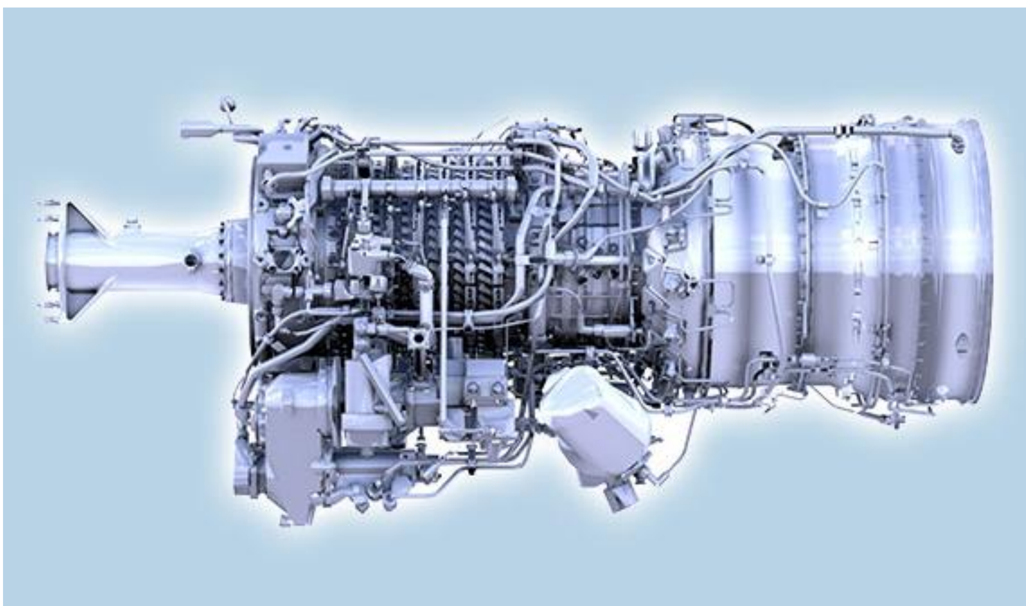

Figure 4: Rolls Royce Allison T406

Lockheed Martin F35 – Lightning II: Pratt and Whitney F135

The latest of the VTOL technology i.e. the Lockheed m artin F35 is a supersonic fighter aircraft of the United States Joint Strike Force (JSF). With a development cost of over $1.508 trillion and a unit cost up to $120 million the F35 is easily the most expensive fighter aircraft development program in the history of military aviation. This fighter aircraft is powered by a Pratt and Whitney F135 turbofan engine with an afterburner and thrust vectoring nozzle weighing about 160 kg. Careful design, top of the line engine capabilities and multi cooling passage ways for blade cooling makes the engine one of the most complex designs ever built. The F35 is seen in 3 variants of F35A, F35B and the F35C. The PW F135 engine consists of multi rotor fan stages of 46” in diameter with guide vanes composed of hollow Organic Matrix

Composites and the subsequent stages with Titanium Alloys for support. The low bypass ratio of 0.567 is compensated by a 6 stage high pressure compressor with internal cooling design. The overall pressure ratio of the compressor stages sums up to 35 for cruise and 20 for powered lift. The low Pressure turbine is composed of two stages with extreme power supply and a single stage high pressure turbine. The turbine blades operate at a turbine entry temperature of $2{,}200^0$C. This is a direct result of extracting high energy for thrust production from the combustion process. Additionally, to operate the aircraft in VTOL mode a power lift fan designed by Rolls Royce Power lift system. The F35A Lightning II is shown in Figure 5 along with the lift mechanism in Figure 6.

Figure 5: Lockheed Martin F35A

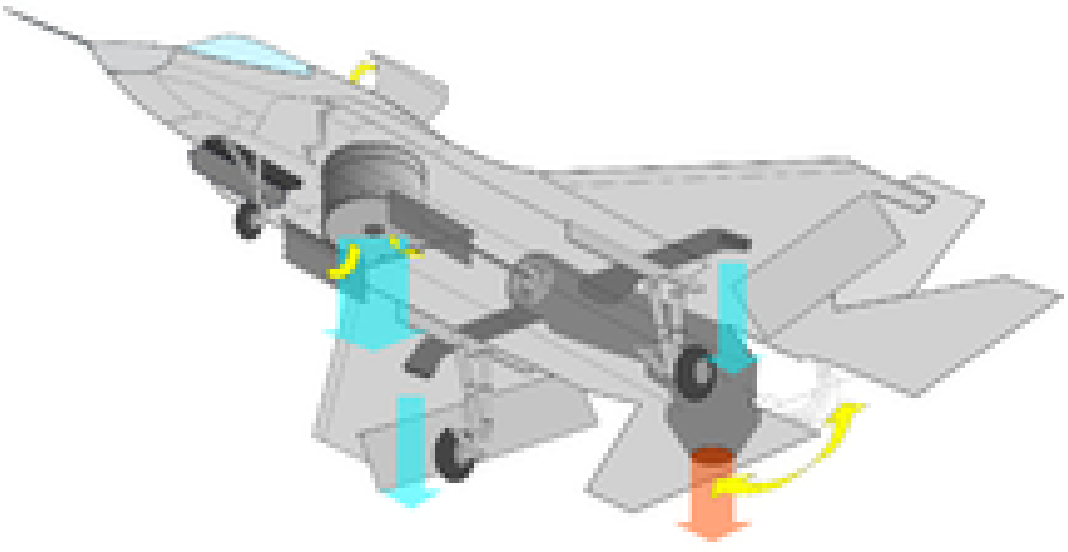

Figure 6: Figure showing thrust vectoring system, power lift fan, and roll posts

The RR lift fan is a two stage contra-rotating hollow titanium blisk fan of 1.3 m diameter capable of producing 80 kN thrust force. The roll posts provide roll stability during vertical take-off and landing applications. The lift itself is produced by the three bearing swivel module vectoring nozzle with a rotational angle of 95^0 in 2.5 seconds vectoring a force of 80 kN. The estimated mass of this engine is not listed but it was revealed that the initial mass exceeded the design mass by 363 kg in 2004 and later reduced to 4.5 kg in a span of 4 years. The PW F135 engine with the power cycle is shown in Figure 7.

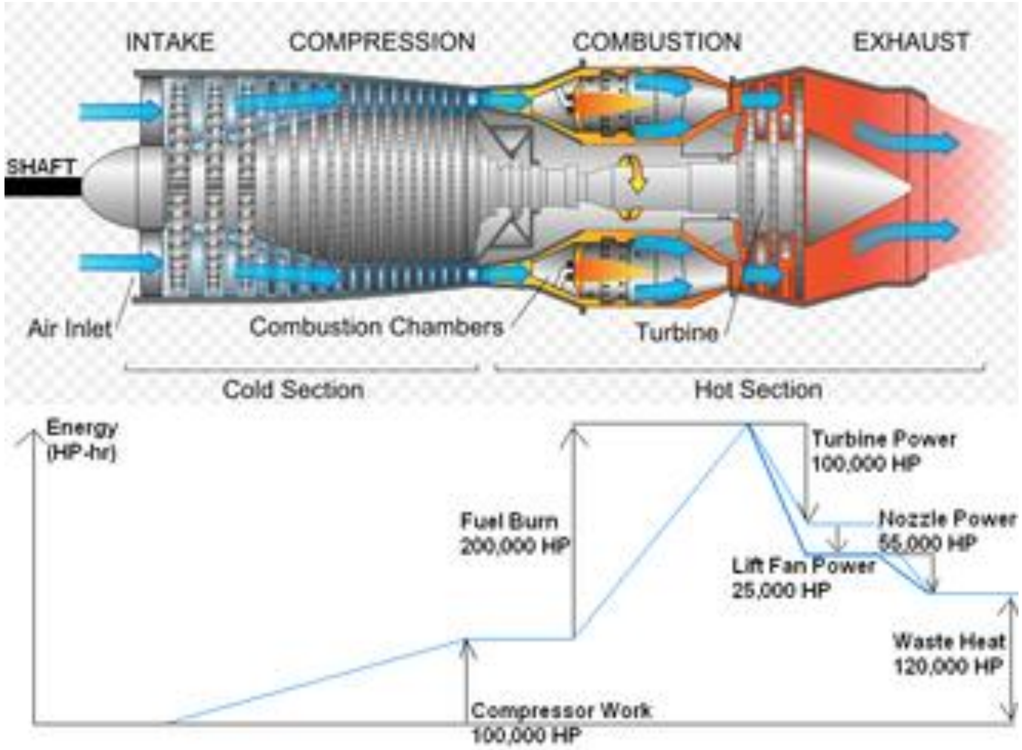

Figure 7: PW F135 engine

The development program encountered several design hurdles of which the primary one was force balancing about the center of gravity this was overcome by advanced hollow casting processes and extensive use of organic matrix composites. The thrust vectoring nozzle is designed as a part of the airframe to reduce the mass of the bulky universal joints. The three bearing module is a Mollart universal joint built out of materials unknown to withstand temperatures up to 2,200^{0}C. The problem of transition from vertical take-off to cruise is achieved beautifully in the turbofan powered aircraft. This has to do with the swivel nozzle which ensures this smooth transition unlike the old Harrier Jump Jets. These are some of the design considerations of a turbo fan jet engine design for VTOL.

Advantages and Future developments

The VTOL technology is a huge trade off in certain design constraints. In rotorcraft, this is compensated by reducing the empty weight to increase the payload/ passengers for transport whereas in jets this is counteracted by increasing the lift/ thrust and reducing the empty weight of the aircraft. The primary advantage being able to take-off from aircraft carriers and any stringent locations for covert operations. This helps reduce the risk of compromising missions by safe drop-off to the battle fronts rather than high altitude parasailing. These necessities have led to the development of the VTOL technology to the stage it is in.

The modern day helicopters are still limited in altitude and speed. The tilt rotor technology is set to solve this problem. It is not uncommon to witness news of new tilt rotor designs from time to time to replace business jets of the future. Bell helicopters and Augusta Westland have been developing technologies to make the tilt rotor aircraft a reality to the commercial sector. A figure showing the BA609 first made flight in the Paris Airshow in 2007 is shown below.

Figure 8: BA609 tilt rotor aircraft

Several such business models are expected to make their way into the market in the next decade. However, the success of the V22 Osprey may lead to the development of heavy air support variant of this aircraft in the following decades to come.

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References

[1]Jane’s Aero- Engines, Bill Guntson. Issue 19 –March 2006

[2]Boeing commercial website
< http://www.boeing.com/defense/v-22-osprey/>

[3]Pratt and Whitney engine catalogue
< http://www.pw.utc.com/F135_Engine>

[4]US military equipment website
< http://www.military.com/equipment/uh-60a-l-black-hawk>

[5]General Electric engine catalogue
< http://www.geaviation.com/military/engines/t700/>

[6]Rolls Royce engine catalogue
< http://www.rolls-royce.com/products-and-services/defence-aerospace/products/helicopters/ae-1107.aspx>