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Aircraft Engine Advanced Health Management: The Power of the Foresee

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Abstract

Over the last few decades a significant change in the business model of the aircraft engine companies has taken place. The relative importance of the fly by the hour (FBH) or power by the hour (PBH) type of approach has grown from being relatively marginal to be, in many cases, the main source of income and an essential tool to improve reliability and safety aspects. In terms of maintenance, a direct consequence, has been the transformation from a mostly preventive maintenance, where the engine was refurbished at fixed intervals, and the actions at each interval were generally predetermined, to a predictive model. To handle these changes, the original Engine Health Monitoring has evolved to an Engine Health Management, both of them preserving the EHM acronym

Some real examples are provided to show how the EHM is able to help in normal operation and also under failure conditions.

Finally, some considerations are made about the future challenges and opportunities of the EHM. All these aspects will be complemented by new on-wing inspection and repair capabilities. A step change is therefore expected in the reliability parameters of the aircraft engine sector, which will be of paramount importance considering the continuous growth of the sector.

1 INTRODUCTION

Over the last few decades a significant change in the business model of the aircraft engine companies has taken place. The relative importance of the fly by the hour (FBH) or power by the hour (PBH) type of approach has grown from being relatively marginal to be, in many cases, the main source of income and an essential tool to improve reliability and safety aspects.

In terms of maintenance, a direct consequence, has been the transformation from a mostly preventive maintenance, where the engine was refurbished at fixed intervals, and the actions at each interval were generally predetermined, to a predictive model.

To handle these changes, the original Engine Health Monitoring has evolved to an Engine Health Management, both of them preserving the EHM acronym, and the gas turbines have also changed in terms of the number and quality of instrumentation and also the exploitation of the huge amount of data generated by such sensors.

Some real examples are provided to show how the EHM is able to help in normal operation and also under failure conditions.

Finally, some considerations are made about the future challenges and opportunities of the EHM, which is expected to play the key role in aircraft gas turbine in service management, combining an even larger number of higher reliability sensors, more accurate models and real time processing, joining individual engine decisions to the global fleet logistics. All these aspects will be complemented by new on-wing inspection and repair capabilities. A step change is therefore expected in the reliability parameters of the aircraft engine sector, which will be of paramount importance considering the continuous growth of the sector.

2 LIST OF ACRONYMS

AOG: aircraft on ground

EFH: engine flight hours

EGT: exhaust gas temperature

EHM: engine health monitoring / management

ETOPS: extended twin operations

FADEC: full authority digital engine control

FBH: fly by the hour

FF: fuel flow

GPA: gas path analysis

IFSD: in flight shut down

ITT: inter turbine temperature

LCC: life cycle cost

LPT: low pressure turbine

MRO: maintenance, repair and overhaul

NH: high pressure spool speed

NL: low pressure spool speed

PBH: power by the hour

TBO: time between overhaul

OEM: Original Engine Manufacturer

3 OVERVIEW OF CURRENT AVIATION MARKET AND ITS NEEDS

Aviation has been a continuous growing market since decades ago. Having a closer look to the first fifteen years of this century, it can be seen (fig. 1 from ref. 1) that with the exception of 2001 and 2009, the rest of the years the number of passengers grew, with a global average larger than 5%. For cargo the increase is not as sustained and the average is also lower.

However, this continuous and sustained growth is not always followed by strong economic results. If we examine the profit margin for the same period of time (fig. 2, ref.1), the scenario is quite different and the average value is a small figure. It is relevant to note that, for instance, after the drop in passenger of 2001 it only took a year to recover but, in terms of economic results it took five years.

If the income of airlines is considered, it can be seen (fig. 3, ref.1) that a simple, but key factor, such as the air fare (at constant economic terms) has dropped for the last twenty years. The drop per year is quite close to the increase in number of passengers.

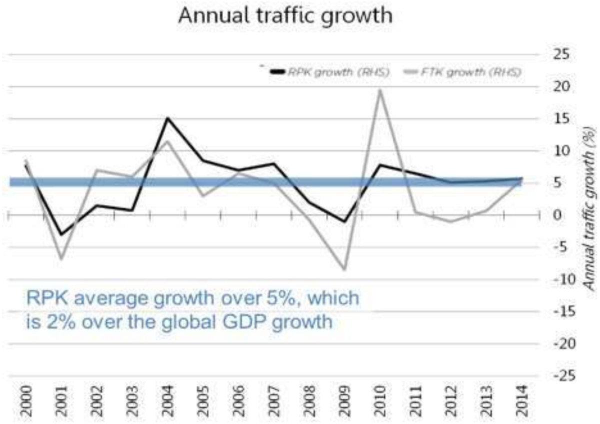

Figure 1: Aviation annual traffic growth

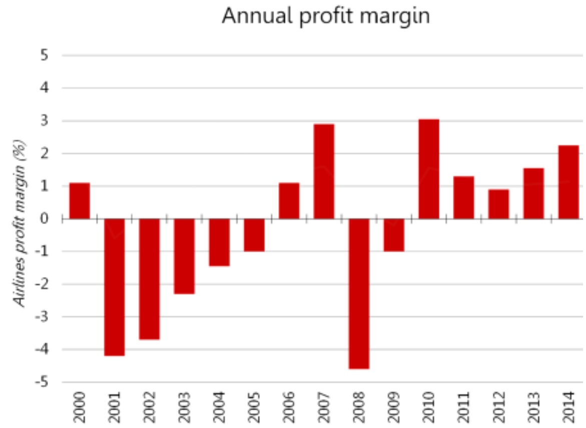

Figure 2: Aviation annual profit margin

In terms of expenditure, fig. 4 shows the split for a typical large aircraft with a fuel price around 80 USD/barrel. As it can be seen, the fuel and the maintenance are the two key factors in addition to the direct cost of the operations, being larger than, for instance, the aircraft cost.

Figure 3: Evolution of aviation average return fare

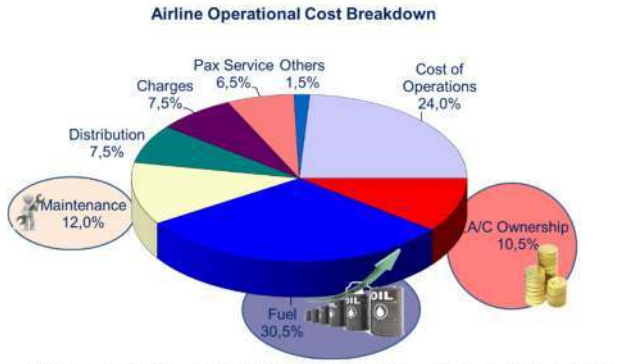

Figure 4: Typical airline operational cost breakdown

Hence, there is a strong appetite to implement all measures that are able either to increase the income or reduce the cost. In these aspects, the Engine Health Management is playing a very important role and it is expected that such role will significantly increase over the coming years and decades. Reduction of disruption in departures, capability to anticipate maintenance actions, increase in the time-on-wing, reduction in fuel consumption, extension of the life of the components, etc. are the type of advantages that we can anticipate. In addition, the large amount of in service data will also help to perform changes to the future engines.

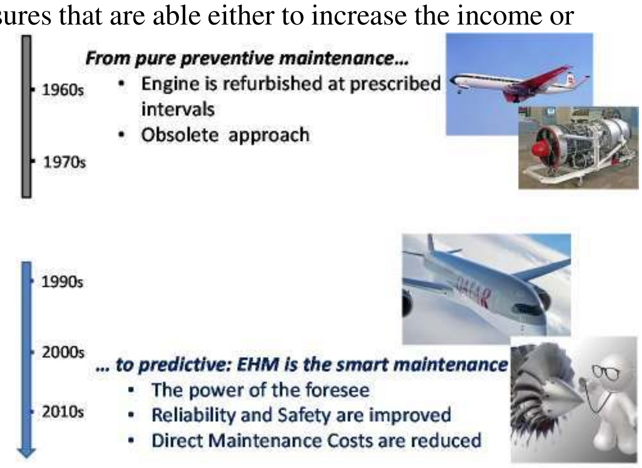

Figure 5: Aircraft Condition Monitoring evolving from preventive to on condition

4 CHANGE IN ENGINE COMPANIES BUSINESS MODEL

Over the last two/three decades there has taken place a significant change in the business model of the aircraft engine companies, moving towards a fly by the hour (FBH) or power by the hour (PBH) type of approach.

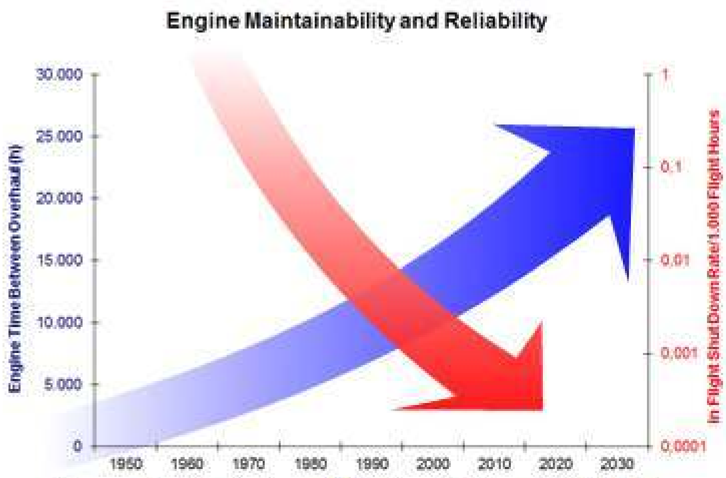

Figure 6: Evolution of Engine TBO and IFSD Rate

In terms of maintenance, the transformation has been from a pure preventive maintenance, where the engine is refurbished at fixed intervals and the actions at each interval are mostly predetermined, to a predictive model. This model is based on the capability to predict and has been of extraordinary importance in the improvement of the safety and reliability parameters as well as the reduction of the direct maintenance cost. Fig. 6 is the result of translating all the improvements into two key parameters: the in-flight shut down rate (IFSD) and the time between overhaul (TBO). There is a clear trend in both of them, which are key to support the current aviation system and to keep flying a worldwide fleet of over 20,000 aircraft between regional, single aisle and wide body. Nearly half of this fleet is in flight at any moment in time.

5 *EHM USE FOR AIRCRAFT ENGINES*

Over three decades ago, this acronym would have been recognised as meaning Engine Health Monitoring. Today its meaning has changed to Engine Health Management. The former refers to passive observations and the latter to an active search and action.

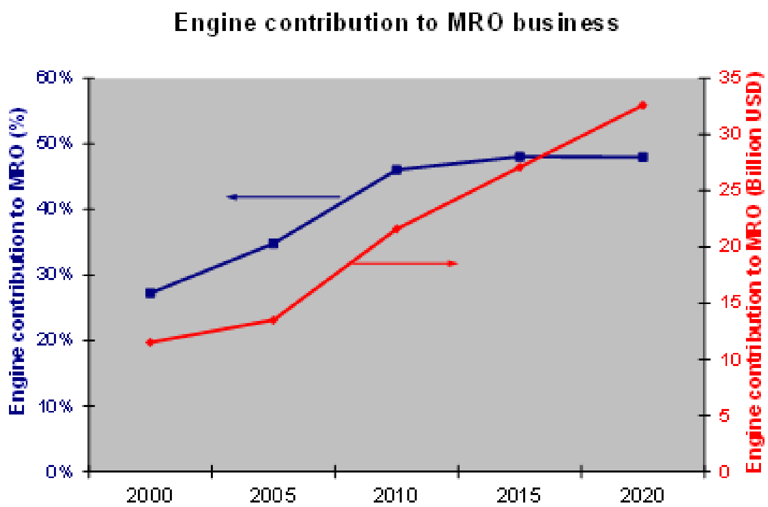

Figure 7: engine contribution to MRO (relative and in billion USD)

EHM was primarily a tool used in the aftermath of a failure or to pre-empt an impending failure of a rotating assembly or engine sub-system. The general health of the engine was, for the most part, maintained through periodic maintenance scheduled on operational time or flight cycles.EHM practices are, therefore, as old as the gas turbine itself.

Monitoring and analysis methods have progressed in sophistication over the past decades as the gas turbine evolved in form and complexity. The primary motivation of this development is, not surprisingly, competitiveness. In the worldwide commercial aviation sector alone it is estimated that $50 billion is spent annually for fleet maintenance activities and this is expected to rise to $65.3 billion by 2020. The engine relative contribution to this value will increase from over 25% at the turn of the century to just below 50% in the near future (fig. 7). In addition, these already large numbers would significantly increase if the military aero-engine fleets worldwide as well as all gas turbines used for marine propulsion applications, power generation and oil pumping stations would be included. Improvements in maintenance logistics, reductions in unscheduled events and their consequences and improvements in operational efficiency have an enormous impact on reducing these costs and EHM has a key role to play in all of them.

Currently EHM systems are intended to improve the business propositions of engine applications by providing

- Marketable capabilities that make the product more attractive to the end customers
- A means of optimising the Life Cycle Costs (LCC) for the end user
- A means of reducing financial exposure for a Fleet Management Services provider.

The aircraft engines health monitoring is based on the three basic aspects (fig. 8):

- Recording of flight parameters (altitude, ambient temperature and pressure, etc.) and on-board engine measurements temperatures at different engine locations, oil pressure and temperature, fuel flow, shaft speeds, vibration levels, etc.) from the sensors.
- Development of a thermodynamic (including air/oil systems) & vibration model simulating the behaviour of the engine parameters under different conditions of their modules (i.e. from new to fully degraded)
- Development of an integrated system that is able to evaluate the current health of the system (diagnostics), to identify and alert about abnormal performances and forecast the future behaviour of the engine identifying potential emerging problems (prognostics). The power is in its ability to predict the future condition of the overall engine, subsystems and engine component, being capable to predict component failures or malfunctions before they actually occur. Certain parts of the system could be on-board, while the majority is expected to be on-ground.

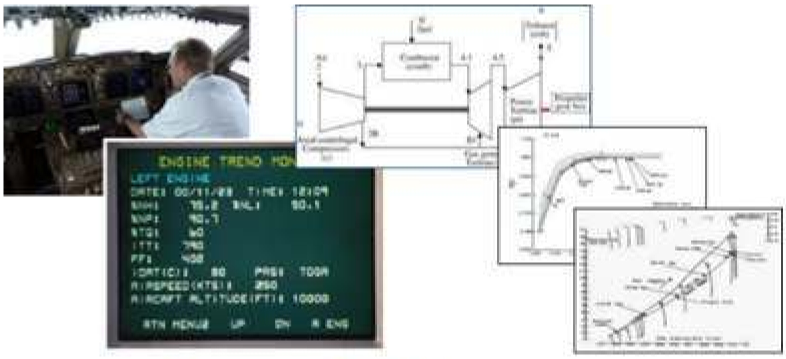

Figure 8: basic aspects for EHM system

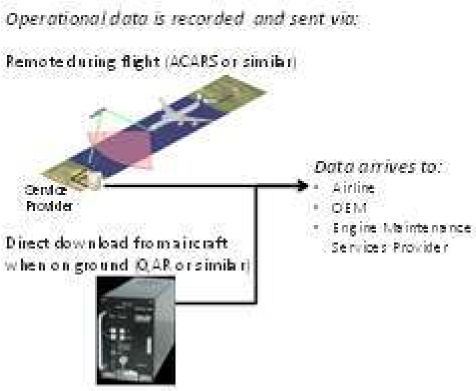

Fig. 9: operational data recording and transmission

The EHM will also learn from the global experience accumulated. It should be able to track individual engines (for which some physical measurements would have been taken, such as nozzle guide vane areas for the turbines, exhaust areas, cold build clearances, etc.) as well as complete fleets.

With continued advances in affordable cost computing, high speed communication and more sophisticated sensors, EHM systems are now found in a variety of applications both commercial and military.

These basic aspects could be not that different to the health monitoring of other type of products, but the inherent difficulty is due to aspects such as the aggressive environment. As an example, the temperatures of interest could be as low as -80ºC at the entry of the engine in altitude conditions and as high as 1700ºC at the entry of the high pressure turbine and the measurement should take place in flows at speeds close to the sonic condition (Mach numbers from 0.5 to 1.0 are quite typical). A similar case can be seen in the acquisition of other parameters of interest, such as pressures, vibrations, oil system conditions, etc. In addition to the intrinsic challenge described, we should also take into account the durability required: periods between maintenance actions for gas turbines have

significantly increase over the last decades and also the modular concept brings the fact that some modules will not be disassembly in nearly a decade. Hence the instrumentation used for health monitoring should also survive such periods providing accurate readings.

In terms of measurements it is important to record the parameters at each flight and also to ensure that stabilised and repeatable conditions (take-off, climb, stabilised cruise, etc.) are continuously available.

6 EHM INFORMATION AND ITS MANAGEMENT

As already mentioned, aircraft gas turbine data is available from a variety of sources, including on-board sensor measurements, maintenance histories, and component models. An ultimate goal of EHM is to maximise the amount of meaningful information that can be extracted from various data sources to obtain comprehensive diagnostic and prognostic knowledge regarding the health of the engine. Data fusion, performed by the integrated system, is the combination of data or information from multiple sources to achieve enhanced accuracy and more specific inferences than can be obtained from the use of a single information source alone.

The information available includes (ref 3):

- Engine gas path measurements: typically a reduced number of inter-module pressures and temperatures, shaft speeds, fuel flow, etc. Gas Path Analysis (GPA) itself can be viewed as a form of information blend, as these parameters individually provide far less information than when considered collectively to form signatures that can be correlated to known fault categories. Basic gas path sensors were always available due to their use in controlling the engine. Progressively, additional gas path sensors were added for EHM purposes since they were relatively inexpensive and fairly reliable.
- Oil/fuel system measurements: consist of various oil system temperatures and pressures. Advanced sensors indicating oil quality, oil debris monitoring sensors, and oil quantity measurements are also available in modern engines. The fuel system is also monitored, although typically has lower number of sensors.
- Vibration measurements: vibration monitoring is typically performed on most engines. The state of the art is to measure the vibration in all the spools (typically two or three) and includes specific instrumentation to monitor the bearing and gearbox. Accelerometers were not as abundant on aero-engines. The bandwidth for vibrations is relatively high (2 to 20 kHz) limiting, in the early days, the type of on- board analysis possible due to CPU capacity. The large amount of information contained in these signals could not be processed on-board and storing the information for on-ground analysis was also limited due to storage constraints. Consequently, this form of mechanical monitoring was restricted to primarily capturing average vibration amplitudes and comparing them to limits, alerting in case of exceeding those. However, with today's storage and CPU capacity, larger on-board processing is possible, as well as preserving all the content of the vibration signals for subsequent on-ground analysis.
- Structural assessment sensors: these aid in assessing structural integrity of the engine, such as inlet and exhaust debris monitoring, acoustic and high frequency vibration sensors, etc.
- Full Authority Digital Engine Control (FADEC): this system, of increased capacity and capabilities over the last years, performs continuous tests on signal condition and fidelity. Cross channel checks can aid in determining whether or not a sensor is drifting, going out of limit or failing, providing information regarding engine health.
- Engine Models: accurate engine models can be used to generate virtual engine measurements to aid in detecting faulty engine instrumentation or confirming degraded engine performance.

- Maintenance/analysis history: information regarding the performance disposition of the major modules that comprise the engine can potentially be used as a priori information to support the identification and estimation of performance changes
- Companion engine data: on multi-engine aircraft, information from the companion engines is proven to be very useful to provide additional independent confirmation / rejection of instrumentation problems or engine events. This is especially true if the companion engine has been through a similar lifetime maintenance activities, etc. so both are truly comparable.
- If information from all sources combined with analytical methods to collectively manipulate them, the (perceived) need for additional sensors can be minimized. Additional sensors would only be necessary if they acquire unique information (not deducible from the information fusion) or as a redundant corroboration to reduce uncertainty which may be inherent in our observations (existing sensors and other information).

7 POWERFUL PHYSICAL MODELS AS KEY TOOL

With the huge amount of data available, there is an obvious attraction to swing towards statistical tools to derive conclusions. However, the use of a powerful engine performance tool could be the difference between a conventional system and a state of the art EHM tool. Advanced models adapt themselves to the conditions observed by the engine, hence providing virtual sensors that can be used to estimate engine module degradation.

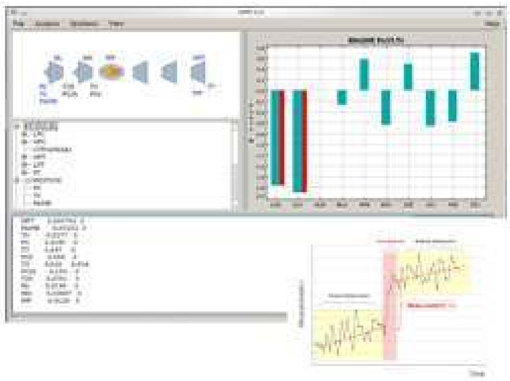

Figure 10: performance tool for EHM

Strong knowledge of the overall engine design (whole engine performance, systems and mechanical model), including as well the different modules, is of paramount importance: location of sensors, deep understanding of the limits, action strategy, etc. are best known when having OEM capabilities. The assembly and pass-off data also represent key pieces of information, to be able to differentiate between individual engines. As an additional benefit, the in service experience will be employed in future design.

8 IMPROVED RELIABILITY AS A RELEVANT OUTCOME

EHM is a mean to mitigate risk in decisions that impact operational integrity and has a profound impact on safety related aspects, such as In-Flight Shut Downs (IFSD). Current values for large engines with ETOPS requirements are in the range of 1 per 1 million hours of operation, although the regulation requirement for ETOPS 180 is to be less than 2 per 100 000 EFH. It basically means that that the pilots starting today will probably never experience an IFSD due to an engine malfunction.

9 EXAMPLES OF EHM MANAGEMENT

- ***Turboprop performance evolution due to normal wear and tear***

In order to determine the performance behaviour we monitor an example is shown here where fuel flow, inter turbine temperature, HP and LP spool shaft speeds are measured. In case of normal performance evolution (fig. 11) a continuous and progressive increase of fuel flow and inter turbine temperature can be observed. As real data is available, the deterioration and the life of the components can be better estimated as a function of real operation rather than standard missions. Boroscope inspection also shows normal degradation. Thanks to the comprehensive EHM follow up, it will be possible to predict the best moment to remove the engine and send it to MRO shop for maintenance action. In addition, the engine repair work scope is better oriented thanks to the in-service analysis results obtained through the data retrieved from the EHM extracts: module deterioration, individual issues, etc. which could lead to the decision of solely refurbish the hot section or to go for a complete engine overhaul.

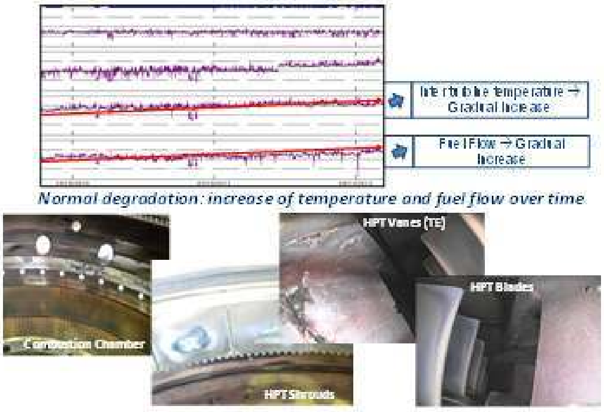

Figure 11: performance evolution and component status under normal operation

- ***Hot section temperature sensor failure***

The case of fig. 12 shows a sudden increase in the turbine temperature. None of the other parameters displayed exhibit an abnormal behaviour, which could suggest that the issue is in the thermocouple. Thanks to EHM daily follow up it was indeed confirmed defective after line troubleshooting. The issue was anticipated following a cruise EHM temperature single step up detected, before it could be detected by aircrew in their ordinary daily activities, which would have generated subsequent aircraft technical dispatch interruption.

Without the help of the EHM, this problem is likely will evolve in the coming days/flight hours at a level it probably would have been trigger by an EGT/ITT exceedance at take-off, with the subsequent rejected take-off/in flight turn-back and associated Aircraft on Ground (AOG) costs.

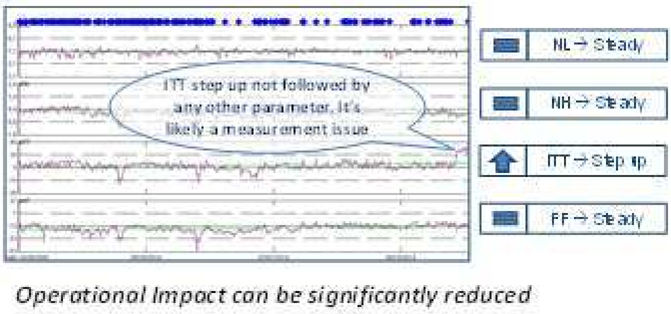

Figure 12: performance evolution under a potential ITT abnormal measurement

This issue, if detected on time, represents an effort of one hour for the removal and installation plus the associated thermocouple costs and replacement can be easily planned at the overnight Turn-around Time (TAT) of the aircraft without incurring in further expenses. But a single hour delay of a wide-body aircraft represents around 20k$ (just expenses directly attributable to the operational interruption) plus the airline reputational impact due to the rejected take-off event. AOG represents a significant cost for airlines which can be drastically reduced thanks to the EHM advance techniques.

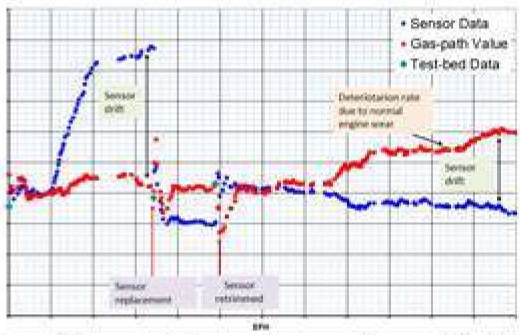

Figure 13: sensor temperature and gas path derived Temperature evolution with EFH

Another example is the one shown in fig. 13. In this case, the temperature calculated by the EHM has a higher level of accuracy when compared with the sensor, due to different on-board technical issues. This was verified when measuring this parameter in the test bed, showing an excellent correlation with the Gas Path values. Hence the alternative use of the derived value rather than the measured value is a more reliable technique. Use of misleading temperatures readings could lead to incorrect thrust control, early or late engine removal, etc.

- ***Hot section component failure detection***

Fig. 14 shows a sudden change in the four parameters displayed (increase in all but the LP shaft speed). This reveals that an issue has occurred, most likely in the hot section and, within the hot section, at the LPT.

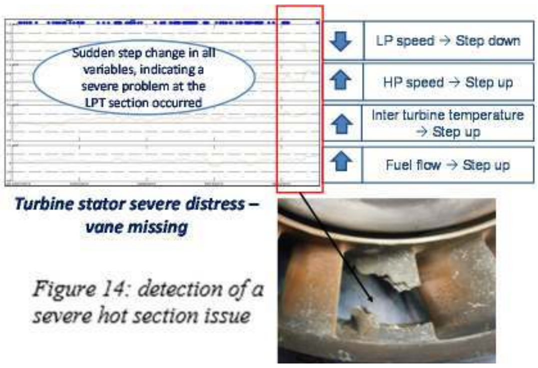

Figure 14: detection of a severe hot section issue

This would potentially represent a hazardous situation: the particular changes found into the EHM curves have led to plan an engine borescope inspection, discovering during the scrutiny some distress at LPT section. Engine removal became necessary and it was confirmed at engine tear down that the LPT first stator had one of its vane missing.

This situation was solved in time by carrying out an engine light repair in a localized section worth by 5% of total engine overhaul, while a major distress of the engine initiated by this damage could have been represented a repair invoice worth 80% of total engine overhaul, which for large civil engines will be between 3 and 5 million USD.

A possible IFSD plus extensive engine damage was avoided by taking immediate action thanks to EHM.

- ***Cold section failure / deterioration***

There are other cases when, for example, potential issues in the cold section are detected. This could indicate failure in a bleed valve or compressor deterioration. Adequate management of the compressor performance through cleaning, identification of valve malfunctions, etc. could lead to fuel savings in a turboprop aircraft equivalent to two full tanks per year, which has a very significant economic and environmental impact.

Figure 15: yearly fuel saving by appropriate cold section management

10 BIG DATA AS PART OF THE FUTURE STRATEGY


Figure 16: Aircraft in operation over Europe (source Flightglobal24)

As mentioned above, at any moment in time around 10,000 aircraft are in operation (fig 16). We can put the same fact in a slightly different way: there are over 100,000 flights per day or around 39 million flights per year in 2016. Each engine on board has instrumentation which ranges from just ten sensors to around a hundred or above. Temperatures, pressures, shaft speeds, vibrations, torque, fuel flow, etc. are the most common parameters. If we consider an acquisition frequency of just 1Hz, which is clearly insufficient for aspects such as vibrations, which will be on the order of 1 to 20 kHz, we could be considering of the order of 10 trillion data for the entire civil worldwide fleet, increasing significantly if the defence, marine and industrial gas turbines are taken into account. If we just consider a modest fleet of 10 aircraft with an average number of parameters this figure will still be 4 billion data per year, which is in itself quite impressive. The technologies currently under development to handle big data will be an excellent complement to the specific gas turbine advances.

11 THE FUTURE SCENARIO OF AVIATION

The future of aviation suggests a sustained growth in the number of passengers and also the dominance of the large twin aircraft, making the improvements in reliability and in safety related aspects even more important. Five key element are identified for the future EHM will be

- Dedicated sensors with improved reliability and durability.
- Improved data management
- Complex accurate integrated system with enhanced prognostic skills.
- Integration with the logistic system of the engine maintenance provider.
- Enhanced inspection capabilities, joined by a larger portfolio of on-wing repair technologies.

The system will continue to be split between on-ground and on-board. It is expected that on-ground systems will continue to dominate in terms of analytical capability, etc. although on-board should grow in its relative importance. The on-ground analysis will happen in almost real time, using fully automated systems for most of the prognostics. The on-board, although is recognised to be more challenging and expensive due to the strict airworthiness regulation, aiming to increase its robustness avoiding false alarms, will play a more important role in the future.

Also, the integration with the logistic system will be crucial, providing a more comprehensive analysis and different potential alternatives taking into account these aspects.

Finally, the enhanced inspection capabilities, linked to the computational systems, will provide the engineers an accurate remote view of the engine. The on-wing repair technologies also need to further develop and the miniaturised robotics will play an interesting role in the future.

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