DESIGN AND SERVICE EXPERIENCE OF ENGINE LIFE USAGE MONITORING SYSTEMS

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Abstract

The Planning of a monitoring system should be embedded in an overall concept which considers beside technical and logistic aspects the principles of the aircraft and engine maintenance concept. The split of the entire system into on-board equipment and local or central ground stations should be agreed in an early design phase. All kinds of changes (engine modifications, variation in operating conditions and mission profiles, software updates and processor hardware development) which are likely to become necessary over a period in service of more than 30 years should be envisaged. Adequate means for configuration control as well as the required compatibility and interchangeability should be provided.

Feedback from service now allows to quantify the advantages gained with an on-board life usage monitoring system in terms of spare part savings and flight safety increase. Furthermore the scatter in life consumption has been analysed and it can be concluded that the often heard opinion that life consumption is directly correlated with the mission type is not supported by the observations. Of course, it is possible to identify particular parameter constellations which occur under normal daily engine operation but cause either excessively high or very low life consumption. However, most of the scatter must be accepted to appear randomly.

1. Introduction

In a couple of projects [1,2,3,4] – which include jet and helicopter engines – MTU have gained experience in the design and operation of on-board engine life usage monitoring systems. Based on the difficulties overcome during the development and introduction phase of these projects as well as based on some feedback from first years in service a lot of information has been gathered which allows for the deduction of some general rules.

2. Engine Monitoring -An Integrated Task

Engine Monitoring – and particularly engine life usage monitoring – is not a stand alone task. It must tit into an overall maintenance concept which includes aircraft maintenance as well as engine maintenance. Clearly, the overall requirements must satisfy the needs of the customer. But the customer himself needs the support of aircraft manufacturer, engine manufacturer and electronic system specialists to get detailed insight into the design target of the monitoring system and into all the functions of the entire system. Fig. 1 illustrates the mutual dependencies.

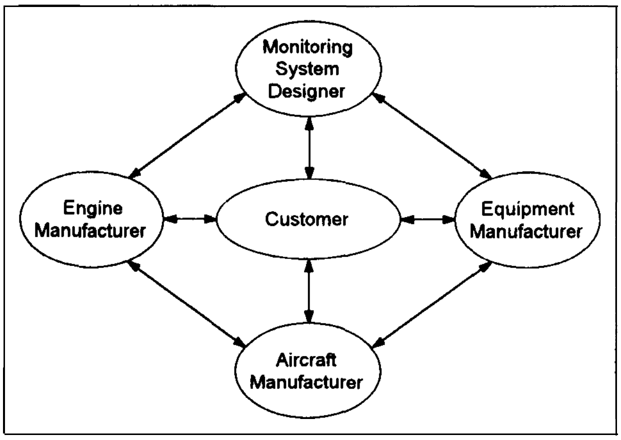

Figure 1: Partners Involved in Monitoring System Design

Generally, an aero engine monitoring system must be understood as a distributed system, what means that some parts of the system are located within the aircraft and engines and others on ground. For most of the components it is a priori fixed where they must be located. But for other components the decision depends on a number of criteria. This is particularly true for the algorithmic functions, where it must be considered when and for what purpose which information (i.e. raw data, preprocessed data, results) is needed. It is essential that all these parts cooperate smoothly. This requires regular exchange of data between them, where between most of them the data transfer is not a one-way route, meaning that bidirectional communication is absolutely necessary. It follows that the complete functionality of the respective interfaces should be clearly defined in an early stage of the project.

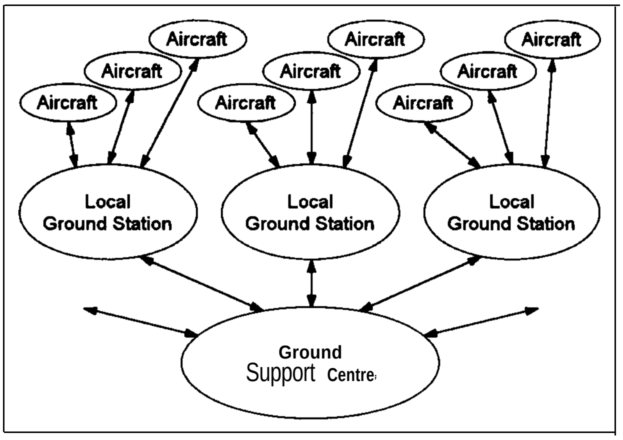

Figure 2: Engine Monitoring as Distributed System

This requires an intensive dialogue between all the parties involved. One of the main problems in the development phase is a communication problem, since more parties (i.e. companies, institutions, authorities) and more people (specialists of all the interdisciplinary subjects necessary) are involved than originally thought. There are examples where the lack of communication has led to uncoordinated design and development of engine related on-board parts, aircraft related hardware and software and ground equipment. This in turn compromises the functionality of the whole system and finally yields in a very low level of system acceptance at the customers side.

3. Units **of Damage**

The introduction of an engine life usage monitoring system provides the user with new and advanced capabilities what in turn requires adequate adaptation of the overall engine maintenance concept. This forces him to think in new terms. Generally, the engine operators were used to count engine life consumption in (engine flying) hours or (engine flight) cycles, where an engine flying hour just meant an hour of engine flight or an engine flight cycle simply one flight. Life usage monitoring systems (which have been employed since life consumption is not proportional to the number of flying hours or flights) measure the consumed life in damage related physical or technical units. For example, if life consumption due to fatigue damage (based on a crack initiation lifing concept) is monitored, the unit will be ‘Reference Cycles’. It should be noted that this type of cycles is completely different from the above flight cycle. The reference cycle is a stressing cycle describing the local stress range at a considered critical area under engine design conditions. Since an engine is normally not (in fact: never) operated exactly to the assumed design conditions, the real life consumption deviates from ‘one cycle per flight’.

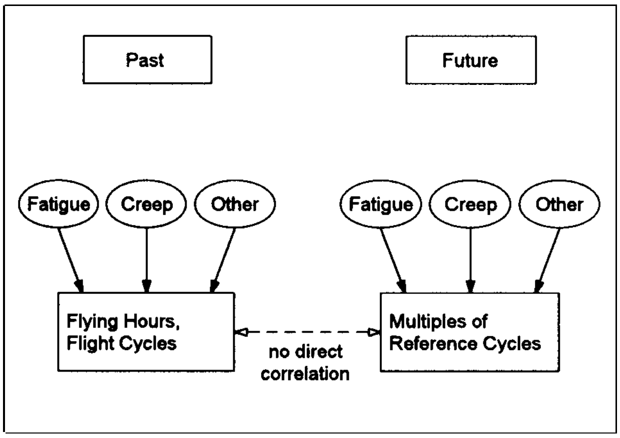

Figure 3: Units of Damage

On the other hand, the released lives of critical parts or components (what includes parts or components which are worth being life monitored) are determined in reference cycles. To overcome the problem with the different units, one could simply measure the consumed life relatively as a percentage of the released life, but this will provoke additional difficulties when the released life of a component will change during the engine life time.

Experience shows that it is necessary to change the released lives when

extended knowledge about the engine behaviour becomes available,
manufacturing processes are changed or
improved lifing concepts are introduced.

An improved lifing concept for a part with life limitation due to fatigue could mean the introduction of a damage tolerant concept. In contrast to the crack initiation lifing concept, the damage tolerant concept allows for the presence of a crack in the considered part. Now the size of this crack (normally measured in mm or pm) could be used as a quantitative measure for life consumption. Nevertheless, the actual size of the crack is not known until detected by inspections. To be on the safe side, the prediction of the possible crack size has to consider worst case conditions, meaning that the predicted crack size is significantly larger than the actual one.

The fracture mechanics crack growth prediction methods are capable of providing correlations between the number of applied loading cycles and the resulting crack size. The crack size itself is of no practical use for the customer (unless observed by inspections). But based on the above correlation between the accumulated number of cycles and the corresponding crack size, the monitoring system can internally handle the respective fracture mechanics algoriihms and convert the damage into numbers of reference cycles for external communication. Thus, for the application of both the lifing concepts the customer needs only one unit for the measure of life consumption.

An additional advantage of this procedure is that internally both lifing concepts can be combined without changes at the interface and without any appearance outside the algorithmic part of the monitoring system.

Typically, the creep damage – technically represented by changes in strain – should be indicated in units of creep life consumption during a predefined test run at high temperatures.

Other damage mechanisms can be treated in a similar way, allowing for a unique appearance of all life monitoring results at the customer's interface.

4. Life Usage Monitoring Tasks

Fatigue and creep life consumption – the most important life limiting damage mechanisms in monitored aero engine parts – generally result from stress -temperature sequences. Affected are only a few locations of a part, the so called critical areas. Monitoring the life consumption of these critical areas simply means to determine the complete history (i.e. from the virgin part to the definite life expiration) of stress (or some other relevant stressing parameter) and temperature development at this area, and to assess the resulting damage.

Details of the applied procedures were already presented at several occasions [1,2,5,6] Here only a short summary is given.

The core tasks for life usage monitoring are

performance calculation; this consists of the determination of temperatures and pressures in the gas path and cooling air paths. These temperatures and pressures form boundary conditions for the following steps.

temperature calculation; the metal temperature distribution in the components is calculated. Starting with the initial temperature distribution (which depends on the final temperature distribution of the last engine run, the current ambient temperature and the time between last engine shut down and current engine start), the development of the temperature distribution history over the entire engine run is computed based on the performance parameters,

stress calculation; total stresses are calculated for each monitored area. The total stress includes thermal stresses (derived from the current temperature distribution), centrifugal stresses (resulting from rotational speed), and additional stresses (due to gas pressure, assembly forces, etc.).

damage assessment; the stress-temperature histories are assessed with respect to the relevant damage mechanism, and the resulting life consumption increments are calculated and accumulated separately for each monitored area over the entire engine life time.

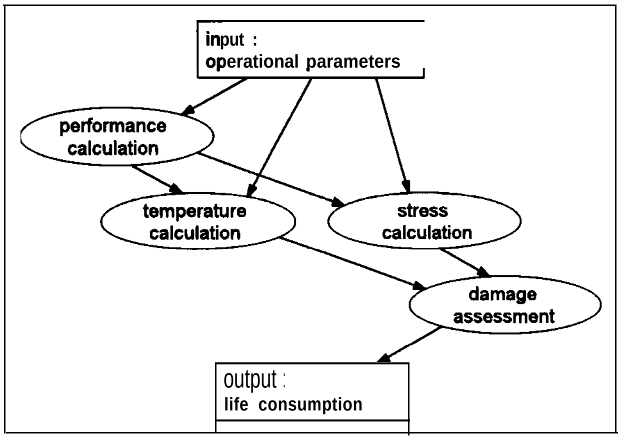

Figure 4: Core Tasks for Life Usage Monitoring

These core tasks for life usage monitoring are on principle the same as for engine design and for the analysis of mechanical integrity. For the monitoring purpose, of course, special algorithms have been developed which are fast enough to allow for on-board real time calculation. Furthermore, the monitoring algorithms encompass not the complete engine structure but only the critical components and the monitored areas. To achieve the requested processing speed for monitoring, some reduction in the accuracy (compared to the engine design analysis) must be accepted. The achieveable accuracy was already reported about [5].

These core tasks alone do not suffice for engine monitoring. Additional tasks as input data acquisition and conditioning, the detection of a start criterion (i.e. when the engine is started and the calculations shall begin) and an end criterion (i.e. when the engine is shut down and the calculations must finish) are necessary.

In order to cope with the ‘imperfection of the real world’ some checks of data are required. The input signals are checked for plausibility. In case of implausible signals (e.g. due to sensor failure) substitute values are estimated. Smoothing of the signals can be achieved by appropriate filtering.

The monitoring results – i.e. the calculated life consumption per flight – also needs to be checked. In case of implausibility again the results are restored by substitute values. Not necessary to mention that the substitutes are determined such that always conservative results (i.e. overestimation of life consumption) are provided.

The life usage monitoring results are evaluated for logistic purposes. This means that life consumption per part, per engine or per fleet is continuously observed, trends estimated and the times for life expiration forecasted. Based on these forecasts maintenance actions are planned and spare parts purchased.

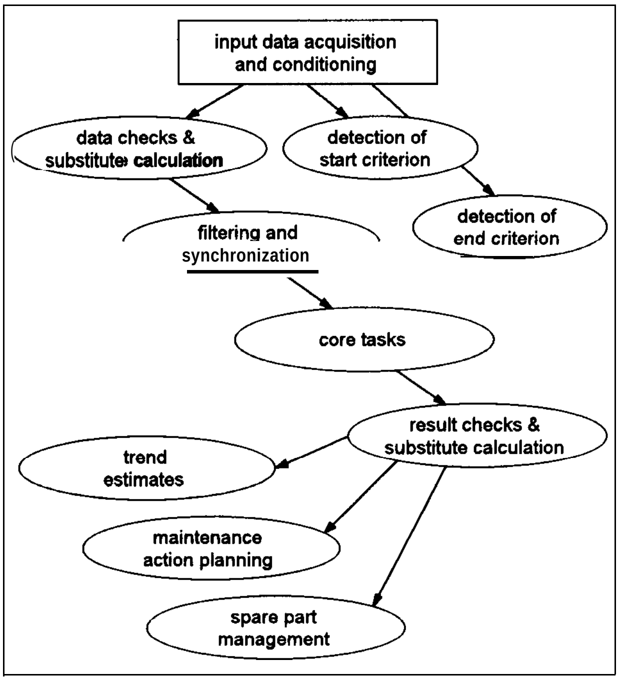

Figure 5: Additional Tasks for Life Usage Monitoring

5. Configuration Control

The main parts involved in an engine life usage monitoring system are

the engine which is to be monitored,
electronic hardware of the monitoring system and
software of the monitoring system.

During the life-time of an aero engine – this is usually more than 30 years – all these parts necessarily undergo modifications. The engine itself is modified to improve for shortages or as reaction to more comprehensive knowledge of its behaviour. New variants of this engine type are introduced to fulfill customer's requirements for changed mission profiles, higher thrust, better performance, lower fuel consumption, extended life, etc.

Most of these modifications are likely to influence the thermal and mechanical behaviour of the engine, the geometry of engine components and subsequently the temperature, stress and life reactions. Therefore, it is clear that for most of the major modifications an adaptation of the life usage monitoring algorithms becomes necessary. It occurs that after some years in service several variants of an engine type are operated in one fleet in parallel. The monitoring system must be able to cope with all the different standards. Experience shows that – to allow for unrestricted interchangeability – it is useful to implement fleetwide unique software capable of calculating the life consumption of all engine configurations. It is self-evident that the monitoring system – and hence the implemented software – must be informed about the configuration of the installed engines. Generally, this means that for each major engine modification new algorithms must be developed and a new software version released. Now it may happen that different software versions together with different engine configurations are operated in parallel. To ensure working of the whole monitoring system, the compatibility of software and engine must be checked and in case of mismatch appropriate measures taken. It could occur that between two flights either one of the engines or the software in the monitoring system was changed. Therefore, it is recommended to perform the compatibility checks before the beginning of every engine run.

Changes of the electronic hardware of the monitoring system are also very likely – particularly, if one reflects on the time scales of ongoing advance in microprocessor and memory technology. Extension of the hardware capabilities may also result from the above requirements. Thus, different hardware constellations should be considered and, consequently, the monitoring system hardware configuration should be checked for compatibility as well.

Based upon these considerations, it can be concluded that the basic concept for a life usage monitoring system should contain the necessary means for configuration checks and configuration control. Software and hardware design should allow for easy adaptation to the foreseeable modifications.

6. **Task Distribution**

Almost all of the above summarized monitoring tasks could be performed either on board or on ground. As expected, each of these solutions has got advantages and disadvantages. Performing all the tasks on ground means that a continuous stream of input data must be transferred to a ground station. Such a procedure may include a lot of implications. The other extreme would be to perform all the tasks – including the logistic planning – on-board. This also does not seem to be the best solution.

Trying a trade off between the efforts for all the single tasks – including considerations about required processing capacity, data transfer capabilities and requested time for result availability – MTU came to the conclusion that the best share of tasks would be to satisfy the following principles.

i) use an on-board system with sufficient processing capacity to treat the individual life consumption of the engines which are installed in the aircraft

ii) provide common software including the features for all variants of an engine type in the on-board system

iii) check engine, software and hardware configuration compatibility in the on-board system

iv) select constants and algorithms according to the configuration of the installed engines in the on-board system

v) perform all data processing necessary to calculate the life consumption on-board

vi) perform recovery actions (i.e.calculation of substitutes) in the on-board system whenever possible

vii) keep an account set with the current state of life consumption in the on-board part of the system

viii) use a ground station (or even a distributed ground based system) with sufficient processing and storage capacity to treat all engines of the whole fleet

ix) provide regular bidirectional data transfer between on-board system and ground stations (all life usage related data of an individual engine should be collected in a single account set)

x) keep account sets of all engines in the ground system as backup for the lifing data stored in the on-board system and as basis for logistic planning

xi) perform logistic tasks on the ground station

xii) provide means for substitute calculations in the ground station (for cases where the on-board system is totally disturbed)

xiii) provide means to generate account sets for repaired or rebuilt engines (including all configuration and lifing data) in the ground station

The principles outlined above seem to provide the best arrangement for the whole system. The advantages are that

valid results are always available and updated immediately after the end of an engine run (except those cases where the on-board system is severely disturbed)

no delay is caused for the decision whether or not the aircraft is serviceable for the next mission

the amount of data transfer is kept to a minimum

the workload for the operational staff is kept to a minimum

A disadvantage might be that the entire complexity of the whole system must be born in mind from the very beginning of the whole project. It does not seem to make much sense to develop one part of the system (e.g. the on-board hardware and software) independently of the other parts.

7. **Feedback from Service**

The system OLMOS (On-board Life Usage Monitoring System) for the RB 199 engine in the TORNADO aircraft was introduced in 1987. Now, after a couple of years in service, some feedback and operational experience is available. First experience has been already reported about 7. The benefits quantified in terms of reduction in spare part costs and increase in flight safety have also been issued 7. It can be summarized that individual life usage monitoring allows nearly double the time a critical engine part can be kept in operational service (compared to life consumption counting based on engine flight hours).

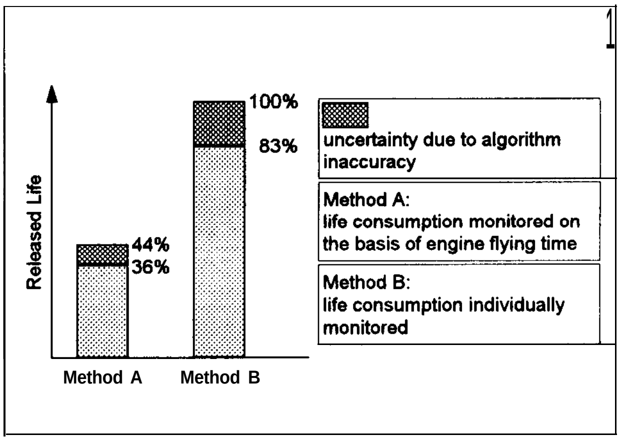

Figure 6: Average Exploitation of Released Life

Additionally, individual monitoring reduces the risk of unintended use of a part beyond its released life to zero (unintended excessive life consumption can not be prevented with flying time based life consumption counting).

First of all we can have a look at the statistical distribution of life consumption per flying hour (Fig. 7). A dimensionless depiction has been chosen to allow for the inclusion of all monitored areas of all investigated engines. Life consumption is shown relatively to the mean value. It is to be noted that the maximum of the distribution curve appears slightly below the average value. The curve shows a wide scatter (about one order of magnitude). Since the data describe the typical operational life consumption of a whole fleet, it becomes quite clear that a measure of life consumption just in flying hours is not adequate.

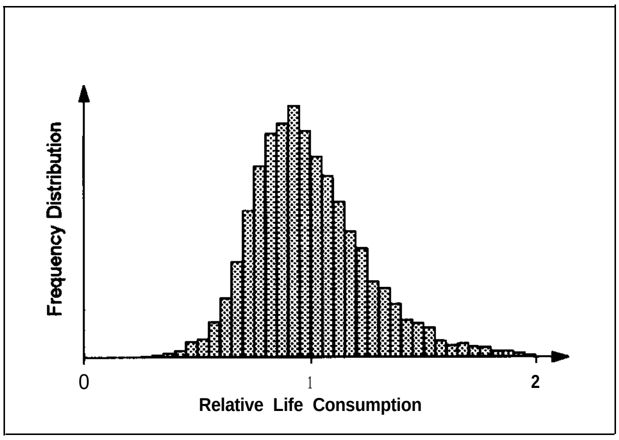

Figure 7: Life Consumption Distribution

The question may be raised whether or not the variance is somewhat systematic in nature or just random.

It was observed for several aircraft that some monitored critical areas of both the engines in one aircraft undergo significantly different life consumption although – obviously – both engines are flown to the same mission pattern. Detailed investigations revealed that the only remarkable difference in the engine operation was that generally the right hand engine was started first (about 10 minutes prior than the left hand engine) and also shut down first (about 4 minutes before the other one). It was assumed that the resulting differences in warming up and cooling down times (with the engines in idle) could be the reason.

In a systematic analysis, calculations with identical mission profiles but varied periods between engine start and take off as well as landing and engine shut down were carried out which could confirm this assumption. As an example, the variation of life consumption with varying warming up and cooling down times is shown in Figs. 8 and 9 for two typical critical areas. Generally is observed that shorter times between engine start and take off or between landing and engine shut down – although desired in order to reduce fuel consumption – have a detrimental effect on life usage. It is evident that more than a factor of two in life consumption can be caused.

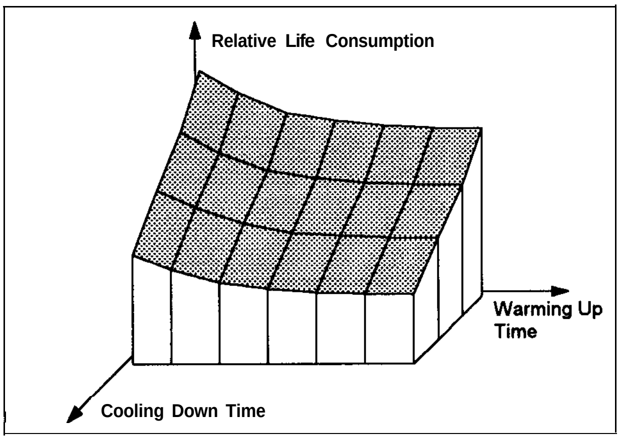

Figure 8: Influence on Life Consumption (Bolt Hole Area)

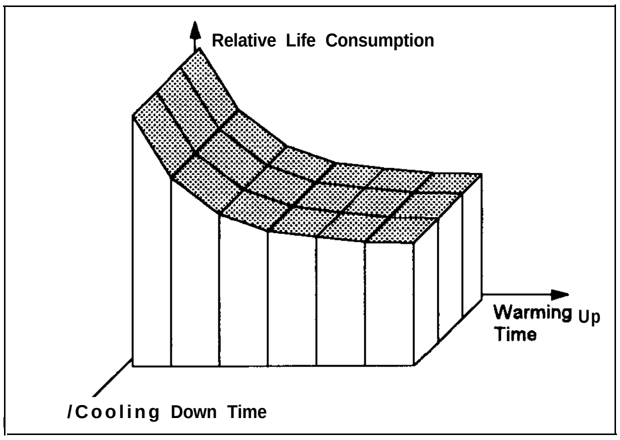

Figure 9: Influence on Life Consumption (Rim Area)

Based upon this investigation, recommendations for optimal warming up and cooling down times could be given. Since the temperature distribution at take off – which is obviously significant for life consumption – also depends on the temperature distribution at engine start, an additional investigation was performed. It could be shown that life consumption of an engine started under ‘warm’ conditions (in the investigated example at temperatures which correspond to a period of 30 minutes between shut down and engine restart) was up to 30% lower than of a ‘cold’ started engine. From this reported example it was concluded that an algorithm to calculate the temperature distribution at engine start could be very useful to increase the overall accuracy of life usage monitoring systems, particularly if the engines are switched off between two successive flights only for short periods. Details of the respective procedures have been already presented 4.

Another interesting observation was that life consumption of critical areas at the low pressure shaft were considerably different for aircraft from air bases in the north and in the south of Germany. Life consumption at these areas was for the engines from the north nearly twice as high as for engines from the south. Stress at these criical areas is governed by the shaft torque which in turn is determined by rotational speed of the shaft and the air density at the intake. It could be shown that the different altitudes of the air bases – nearly sea level in the north and about 500 m in the south – led to different air densities at take off conditions, subsequently to different maximum torques in the shaft and eventually different life consumption. The predicted difference in life consumption came fairly close to the observed one.

8. **Variance in Life Consumption**

The distribution of life consumption shows significant scatter as illustrated in Fig. 7. Some reasons for these differences could be already identified (see section 7.). Combining these facts, it is possible to construct constellations which cause either excessively high or very low life consumption. These constellations are not so extreme that they cannot appear under normal daily engine operation, and – what seems very important – are not related to particular mission types. Of course, there are mission types known which produce very high or significantly low life consumption, but these are relatively rare and the differences disappear as consequence of the accumulation effect. The above discussed influences, in contrast, are systematic and therefore not balanced but amplified by the accumulating process. Generally, it seems that the differences in life consumption are better correlated to individual engines than to mission types or different squadrons.

It must be concluded that the mission type – or at least the mission type alone – is not the dominant factor in engine life consumption. Based on the current experience, most of the scatter must be accepted as random occurrence.

9. **Prospect**

Currently, life usage monitoring results are used for maintenance and logistic purposes only. The systems are designed such that the information about life consumption is available to the maintenance staff immediately after the flight. Since life expiration does not directly influence flight safety (as long as not exaggerated) and neither does require any pilots action, it has been decided not to inform the pilot about the lifing status during flight. This could mean additional workload to the pilot without any beneficial effect.

Nevertheless, the situation can change. So, one should consider to provide the pilot with some hints which engine manoeuver in the current situation would be beneficial or detrimental for life consumption. Furthermore, some interaction between engine monitoring and engine control could be discussed. This type of interaction could mean that the engine control system could allow only for manoeuvering in a life-saving manner. However, one should be very, very careful when introducing such interactions, because flight safety and operational needs must be always the predominant requirements. Possible implications to the development of the monitoring system should be also born in mind. Currently, monitoring systems are developed to a risk class not specified as ‘single mission critical’. But if interaction with the engine control system is required, then the highest risk class becomes applicable, and subsequently paperwork and cost of monitoring system development will increase.

Finally, a commercial aspect should be mentioned, namely the insurance aspect. One could imagine that aircraft and engines with monitoring systems – which are assumed to fly safer than those without such systems – can be insured for lower rates. Particularly for second hand users benefits are seen. They will have advantages when purchasing aircraft with realistically logged life consumption, and subsequently the first hand user can achieve higher prices since continuous monitoring reduces uncertainties about previous usage.

In the long term, a user of a life usage monitoring system will have significant advantages with respect to the total cost of engine ownership. The investment into the monitoring system will be compensated in the first years in service by extended inspection intervals, reduced spare part costs and optimisation of logistics and maintenance.

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