STUDIES ON PERFORMANCE DETERIORATION OF A LOW BYPASS TURBOFAN ENGINE IN SERVICE

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Abstract

The performance deterioration of a low bypass turbofan engine is analyzed to find out its causes. The performance parameters are compared with their limitations for a specific throttle setting. Dirt buildup, soot deposit, de-twisting of turbine blades, malfunction of atomizers and fuel system accessories are found to degrade the engine health and performance before the intended service period. Periodic compressor wash and engine maintenance, cleaning or replacement of fuel filters and good assembly practices are found beneficial in addressing the issues and retaining the engine performance.

Abbreviations

TBO = Time between overhaul
NGV = Nozzle guide vane
FOD = Foreign object damage
LP = Low Pressure
HP = High Pressure
NH = Speed of high pressure spool, rpm
EGT = Exhaust Gas Temperature
ISA = International Standard Atmosphere
LCF = Low Cycle Fatigue
HCF = High Cycle Fatigue

Introduction

Low bypass turbofan engines are widely used for military combat and training aircrafts. They generally operate at extreme conditions with high throttle excursion. The nature of their application leads them to operate under arduous environmental conditions and high g load variations during different maneuvers. This often leads to deterioration of performance, accumulation of damage and failures of components forcing for premature withdrawal of the engine from service affecting the flight management of the operator. The deterioration may be due to external damages affecting geometrically or surface quality as a result of mechanical and chemical effects such as fretting, wear, erosion, corrosion or oxidation [1]. On the other hand, internal damages may affect the microstructure of highly stressed components due to aging of the material microstructure or due to creep or fatigue.

External damages affect significantly on functionality of the parts, including the aerodynamic performance of components as well as reduce their load bearing capacity. Surface damage in the form of Low Cycle Fatigue (LCF) cracks, scars or dents, fretting-wear or Foreign Object Damage (FOD), respectively, may lead to High Cycle Fatigue (HCF) failures [2, 3]. Internal damage may reduce component strength and lead to component distortion. Its accumulation also causes the initiation of flaws, which may ultimately lead to cracking and component failure. These service-induced damages deteriorate the engine performance and limit the usable life of many engine components [4]. The deterioration can also be attributed to defects in raw material, improper material selection, inappropriate design, incorrect processing and improper maintenance etc. The present paper analyses some of the causes that are responsible for deterioration of performance in a low bypass military turbofan engine in service.
The paper also suggests corrective actions for improvement and recovery of the rated thrust of the engine.

**Engine Configuration**

The configuration of the turbofan engine under investigation without air intake is shown schematically in Fig.1. It is a twin spool low bypass engine with multi stage axial fan and compressor each driven separately by single stage turbines. It has an annular type combustion system incorporating airblast atomizers. The High Pressure (HP) compressor comprises of machined discs welded together to form a drum into which rotor blades are keyed and locked in position by blade retaining plates. The HP compressor drum is bolted to the HP turbine rotor shaft and transmits the turbine drive. Compressor stator assembly consists of a series of vanes welded on the outer platform to form a ring behind each row of rotor blades in each stage.

The HP turbine rotor assembly comprises of a disc, blades, rotor shaft and stub shaft. The blades are directionally solidified, air-cooled and are keyed to the disc by fir-tree roots. The Low Pressure (LP) turbine NGV segments are fitted to the outer case. Attached to the rear of the segments is a bearing support panel which houses the HP and LP bearings. Both high pressure and low pressure turbine nozzle guide vanes are of hollow, airfoil shape and are welded in sets of two or three. LP turbine rotor assembly consists of a shaft, disc and even number of equiaxed blades. The blades are keyed to the disc by fir-tree roots and are retained by locking plates. The other modules of the engine are exhaust mixer and cone assembly, afterburner system, gear box and accessories.

**Service Experience**

The engines are released for service after production or repair or overhaul after fulfilling the requirements of tests, analyses and inspection laid down in the acceptance test procedure. They are intended to operate safely and reliably with all performance parameters within acceptable limits for a reasonable time known as Time Between Overhaul (TBO). TBO is a time recommended by the designer/manufacturer based on the engines complexity, operational envelope and severity of the mission cycles it is intended for [5]. It depends on a number of variables such as aircraft stage length, experience on engine type, operational procedures, environmental conditions and modification standards etc. From the safety point of view, overhauling the engine at this time is mandatory and has to be complied. But service experience shows that many engines are withdrawn before completing the TBO life either due to service-induced damages or due to performance deterioration of engine. Assessing the engine performance during flight is a difficult task as a few engine parameters are recorded in Flight Data Recorder. In absence of thrust, Exhaust Gas Temperature (EGT) is a representative of the engine health and performance. It is measured through K-type thermocouples at downstream location of LP turbine where gases discharged from LP turbine enter the jet pipe. The averaged EGT is displayed in the aircraft cockpit as well as recorded in the Flight Data Recorder. A consistency of EGT at different stages of TBO life for a healthy engine is presented in Fig.2.

However, the database of engines that are withdrawn prematurely for various reasons show the deterioration in thrust and EGT when tested in ground test bed. The thrust and EGT of the cases investigated are shown in Figs.3 and 4. These values are at 100% high pressure rotor speed (NH) and corrected to ISA sea level condition. Due to proprietary nature of data, they are presented as fraction of the acceptable value. This necessitates to find the causes of deterioration and to suggest remedial measures to address these issues.

Other important engine parameters need to be within acceptable limit when engine is tested in test bed are idle speed, vibration level, oil pressure at oil filter, compressor working line, nozzle area etc.

**Results and Discussion**

Thrust and slam acceleration are the most important performance parameters of a military gas turbine engine. They can be expressed in terms of measurable parameters such as spool speed, EGT and slam time with respect to throttle position or movement. The engine cycle parameters such as pressure, temperature, air flow rate and fuel flow rate are directly linked and are proportional to the engine rpm. Any fluctuation in rpm or rpm not attaining the max at take-off or required level as per demand will affect the thrust and engine will not be able to meet the mission requirements. Similarly, in the absence of turbine entry temperature measurements in a service engine, EGT is a health monitoring parameter. EGT within the specified limit ensures a safe life of the engine hot end components. Engine slam is defined as the acceleration of the engine from ground idle or flight idle condition to the max rpm within a specified time. It is the engine’s response to the throttle movement and the fuel system should be compatible to cater this rate of fuel flow requirements of the engine. The slam time greatly depends on the engine...
architecture, inertia of rotor systems, compressor efficiency, and compatibility of the exhaust nozzle in addition to the configuration of the fuel system. It is generally defined as a function of ambient temperature or altitude based on a standard day atmosphere. Meeting the slam requirements of an engine during combat mode is very important. Generally 15% of the engines prematurely withdrawn are due to low thrust and almost a similar number of engines for not meeting the slam requirement. To find out the causes of performance deterioration, thorough investigations of engines were carried out focusing on

- Flight data analysis
- Review of operating and maintenance records
- Study of engine sortie profiles
- Visual examination of the engine air intake, inlet guide vanes and external casing and exhaust nozzle
- Measurement of tip clearances
- Evaluation of performance on ground test bed
- Teardown examination
- Rig test and checks for accessories

The findings of the investigation are as follows:

- Carbon or dirt deposit on compressor aerofoil is a common phenomenon found on many for the engines investigated as shown in Fig.5. Hydraulic oil leak from flap / rear selector bay finding way into the air intake and wetting the engine compressor blade profile have aggravated the process of dirt/carbon deposits. The deposits change the geometry of compressor flow path leading to considerable reduction in air mass flow and loss of compressor efficiency, both causing loss in thrust level [6-8]. Compressor wash is a recommended practice to overcome this issue partially. Wash/cleaning at regular intervals are cumbersome and sometimes introduce problems of corrosion and damages in downstream components, accessories and sensors. Assessment of compressor characteristics with such deposits and prediction of its equilibrium running points may be worked out to address this issue [9-11].

- Accumulation of reddish brown deposit on the NGVs of HP and LP turbines is found to clog cooling holes resulting in local overheating of NGVs. Such an NGV is shown in Fig.7. This hot section fouling leads to variation in NGV throat area. As the NGV throat area affects/controls the equilibrium running of compressor/turbine spool, its reduction will cause a movement away from the design match point and results in a corresponding loss of performance [6, 9]. Also any deviation of blade flow angles from their design value will affect the turbine performance adversely. Increase in HP and LP NGV flow area due to erosion can also cause low thrust [6, 7].

- Carbon accumulation on atomizers and liner front end as shown in Fig.8 causes improper atomization and incomplete combustion [12, 13]. This may lead to high non-uniformity at combustor exit as well as lower turbine entry temperature resulting in low thrust. The combustor exit temperature non-uniformities are generally defined in terms of non-dimensional parameters known as radial and circumferential pattern factors [14]. Since measurement of these pattern factors are not feasible in a service engine, their controlling parameters like atomizer flow rate and spray cone angle are generally measured. Shifting of atomizer characteristics is generally noticed due to service exploitation. Typical test results of spray cone angles of atomizers taken from engines under investigation are shown in Fig.9 which is found out of acceptable limits. Smaller spray cone angle shifts the fuel-air mixing downstream so also the combustion and local peak temperatures [15-16]. This affects the combustor liner and turbine blades adversely. Similarly, higher spray cone angle will cause hot spots in combustor liner leading to erosion and cracks. The fuel flow rate through the atomizers is also found to be beyond the acceptable range of ±5% from the mean value as shown in Fig.10 which again can cause local hot spots on the turbine NGVs and rotor blades [17, 18]. The spray cone angles and atomizer flow rates presented in Figs.9 and 10 are based on measurements carried out in test rig on one set of atomizers of specific engines withdrawn prematurely or received for overhaul.

The measured thrust in ground test bed with soot deposits on compressors as it is received from service for overhaul and thrust measured after the compressor wash is presented in Fig.6. Though the graph is shown without scale in y-axis as there is no reference value for thrust at operating points other than 100% NH, 3-5% improvement in thrust due to compressor wash has been noticed at all speed zones.
De-twisting of relatively longer LP turbine blades which occur due to prolonged operation in max rating or exposure of high gas temperatures is another important factor deteriorating engine performance. After strip examination, blades in each engine are measured to establish the extent of de-twist and in many cases, de-twist has occurred beyond the acceptable limit. Once blades are de-twisted, gas reaction force to the blade segment is comparatively reduced to rotate the turbine to the extent required. This results in low rpm leading to low air mass flow and thus reduced thrust. The de-twisting of three cases is presented in Fig. 11. As it is seen, the blades in the case-1 engine are well within the limit throughout the TBO life delivering the performing as intended. The blades in case-2 have just reached the limit at TBO life where the blades in case-3 have exceeded the limit well before the TBO life is reached. This engine has exhibited low performance in flight leading to withdrawal at 80% of TBO life. Extended operation at max stress region and manufacturing or material defects are found to be the probable cause for this defect.

**Conclusion**

Maintaining the integrity, reliability and engine performance over the stipulated TBO life is very important from the safety and serviceability of the aircrafts. The following conclusions can be drawn from the present study on performance deterioration of a low bypass turbofan engine in service;

- Carbon or dirt deposit on compressor aerofoil changes the geometry of compressor flow path leading to reduction in air flow and compressor efficiency, both cause loss in thrust.
- Accumulation of reddish brown deposit on the NGVs clog cooling holes resulting in local overheating of NGVs. Change in NGV throat area affects the equilibrium running of compressor-turbine spool and loss of performance.
- Carbon accumulation on atomizers and liner front end leads to high non-uniformity in temperature at combustor exit. It also lowers turbine entry temperature resulting in low thrust.
- Atomizer spray cone angles higher or lower than the desired band dictates the location of peak temperatures inside combustor liner. Higher spray cone angle causes hot spots in combustor liner leading to erosion and cracks. Non-uniform fuel flow rate beyond the acceptable range can cause local hot spots on the liner, turbine NGVs and rotor blades.
- De-twisting of turbine blades is an important factor responsible for deterioration in engine performance. Once blades are de-twisted, gas reaction force to the blade segment is comparatively reduced to rotate the turbine to the extent required. This results in low rpm leading to low air mass flow and thus reduced thrust.

To address the above issues, a well laid procedure has to be followed for the maintenance of aero engines at manufacturing and operators’ end. Good housekeeping is essentially required to avoid any foreign object debris and damages during service. Periodic compressor washes and engine maintenance complying the service and instruction bulletins will enable the engine to retain the performance over a specified period. Following fuel disciplines and calibration standard of atomizers will help to maintain the required flow characteristics over a specified service life. Also strict adherence to the operational schedules without exceeding the engine limitations can reduce the performance deterioration of engines in service.

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**References**


Fig. 3 Engine Thrust Measured During Testing at Ground Test Bed at 100% HP Spool Speed Corrected to ISA Sea Level Condition

Fig. 4 Engine EGT Measured During Testing at Ground Test Bed at 100% HP Spool Speed Corrected to ISA Sea Level Condition

Fig. 5 Soot Deposits on Low Pressure Compressor

Fig. 6 Effect of Compressor Wash on Engine Performance

Fig. 7 Erosion and Deposits on NGV

Fig. 8 Carbon Accumulation on Liner Front-end
Fig. 9 Atomizer Spray Cone angles of an engine Under Investigation

Fig. 10 Typical Fuel Flow Distribution in Main Combustion Chamber

Fig. 11 De-twisting of LP Turbine Blades in Service