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cruise sfc reduction using a novel technique

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Abstract

Jet engines play a pivotal role in propelling most of the modern day aircraft. The design and development of any new propulsion system involves propulsion system manufacturer, aircraft manufacturer and airliners. The jet engine manufacturers focus on several aspects like design, testing, certification, production, delivery to the aircraft manufacturer and aftersales support in the form of maintenance, repair and overhaul of the propulsion system. The airliners are primarily concerned about the cost-effectiveness, return on investment and the reliability of the propulsion system.

The need to reduce cruise Specific Fuel Consumption (SFC) is driven mainly by financial and environmental factors. The reduction in cruise SFC results in savings worth millions of dollars and also reduces the aviation carbon footprint.

A traditional problem faced by the civil aerospace industry is the SFC loss during the first fifty hours of the brand new engine's flight. This loss in cruise SFC is due to deterioration caused by the rapid throttle movements by pilots, during flight operations. The deterioration could push the propulsion system components beyond their operational limits, resulting in loss of thrust, higher fuel burn and potential engine damage due to higher heat loads and cyclic stresses. In recent times, the prime area of research has been on how to control and minimize the performance deterioration of propulsion system and its components.

Summarizing, the deterioration during the first fifty hours of flight has a significant impact on the cruise SFC. It leads to an increase in fuel burn which impacts the profit margins of the airliners. With the aviation fuel prices soaring to new record highs, cruise SFC is a prime area of concern to the commercial airline industry. This white paper provides a solution to tackle the traditional problem of increase in cruise SFC, caused due to deterioration of a brand new engine, during the first fifty hours of operation - a challenge faced by the civil aerospace industry.

Turbofan Propulsion System - an Insight

Every propulsion system manufacturer aims to provide robust, efficient and highly reliable engines. It is a well-known fact that safety and efficiency are paramount in the aviation industry.

Turbofan propulsion system is commonly used in most aircraft around the globe. The word "turbofan" is a portmanteau of "turbine" and "fan", which are the basic parts of this type of engine. The core which consists of compressors, combustion chambers and turbines, acts as a gas generator which converts the fuel energy in the combustor into useful kinetic energy. This kinetic energy is converted into effective propulsive energy by the nozzle. The bypass duct is a ring-shaped channel with a fan. The compressed cool air that has bypassed the combustion process completely is exhausted by a cold nozzle. The cooler bypass air forced out through the nozzle, enables engine designers to enhance efficiency, and decrease noise levels.

Turbofan is recognized for its efficient performance and superior ability to cruise at high altitudes. There are two kinds of turbofans based on their by-pass ratio (ratio of by-passed airflow to the core airflow) namely,

- Low by-pass turbofan
- High by-pass turbofan

High by-pass turbofan is widely preferred among the civil aircraft manufacturers and airliners. In a high by-pass turbofan, the by-pass ratio is of the order of 9:1 (commonly used in recent times). In a 9:1 by-pass turbofan, 90% of air by-passes the combustor and 10% of the air enters the engine core. The core airflow produces about 25% thrust, while the by-passed air provides the remaining 75% of the thrust.

Fig 1: A high bypass turbofan engine

Importance of Cruise SFC

For civil airplanes which spend most of their time cruising, fuel burn is of immense importance. The amount of deterioration the engines undergo during the initial fifty hours of flight, impact the cruise fuel burn throughout its lifecycle.

Improvements in aircraft propulsion system are encouraged in order to reduce and optimize the fuel usage. These improvements are highly lucrative in terms of financial gains for the airliners. The other important factor is the reduction of aviation carbon footprint on the environment. Of late, the engine manufacturers are striving hard to produce greener propulsion systems, wherein the emissions of carbon dioxide, nitrogen oxides and aerosols are reduced. These factors clearly illustrate the fact that the need to minimize fuel burn is a quintessential requirement (reference 1).

Effects of Aircraft Propulsion System Deterioration

Airliners require highly efficient propulsion systems, which could meet the thrust demands with minimal fuel consumption. With increasing fuel costs, maintaining higher fuel cost-effectiveness has become the need of the hour. In general, a propulsion system would need circa five billion dollars, only for its fuel supplies over its lifecycle of twenty years (reference 2). This is sure to increase with the passage of time, mainly due to the diminishing oil reserves and continuously increasing fuel costs.

During the first fifty hours of flight, several forms of deterioration occur on the propulsion system. They can be classified as recoverable, non-recoverable and permanent (Figure 2). The non-recoverable and permanent deteriorations have severe impact on the performance of a high by-pass engine. As an example of non-recoverable deterioration, one millimetre increase in blade tip clearance causes about 2% drop in turbine efficiency, which typically translates to more than 1% increase in SFC.

The propulsion system manufacturers have not only raised alarming concerns about the increased SFC during the initial fifty hours of flight, but also about the performance deterioration on the propulsion system components. This initial deterioration in service has detrimental effects on the propulsion system performance throughout its

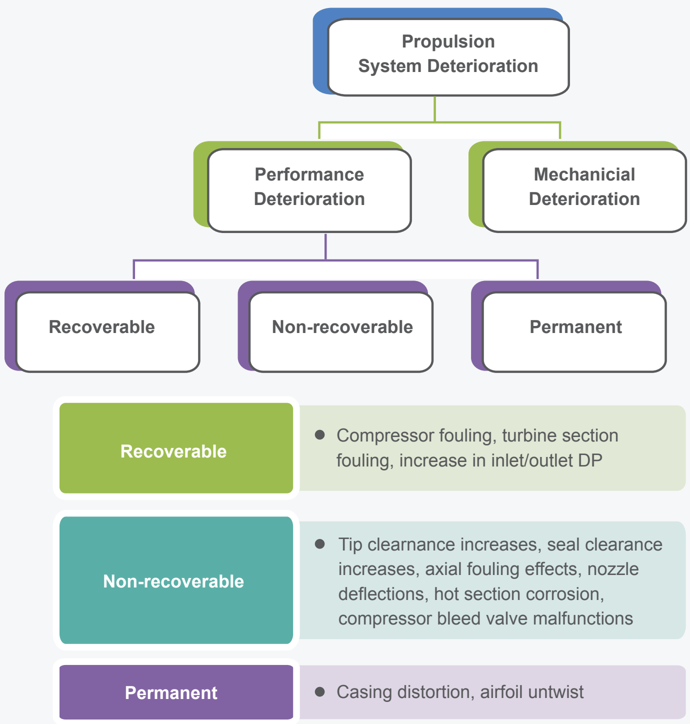

Fig 2: Classification of performance deterioration

lifetime. This results in an increased SFC, and also drastically reduces the time of the propulsion system on the wing. Lesser profit margins are seen among the airliners and airframe manufacturers due to the propulsion system overall lifecycle costs. Added to the airliner's operational costs are the maintenance costs which put the long term contracts with the engine manufacturers at stake.

At the initial stages of propulsion system operation, wear is a significant problem to look out for. It is mainly caused due to thermal and centrifugal stresses, which cause the growth of blades in service. Though analytical models could predict the blade growth for set throttle conditions, the prediction of rapid throttle movements caused by pilots is complicated. These rapid throttle movements cause inconsistent growth behavior in blades, which in turn causes uncontrolled deterioration. Increase in tip clearance reduces the efficiency of the components significantly and also causes serious performance deterioration.

Mechanical deterioration refers to the wear in bearings and seals, coupling problems, excessive noise or vibration, and blade rings distorted due to thermal ratcheting caused during repeated cold starts. Mechanical deterioration is caused due to improper maintenance activities, or due to lack of inspection procedures after overhauling of propulsion systems.

Traditional Problem and an Unconventional Solution

A traditional problem faced by the civil aerospace industry is the deterioration during the first fifty hours of the brand new engine's operation. This deterioration is caused by the rapid throttle movements by pilots during the flight operations on a brand new engine, leading to a rise in cruise SFC. Hence, there is a strong demand among airliners to control and minimize the performance deterioration during the first fifty hours of a flight as it directly impacts the profit margins of the airliners.

This whitepaper provides a solution to this chronic cruise SFC problem faced by the aviation industry using a novel technique of controlled deterioration. The idea is to mimic the initial fifty hours of deterioration on the new engine in a controlled manner. This controlled deterioration translates to better overall efficiency, reliability and better health of the propulsion system throughout its lifecycle, compared to an engine which generally undergoes uncontrolled deterioration during the initial part of its life in service.

An empirically designed performance curve, derived from the experimental test results of a high by-pass turbofan engine together with the turbine casing cooling system schedule, is applied on the engine as a part of the production pass-off program.

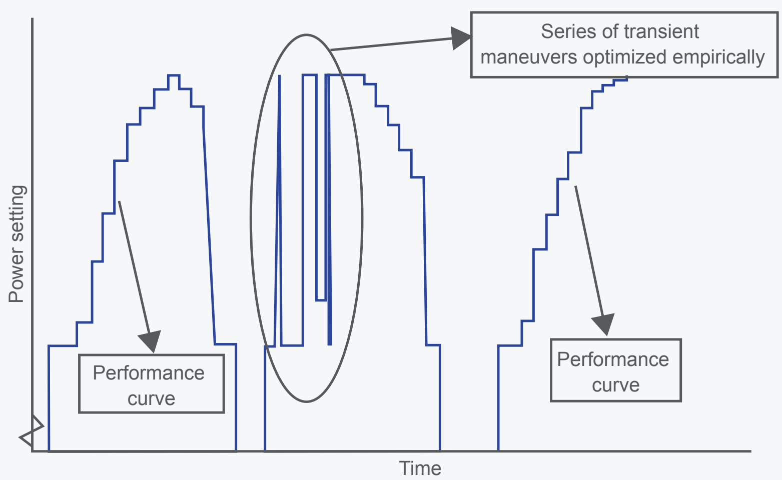

Fig 3: Empirically designed performance curve

The solution provided here is a combination of the following essential functionalities:

- The engine handling procedures to mimic the initial fifty hours of deterioration on the new engine in a controlled manner
- The turbine casing cooling system
- Integration and optimization based on the empirical performance curves carried out during the development tests

Based on the empirical performance curves, a series of transient engine maneuvers combined with a turbine casing cooling schedule is identified as per the desired baseline configuration of the customer. The transient engine maneuvers and turbine casing cooling are further optimized to run-in the turbine seals into the casing linings in a controlled manner to produce nearly ideal tip clearances on the components, significantly reducing the cruise SFC loss during flight operations.

The following steps are carried out to mimic the initial fifty hours deterioration on the new engine in a controlled manner:

- Accelerations and decelerations are carried out to prove that engine meets its specific requirements
- Rotor is made to cut gradually into static linings by a series of accelerations/decelerations using the data derived from in-flight operations that mimic the first fifty hours of flight
- The technique is carried out to cut the linings in a controlled manner to optimize tip clearances. It is done to minimize the depth of in-flight rubs within the first fifty hours of flight.

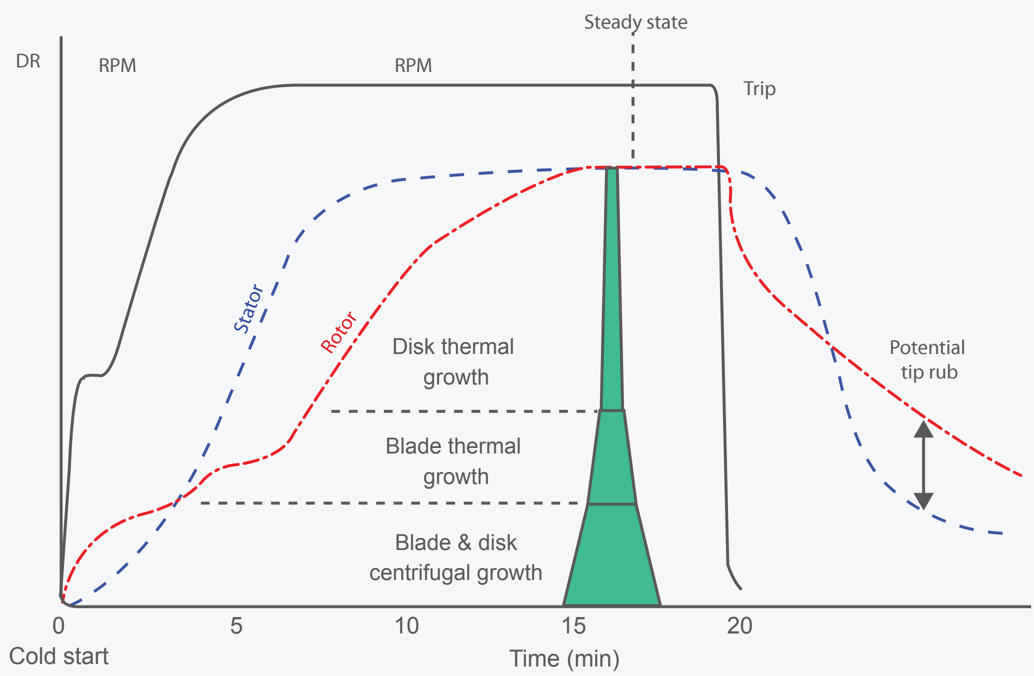

Fig 4: Graph representing the rubbing of rotor into stator linings

Figure 4 shows a generic growth behavior of the turbine rotor and stator linings (reference 3). Turbine Case Cooling (TCC) is used to cool the stator linings on the turbines to reduce the tip clearances due to thermal expansion of the linings.

Both the TCC operation and the performance curves are carried out simultaneously on the new engine, and finally optimized based on the test results, which can then be used on the production engines.

The above mentioned procedures prevent the over rubbing of compressor and turbine blades, which reduces the component level deterioration significantly. It creates a revolutionary improvement in the cruise SFC levels. Such a reduction in SFC due to the controlled deterioration and optimized tip clearances clearly indicates that the efficiency of the machine has improved tremendously.

Further Scope of Work

The predictions from computational flow and thermal models could provide interesting validations, and the scope for optimization will be thoroughly broadened.

Using Computational Fluid Dynamic (CFD) analysis, the velocity, temperature, and pressure profiles could be obtained throughout the engine using relevant models, which could further help in validating performance data obtained at specific locations.

FEM/FEA model calculates the stresses and strains in the component, caused due to varying temperature distribution and externally applied loads, which could prove useful to improve the propulsion system components further.

A large number of specific life prediction models have been developed for propulsion systems. Models are classified as total life models and crack growth models. Total life models only calculate the time leading to failure, and will not consider the approach to failure. Crack growth models demonstrate damage tolerance, which accepts the presence of material defects, aims to monitor crack growth, and suggests removing the component before the crack becomes unstable.

Conclusion

An in-depth thermodynamic analysis at component level suggests that the controlled deterioration process on the engine accounts to limited deterioration levels on the core turbo machinery, unlike the uncontrolled deterioration during flight operations. Reduction in cruise SFC is worth hundreds of million dollars, for saving fuel, maintenance and operational costs. This further improves the reputation and reliability of the engine program and its manufacturer.

It is found that around 1% cruise SFC could be saved if this methodology can be applied properly on the production engines. Airliners can save about 50-70 (approx.) million dollars per year based on their aircraft fleet (reference 4).

For example, Lufthansa’s fuel cost amounts to about 4 billion euros per year. A 1% increase in fuel efficiency of the whole aircraft fleet would accordingly save about 40 million euros per year (reference 4).The determination to improve the efficiency of jet engines will be kindled by intervention of mathematical modeling and simulations. There is no doubt that the propulsion system business will further thrive, even more convincingly with the introduction and evolution of such novel concepts to tackle problems faced by the aerospace industry.

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Author Profile

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Janakiraman specializes in aerospace engine thermodynamic synthesis and performance analysis, computational modelling, analysis and experimental aerodynamics.

He graduated with a Bachelor of Engineering (Aeronautical) degree from Tagore Engineering College, Anna University with a University Rank in the year 2010. He was a research fellow at the Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR) and worked at the Indian Institute of Science (IISc) briefly. After his stint at IISc, he joined the Indian Institute of Technology, Madras (IITM) as a Project Associate and worked on experimental aerodynamics till April 2011.

While working at IITM, he pursued a program in Project Management at the Loyola Institute of Business Administration (LIBA).

Janakiraman joined the Performance team at QuEST as a Trainee Engineer in April 2011 and supported Rolls-Royce plc. He is currently working as a System Design Engineer supporting Honeywell Aerospace. During his under graduation, he had worked as a part time content writer and had written a number of scientific articles.

Janakiraman is credited with the following achievements:

- A Six Sigma Green Belt, certified by Micro, Small and Medium Enterprises (MSME), Government of India
- Published two international papers on Ornithopter design and development at the Asian Congress of Fluid Mechanics (ACFM) and Fluid Mechanics and Fluid Power (FMFP) conference.

At QuEST, his current role includes:

- Supporting Honeywell Aerospace in systems design, verification and validation
- Data mining, root cause analysis, system level problem solving and troubleshooting
- Integration of component design, analyses, performance and manufacturing teams
- Team building and knowledge sharing

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QuEST partners with customers to continuously create value through customer-centric culture, continuous improvement mind-set, as well as domain specific engineering capability. Through its local-global model, QuEST provides maximum value engineering interactions locally, along with high quality deliveries at optimal cost from global locations. The company comprises of more than 7,000 passionate engineers of nine different nationalities intent on making a positive impact to the business of world class customers, transforming the way they do engineering.

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