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Cost Reduction and Engine Life Extension Through Engine Life Monitoring at SNECMA

Frédéric Genot
SNECMA MOTEURS
Centre de Villaroche - Réau
77550 Moissy Cramayel, France

I - SUMMARY

The current market of the military Aircraft Gas Turbine Engines imposes reductions in the support costs. It has now become necessary to adapt our maintenance policy to comply with the new requirements. The present tendency focuses on a better knowledge of the real engine operation conditions to better relate damage to mission types. Our former maintenance policies for military engines were too expensive. SNECMA adopted the damage tracking on the ATAR, the flight recorder for the LARZAC and a life monitoring system for the M53 and the M88. It has become necessary to be more aware of the importance of feedback information on real engine operation conditions in order to specify design missions. After the control of engine parts life, it is now necessary to control the consumed life of fracture-critical rotating components in operation. Finally, the use of life monitoring system for the damage parts tracking in association with an adequate maintenance plan lead reduced support costs and improved engine parts life.

II - INTRODUCTION

Today, engine manufacturers are under heavy customer pressure to find a compromise between performance, mass and cost. The development of new contributes to an optimized performance/mass ratio but this often results in increased production cost. An engine is sold for a certain number of flying hours. The total support cost is calculated mainly according to the maintenance plan, the flying hours and the prices of spare parts. It is therefore easy to understand why long service lives combined with a good maintenance policy contribute towards reduced costs. SNECMA Moteurs develops an Engine Life Monitoring System (ELMS) called Damage Counter which makes it possible to comply with the latter requirements.

We should perhaps first illustrate various maintenance policies in order to better understand our customers' motives. Several examples will be presented as regards the maintenance policy adopted by SNECMA for its military engines ATAR, LARZAC, M53 and M88. An analysis will demonstrate the advantages and disadvantages of each policy. We will then present the Engine Life Monitoring System developed by SNECMA. Finally, we will explain the combined advantages of Engine Life Monitoring and optimized maintenance to reduce engine support costs and to improve engine life.

III - MAINTENANCE POLICY

Several maintenance policies have been developed by Aircraft Gas Turbine Engine Manufacturers. Two parameters were essential: design engines in a conservative way and control damaged parts to avoid rupture in service. It was therefore necessary to develop and set up a maintenance policy. The two primary criteria to be considered for the success of a maintenance policy for fracture-critical rotating engine parts are aircraft airworthiness

(parts removed in time) and combat readiness. An engine manufacturer must provide the customer with an optimized damage tracking system.

In maintenance, all parts must be capable of being traced to an engine. To simplify our description, we have identified two categories of parts. In the first, we have gathered those critical parts which do not ensure aircraft integrity in the event of rupture (disks for example) while the second category includes all other parts. Every engine is sold with usage hour limits for each one of its individual parts. As soon as a part life limit is reached, the maintenance service must carry out a maintenance operation called shopvisit.

At SNECMA maintenance policies have varied with the various military engines developed over the years such as the ATAR, the LARZAC, the M53 and finally the M88.

The ATAR is an engine developed in the 50's and 60's. The various versions of this family powered the Mirage F1, 3, 4 and 5, the Etandard, the Super Etandard, the Cheetah and Panthera. The tracking unit for engine parts such as discs and blades was the number of Engine Flying Hours (EFH). An inspection schedule was determined according to part ageing tests and the analysis of missions carried out on several engines. The pilots of several aircraft of the fleet had to declare their flight profiles to SNECMA. A data base consisting of theoretical reference flights provided for each tracked part a conversion factor between the EFH and Low Cycle Fatigue damage. Damage to parts could thus be assessed for a number of engines. Assessment of damage for the whole fleet was done by a conservative extrapolation. In many cases, the only way to extend life limits consisted in carrying out statistical ageing tests to evaluate the residual life of critical parts.

The LARZAC entered service in 1979 on the twin-engine Alpha Jet. Engine parts monitoring was also based on the number of EFH. The LARZAC maintenance policy principle was similar to that of the ATAR except for a major technological development: a few aircraft operated by the French Air Force were equipped with flight tape recorders to record, for each engine, the evolution of engine parameters (time, Low Pressure Rotational Speed, High Pressure Rotational Speed) which were measured every second. Periodically, the magnetic tape was retrieved and downloaded in a microcomputer to calculate life consumption for the recorded flights. The life algorithms implemented were very simple and they reduced computation times to a few hours with accuracy rates within $\pm 10\%$. These models were composed of the following algorithmic blocks: thermodynamic, thermal, mechanical and damage. Inspection dates were set on the basis of simplified Engine Life Monitoring of damage for seven parts on selected engines. To ensure flight safety and the representativeness of all the engine parts, it was necessary to extrapolate the results in a conservative way for the whole fleet.

The M53 powers the Mirage 2000. Monitoring of parts service lives is based on Mixed Mission Units (MMU). A mixed mission is a mix of representative missions for a given engine, a so-called "average mission". The maintenance policy for the M53 is based on the LARZAC policy. The guiding principle is damage tracking by mission calculations using recorded engine parameters. For the M53, all engines are monitored and a special electronic unit is integrated into the on-board electronic systems. This unit calculates in real time damage consumption for 17 first-category critical parts in MMU. At ground level, an operator uses a microcomputer to download and retrieve consumption data. All parts are then monitored by conservatively extrapolating the results for the 17 parts. Maintenance operators can therefore manage all engine parts by cumulating MMU damage. When a part reaches its MMU limit, the ground operators must consider a maintenance operation. The damage algorithm hardware implemented includes four algorithmic blocks: thermodynamic, thermal, mechanical and damage. These blocks consist of reduced models which ensure an accuracy of $\pm 10\%$ compared with complete complex calculations.

IV - ANALYSIS

All the cases presented share a basic architecture. A complete maintenance policy shall include an analysis of parts life to process life limits for a specific unit, calculations of service times for critical parts and a life managing unit providing information on parts service lives to support decisions on aircraft deployment, component retirement, engine removal and engine and spare parts management.

As to the developments in life calculation methods, two approaches have emerged. The first development is related to the damage calculation method while the second concerns the service life monitoring unit.

The various maintenance policies feature major changes in calculations for service life control. Compared with the highly conservative methods based on correlations calculation/ageing tests, the complex numerical models used by design offices to compute parts life have become highly predictive. The first ultra conservative calculation integrated important safety margins while the EFH monitoring method provided accurate measurements unit. Current life limit determination takes into account fully modeled parts behaviour using 3-D numerical calculations and complex damage models. Crack propagation, multi-axial low cycle fatigue, creep, creep-fatigue interaction and crack probability are all considered by the designers. Critical components are identified in a very predictive way and the same part can have more than one critical location. Damage also depends on mission types. Therefore, life monitoring becomes very difficult for these parts.

Life design methods change whenever a further step in the understanding of engine operating conditions is reached in the design process. And customer pressure is equally important. To avoid losing our advantages, we must reconsider and adapt service life monitoring procedures in operation. Life monitoring calculations must be capable of being changed. This is why SNECMA has developed a modular structure for its simplified life models.

The easiest life monitoring unit is the Engine Flying Hours. An engine manufacturer sells its engine and ensures it reaches a number of flying hours. This damage unit does not provide for differences in mission severity and imposes a very strong conservatism through the use of penalizing design missions (Figure 1). This is why SNECMA decided to launch an analysis of missions in order to define missions more representative of real operating conditions. As safety margins in design life calculations and in mission definition became increasingly limited, it was necessary to develop a maintenance procedure using a life monitoring system taking real damage parts into account. Consequently the life monitoring unit logically became a Mixed Mission Unit. But this must still be translated into flying hours to be consistent with the number of hours sold to the customer.

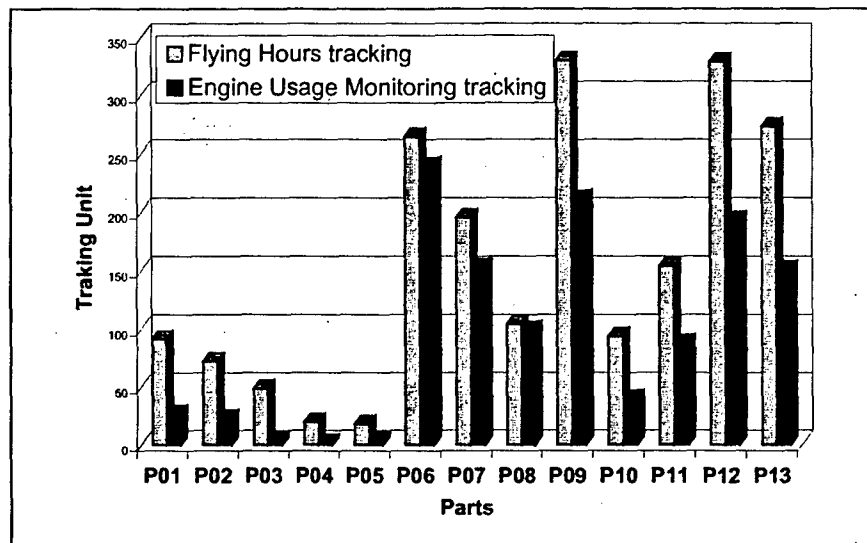


Figure 1 : Difference between Flying Hours tracking and Engine Usage Monitoring tracking after several flying hours

Service life management is at the core of a maintenance policy. A key element is undoubtedly the number of engines monitored since the control of only one or of several engines requires a conservative redistribution of the damage calculated on those parts which are not controlled. Differences in mission profiles observed between a leader and a follower in a patrol of interceptors or discrepancies in damage consumption between two air bases show that an individual monitoring method avoids taking excessively conservative safety margins to translate individual damage into fleet damage. The adoption of a systematic individual monitoring system has been an essential feature in the maintenance policy developed by SNECMA.

However, even if all the engines of the fleet are monitored, not all engine parts are tracked. Apart from the parts monitored in EFH, only the locations indicated as critical by the Design Offices have simplified algorithms to calculate their damage in operation. A procedure is required to redistribute damage on all the other parts. This problem especially affects blades: as only one algorithm is specified, the M53 ELM unit calculates the damage of only one blade. The problem becomes complex when there are several blades of different ages on the same disc. To preserve flight safety on the M53, we always monitor the oldest blade to redistribute its damage on the other blades. The solution is to apply a conservative policy.

V – THE M88 ENGINE LIFE MONITORING

The maintenance policy worked out for the M88 integrates the important points stated above. It is based on the use of a Life Monitoring System (Figure 2) developed by SNECMA. All the M88 engines powering the twin-engine RAFALE are monitored. The ELM structure is based on a data acquisition system equipping all engines and recording specific data on each mission, i.e. 10 thermodynamic parameters and 10 control values. The system tape is retrieved and downloaded in the ground station data processing system. The ELM Life Monitoring System is the software used for transient thermo-mechanical analyses on recorded flights and for damage assessment on thirty engine parts. Finally a ground maintenance software manages service life for components and residual engine lives for the engine. This maintenance software is capable of monitoring several engines. Only thirty parts are tracked and the maintenance system must manage all the parts of the engine by distributing the calculated damage to all the parts in an optimized way.

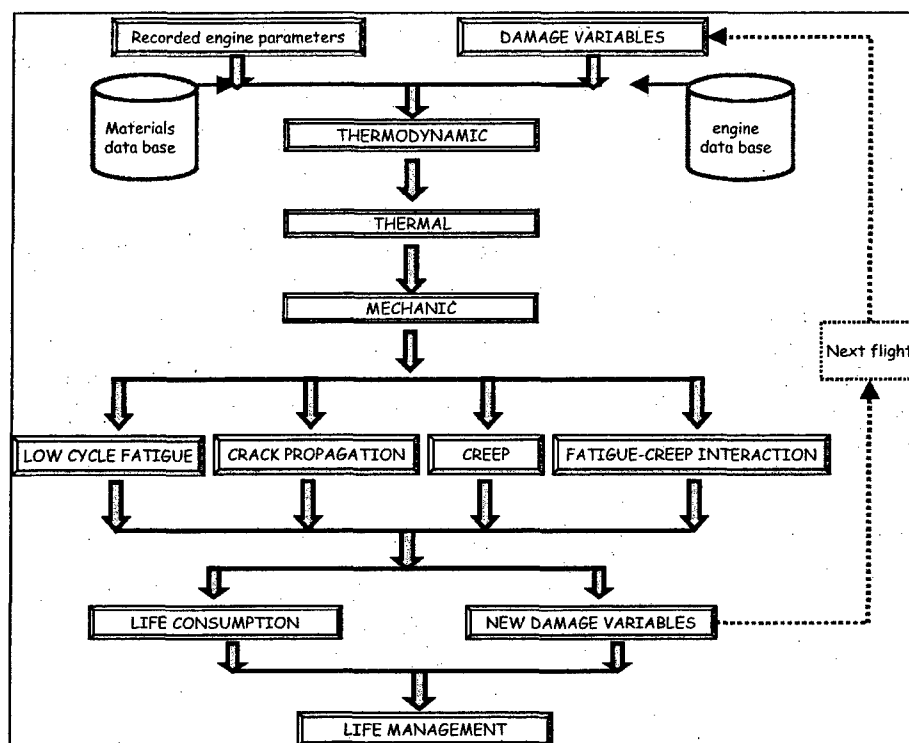


Figure 2: The Life Monitoring Software

SNECMA has identified significant engine parameters and aircraft parameters to define a mission in terms of damage. A data storage system has been developed. The engine control system transfers all the parameters to the ELM data acquisition. The system has a sufficient data capacity to record 10 thermodynamic parameters sampled every second on every engine. These parameters are pressure, temperature, flow and rotational speed. After each flight, the data acquisition system has a file for each engine. This file not only includes records for the 10 thermodynamic parameters but also for 10 additional values. These values are specific operating counters such as total engine operating time, after-burner operation time, x% over nominal values, number of engine starts, number of flights, number of take-offs. The latter is required for degraded damage calculations in the event of problems affecting the transmission of parameters to the acquisition system. The data recording system has a recording capacity for several missions so that maintenance operators do not have to download the files after each flight.

The ELMS is initialised with the engine identification informations, the residual life and damage continuous variable of the monitored components. The damage calculator works independently of the ground system. Life consumption is computed for thirty parts: each is individually monitored for Low cycle fatigue, Crack Propagation, Creep and Creep-Fatigue Interaction. This is performed using a conventional computing system. The software is divided into four main units: thermodynamic, thermal, mechanical and damage. The thermodynamic unit measures pressures, air temperatures and air flows. The thermal unit computes temperature for solid parts with the following inputs: air flow temperature, pressure and rotational speed. The mechanical unit determines local stress based on local temperature and rotational speed. Each critical localisation is defined by a thermo-mechanical background. Finally, damage computation is based on reduced damage models. Damage results are computed in an appropriate engineering unit such as LCF cycles and damage variables. For homogeneity reasons, damage is translated into authorised life units using exchange rates.

The maintenance system cumulates life consumption to determine the residual life of each component. The life management system is able to provide suitable outputs for maintenance and logistics. The system provides the operator with data such as flight clearance or flight ban, engine shop visit, statistic information. This information is required by the maintenance policy in order to plan maintenance operations and manage the stock of spare parts.

As mentioned previously, the Life Monitoring System is initialised with continuous damage variables of the monitored components. The problem is related to non-linear damage such as crack propagation or creep-fatigue interaction. The cumulative linear method cannot take non-linear damage behaviour into account. The non-linear models are implemented in the ELM and the required inputs are crack size for the parts tracked in Crack Propagation and engineering damage variables for the parts tracked in Creep-Fatigue Interaction damage. This additional information is stored for these parts by the ground system which restores them following ELM calculations.

An additional extrapolation method is implemented for blade damage consumption calculation in the life management system. Input data for the blades are life consumption and damage variables of the least damaged blade and the most damaged blade. In this way, all the blades can be tracked by interpolating damage consumption results. This optimized redistribution of life damage helps reduce conservatism.

VI - REDUCTION OF COST AND EXTENSION OF LIFE

The development of the Life Monitoring System is part of a programme of cost reductions and extended life. The cost reduction considered here applies to both development costs and ownership costs which are approximately the same. Several issues have emerged: mission analysis, design process, probabilistic approach and the reduction of safety margins.

This article focussed attention to the importance of a good knowledge of real engine use by defining design missions. The closer the design missions will be to the real missions, the more the sold Hours will be consistent with the consumed hours calculated by the ELM, reducing the margin between estimated and actual life consumed. Before the ELM was developed, mission analysis were too expensive. Without ELM data recording, the methods used to obtain required input data were: asking the pilots for their flight profiles and equipping an aircraft with a data recording device. The design missions established by the pilots were simply described in terms of sequences of throttle, altitude and speed and mission definitions were too theoretical. Only on aircraft equipped is not representative. The only way to be more representative is to equip more than one aircraft with a data recording system and operate them in standard use. The latter method is expensive in terms of human resources, hardware system and it must be accepted by the customer. Without a continuous mission analysis process, the gap between design life predictions and real life consumption is widening. One of the advantages of an ELM such as the Life Monitoring System is the possibility to create a huge engine mission data base. Operation feed-back becomes systematic and less costly.

The Life Monitoring algorithm is composed of different blocks. The life design is divided into the same blocks: thermodynamic, thermal, mechanical and damage. The ELM is a reduced model which allows rapid design life evaluation. SNECMA has decided to develop for its Design Offices a special Life Monitoring software version. This Design Version (Figure 3) will help the designers take decisions for advanced studies through optimization studies. The designer will regulate missions, thermodynamic behaviour, thermal behaviour, mechanical behaviour and the active damaging mechanisms to determine life design. This design tool will be extended to other engines and the constitution of a database for results

will allow the designer to extrapolate future developments. This complete ELM version will make work easier for the Design Offices while reducing considerably computation time for developments: it will thus contribute to reduced development costs.

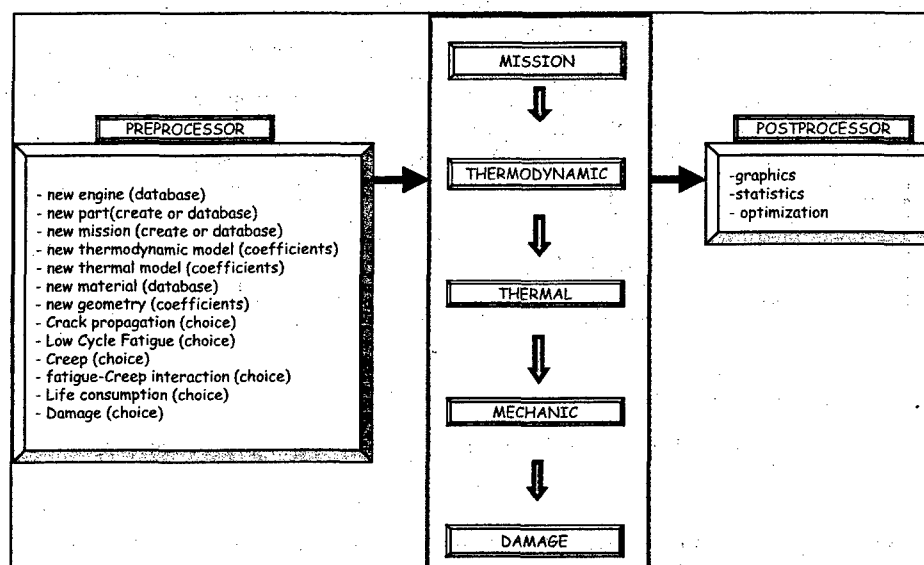


Figure 3 : The Design Version of the Life Monitoring Software

As part of the maintenance policy, an in-service life limit is imposed for all the critical parts to control potential risks of failure. Life consumption estimation are used to define a maintenance plan. The maintenance plan needs to be updated periodically as significant new life consumption data becomes available. The number of tracked parts and the different damage mechanisms lead to different levels in mission severity factors. All parts do not reach their life limits at the same time. Since a maintenance operation is expensive, inspection intervals must be optimized to avoid too many overhauls, especially for the parts with damage tolerances. Optimizing inspection intervals consists in offering flexible inspection dates for the customer. Authorized margins are associated with risk evaluation. For example, an operator will take the risk to do only one inspection instead of two inspections with few operating hours in-between. As the Life Monitoring Software is integrated into a probabilistic system (Figure 4), it allows random calculations to evaluate risk. Its algorithmic structure can be easily integrated in a probabilistic environment. All the in-service limits will be announced with a margin and an associated risk. Optimizing inspection intervals using the Life Monitoring Software contributes to reduced support costs.

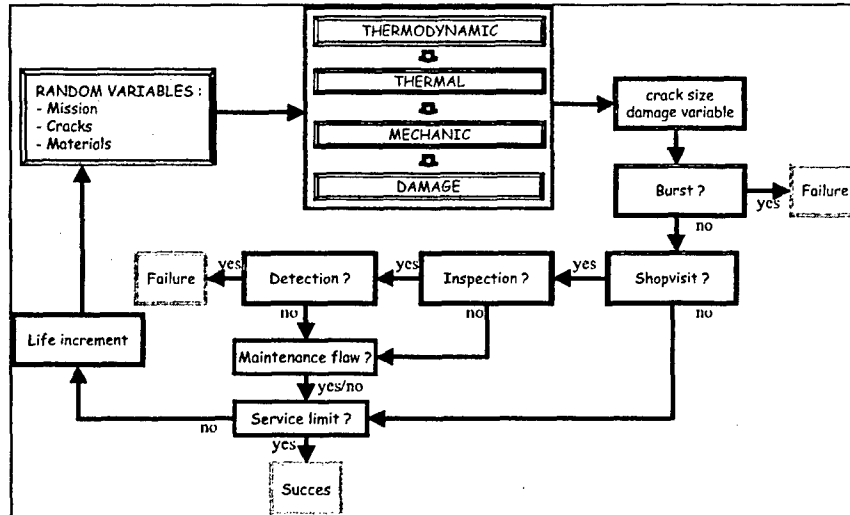


Figure 4 : The Probabilistic Version of the Life Monitoring Software

In the absence of Engine Life Monitoring, a maintenance operator should monitor engine parts using Engine Flying Hours for example. Figure 1 demonstrates that damage can be twice as important as the damage calculated by an Engine Life Monitoring. Life limits would be reached twice as quickly and customers would have the impression that life are too limited. With the development of the ELM, the design calculator reduces the conservative margins integrated in the mixed mission definition. Moreover the quality of the reduced model implemented in the ELM system reduces the safety margins used in life consumption calculations. Finally, individual engine monitoring avoids conservative damage extrapolation to the fleet. In general, the individual ELM recommended by SNECMA contributes to improving life by reducing conservative margins.

VII - CONCLUSION

A survey of SNECMA's Engine Life Monitoring approach demonstrates the advantages provided by a systematic use of Engine Life Monitoring to reduce costs and extend life. The Life Monitoring System software implemented in the M88 Engine Life Monitoring System contributes towards reduced costs through Mission Analyses and the development of Design and Probabilistic Versions. It also improves engine part life through reduced conservative margins. The conditions for success are systematic individual monitoring, the quality of reduced damage models, the variety of the damage mechanisms implemented, the representativity in operation of the Mixed Mission, change capacity in the algorithmic structure, the quality of critical components identification and a good understanding of engine damage behaviour.