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INCIDENT MONITORING - GENERAL REQUIREMENTS AND FIRST IN-SERVICE EXPERIENCE

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Abstract:

Incident monitoring functions (IMFs) integrated into on-board engine monitoring systems can provide substantial support to ascertain whether an aircraft engine is serviceable after an engine failure event. A major aim of on-board IMFs is to minimize the extent of inspection and maintenance activities after the occurrence of a failure event during flight and to eliminate the need for a lengthy analysis of recorded flight data.

Concepts for the design and improvement of IMFs are discussed, based on the experience gained through military engine operation and maintenance. The development process has to cope with large delays between system definition, the selection of instrumentation and monitoring system hardware and the availability of operational experience. After the discussion of some selected topics, such as the partitioning of tasks between control system and monitoring system, event classification and sensitivity selection, a short survey of IMFs currently under development for new jet and helicopter engines is given.

Glossary:

CS	Control System
DAU	Data Acquisition Unit
EIS	Entry Into Service
EMS	Engine Monitoring System
GAF	German Air Force
IMF	Incident Monitoring Function
MS	Monitoring System
NH	High Pressure Spool Speed
NL	Low Pressure Spool Speed
OLMOS	On-board Life Monitoring System
PLA	Power Lever Angle
TBT	Turbine Blade Temperature
TT1	Engine Inlet Total Temperature

1. Introduction

A substantial part of the total cost of operating an aircraft is related to the operation and maintenance of its engines. In-flight failures of gas turbine engines are one of the most serious hazards to flight safety. Considerable effort has therefore been directed to improve the reliability of engine components and to develop inspection and maintenance procedures which minimize the risk of catastrophic failures. Shrinking profits of civil airlines and dramatically reduced military budgets dictate a thorough examination of existing maintenance concepts with the aim of reducing costs without compromising flight safety.

One of the most promising measures in this direction is the rapidly growing application of on-board monitoring systems including integrated or dedicated engine monitoring systems (EMS). Various systems have been proposed and implemented [1]; the basic principle is illustrated in the following figure.

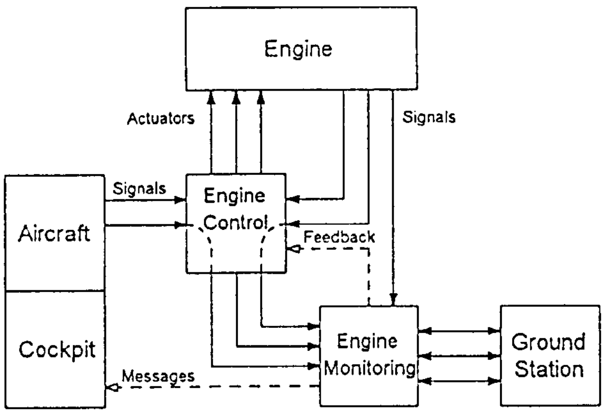

Figure 1: Layout of Monitoring Systems

2. Major Objectives of Engine Monitoring Systems

The main aim of an EMS is to detect whether an inspection is necessary and to minimize the extent of maintenance actions. Supposed damage, wear or fouling of mechanical engine components shall be recognized as well as malfunctions in the CS or engine subsystems. As the risk of consequential damage is rather high in such a complex system as an aircraft engine, an EMS should provide information on potential hazards to engine components taking into account known or probable fault paths. EMSs can also provide reliable information in case of discussions on defect liability after severe failure incidents, e.g. if violation of operating procedures is suspected.

The output of IMFs can also help to develop improved operating procedures which can be applied when an engine malfunction occurs. As certain faults are hard to recognize by the pilot or cockpit crew during flight from available cockpit indications, the results of IMFs can be used to improve pilot training, e.g. by incorporating prototypes of IMF-detected rare events into the engine part of flight simulators.

3. Examples of Events to be Monitored

Candidates for inclusion in an IMF typically fall into the following categories:

- **Exceedances of prescribed limits for continuously measured single signals, such as spool speeds, temperatures, pressures:**

Limitation values for these parameters may be selected as fixed values according to mechanical or thermal limits of engine design, sometimes also to identify reasons for high life consumption. The limits can also depend on mission type or even vary during one flight (e.g. increased limits for take-off). A continuous modification of limits by the CS with transfer to the EMS is also possible. To enable classification of the impact of exceedances on required maintenance actions, an incident intensity has to be determined and stored together with other incident related information. A very flexible approach is shown in Fig. 2.

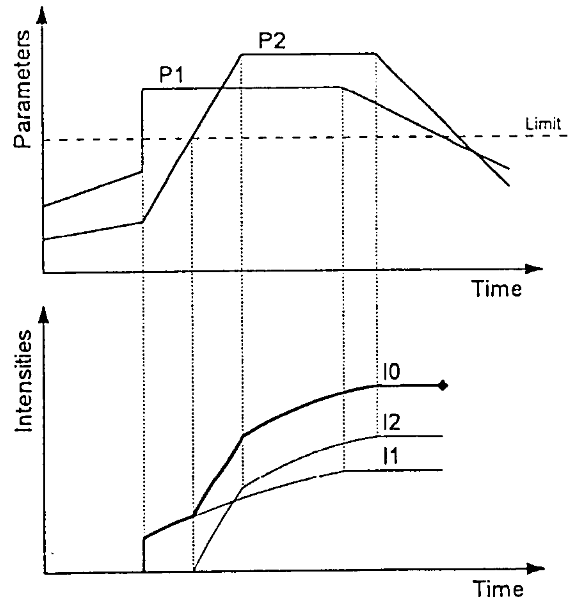

Figure 2: Determination of Intensities

The overall intensity of a highly probable simultaneous multiple violation of limits by more than one parameter is determined by a weighted sum of the intensities of the individual exceedances. The single parameter incident intensity is a monotonously growing function of exceedance level and exceedance duration. The growth rate in time and the dependency on exceedance level can be adjusted individually by monitoring control parameters.

- **Exceedances of vibration levels:**

A detailed discussion of vibration monitoring is beyond the scope of this presentation; typically vibration data is pre-processed by the application of Fourier transforms. Exceedances may then be determined for broadband signals or for selected spool speed dependent frequencies. As excessive vibration levels are an indication of a severe engine malfunction a cockpit warning also has to be triggered.

- **Partial or full flow breakdown (surge, stall):**

This type of failure manifests itself in rapid changes of engine behaviour. To detect these phenomena the recognition of characteristic time dependent signal patterns is required.

- **Status information from the CS:**

The CS performs extensive signal and self-tests to ensure continuous safe operation of the engine. Far-reaching degradation of the functionality of the CS, such as actuator malfunction or even loss of control has to be detected by the continuous self-test of the CS.

- **Oil or fuel system related failures:**

Signals indicating low oil level, high temperature, oil debris and filter blockages are generated by special sensors and are sent to the EMS as logical signals.

4. Partitioning of Tasks between CS and MS

To avoid safety critical software design for the incident monitoring function, the recognition of failures requiring immediate corrective actions should be performed within the CS.

Examples are the occurrence of jet pipe resonance (Buzz or Screech), failure of actuators or possibly also engine surge.

In many cases the MS has access to only one of several redundant signals, whereas the CS can select between independent signal paths for the most important signals. The CS performs comprehensive signal checks and corrections with the aim of retaining the ability to safely control the engine. IMFs should, at least in our opinion, try to use the original signals for their detection algorithms. Applying filters to the input signals of IMFs always implies the risk that the system fails to notice certain unexpected failures.

The MS can supplement the incident detection part of the CS by providing bookkeeping and snapshot functions. For this purpose event trigger signals have to be transmitted from the CS to the MS indicating the type and, if applicable, the intensity of the detected failure. The incident monitoring function will then calculate a combined intensity if other events are active simultaneously and compare the overall intensity of the current events with already stored events and initiate the storage of summaries and of snapshots for top intensity events.

5. The Role of Engine Instrumentation

Military aircraft production engines are usually planned to have only the minimum instrumentation necessary to control the engine. Whereas the amount of additional instrumentation for life usage monitoring is easily predictable, there is a high probability that unforeseen fault modes occurring a long time after engine design require signals for their unambiguous detection which have not been considered in the original instrumentation.

If existing MSs are amended by new or improved IMFs, there is normally not the opportunity to change or enhance the instrumentation of the engines. Algorithmic methods have to be found which meet the required criteria for the quality of failure detection.

Algorithm performance can be evaluated using the following criteria [2]:

- Probability of failure detection,
- probability of false alarms,
- time of detection .

The usual technique to compensate for incomplete instrumentation in a detection algorithm for abnormal engine operation is to look for typical parameter relations or characteristic patterns in the time series of selected parameters. A large number of different algorithms exist for the analysis and classification of time series; a general survey is given in [3]. Turbomachinery applications are discussed in [2,4].

By analysing recorded data from testbed runs and especially from flight trials, the characteristic patterns of engine faults and also the nominal behaviour of the engine has to be isolated from the recorded data. Due to the lack of proven analytical models of the failure modes the analysis of non-stationary engine behaviour during engine malfunctions is a candidate for flexible learning and model building processes as e.g. neural networks [4].

The search for suitable pattern matching algorithms usually requires the analysis of a vast amount of testbed and flight data. Advanced systems for flight data analysis [5] can provide substantial help to find suitable parameter settings during the development and learning phase of an event monitoring system.

During the extraction of information from flight trials, one has to bear in mind the applicability in the target system with standard instrumentation w.r.t. sampling rates, accuracy and signal quality. Also to be considered is that engine operation during flight tests may differ significantly from later engine usage in regular operation.

An IMF will contain a couple of data patterns for the failure phenomena to be recognized and algorithms for the comparison between the actually measured engine parameters and the failure templates.

To detect a deviation from normal engine behaviour a number of different methods are utilized, some of which are e.g. [2]:

- pattern recognition methods
- model-based fault detection and isolation methods
- artificial intelligence methods.

Although much effort is dedicated towards the validation and verification of selected algorithms in the development and integration process, including testing on the development environment and with real-time engine simulators, the verification on the target system is sometimes difficult or even impossible due to very rare occurrences of a particular event. Dedicated testing, sometimes even provoking certain failure incidents is the only way to get full confidence in the correct operation of a particular IMF. If the event implies the risk of damaging the engine, an intentional provocation during flight is however avoided in most cases due to budget and safety limitations.

6. Storage of Results

The presentation of the results of an IMF in a neat, concise manner is crucial for its practical usability. To avoid time-consuming manual analysis of unstructured event data, the corresponding information has to be sorted by its importance, i.e. failure incidents supposed to require urgent maintenance action have to be placed before information only used to update some statistics. By assigning intensities, either fixed or computed as outlined above, to each incident, summaries can be stored in an order based on these intensities overwriting low intensity events by those with higher priority, if the allocated memory for incident summaries is exhausted.

Much has been written on the usability of information reported by aircraft crews for aircraft or engine fault diagnosis. In most cases the reports give only a qualitative description; to be fair we cannot expect a detailed recording of parameter values from a military jet pilot trying to recover from thrust loss of one engine when flying at Mach 0.8 and 500 feet above the North Sea. We have also found that pilots tend to describe their recovery action (or even only the successful part of this action) rather than giving usable information on the situation preceding the incident.

When compared to available flight recorder data, the pilot's information has been found to be sometimes biased, incomplete or even missing.

The request for more reliable information on the circumstances of failure incidents can be fulfilled by storing certain aircraft and engine data from a selected time interval including pre-incident conditions. With current EMSs the memory assigned to this snapshot data is rather limited. Therefore, only a few such snapshots triggered by high priority failure events can be stored. This situation will probably change in the long run with the availability of high capacity memory devices.

Extracting event-related information from available tape recordings, e.g. from crash recorders, typically takes a long time and requires additional manual work to remove the recording medium from the aircraft. The difficulties to recover information impede the usage of tape recordings for everyday analysis of non-catastrophic incidents. In addition to this it has been found that the quality of on-board tape recordings may be adversely affected by high g loads or high vibration levels of the engines and the aircraft.

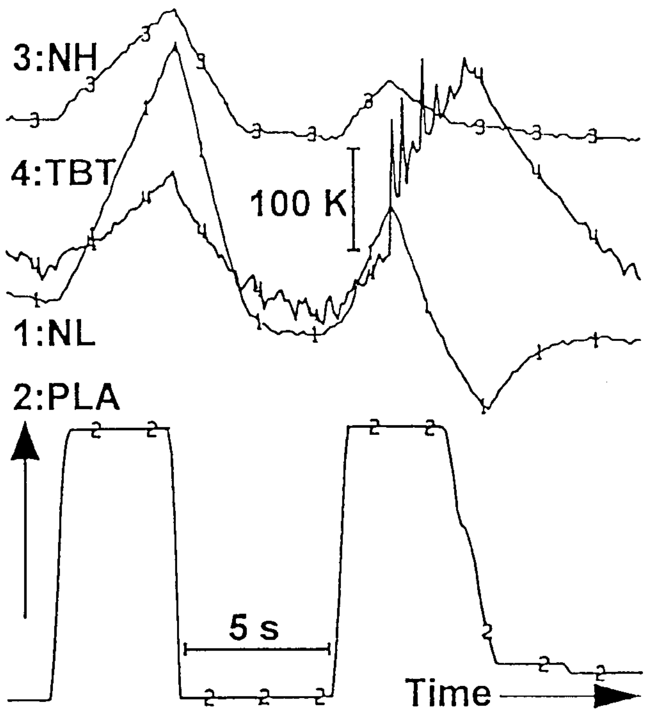

Figure 3: Surge Event during Flight Test

7. Example

A closer look at the engine surge detection function implemented in the GAF Tornado OLMOS may give some insight into the problems associated with the development and the adaptation of algorithms for the classification of dynamic phenomena. An engine surge is characterized by the following process: Due to a breakdown of air flow within the compressors there is a sudden pressure drop which can be easily identified in HP compressor outlet pressure. As a consequence a mismatch between fuel flow into combustion chambers and air mass flow occurs which leads to high turbine blade temperatures and subsequent corrective actions of the control system.

A major problem of the RB199 standard instrumentation is the lack of a pressure signal from the compressors. The detection algorithm is therefore mainly based on a comparison of the change rates of throttle movement, spool speeds and turbine blade temperatures measured by an optical pyrometer. By analysis of existing data recordings with fully instrumented test engines and high sampling rates (32 Hz) it was found that even under normal operating conditions the fluctuations of the TBT signal differed significantly depending on the build standard of the combustion chamber and on the type of control unit (analogue or digital). It was also found that the frequency of TBT fluctuations was sometimes higher than the resolution offered by the monitoring function (8 Hz).

A typical correct trigger condition for the detection of a surge event is shown in Figure 3, which shows two successive slam accelerations of one engine. Whereas the first throttle movement from idle to max. shows the desired smooth rising of spool speeds and turbine blade temperature, the second acceleration is suddenly interrupted by a series of TBT spikes accompanied by a drop of both spool speeds. As a consequence of the mismatch between demanded and measured spool speeds the (digital) CS tries to counteract the speed decrease by increasing TBT with a suitably chosen fuel flow. The failure situation is only cleared by a corrective action of the pilot, namely moving the power lever back to idle and possibly some other measure, e.g. reducing the aircraft's angle of attack. The example just shown is somewhat academic, as the data were taken with a flight test instrumentation with a sampling rate of 32 Hz and there was only a little noise on the TBT signal.

The situation changes completely if we look at a TBT recording taken from an engine of an early build standard, controlled by an analogue control unit. Fig. 4 shows a normal acceleration of the engine followed by a longer steady state phase. The TBT signal continues to fluctuate

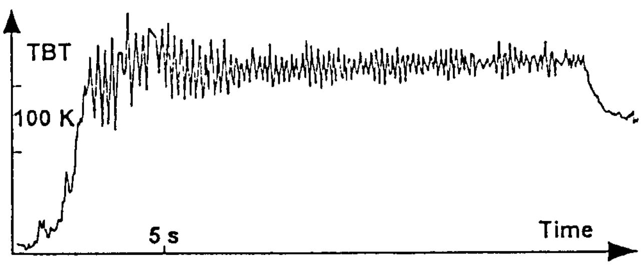

Figure 4: Fluctuating TBT Signal

heavily after the end of the acceleration having amplitudes comparable to those also occurring during a surge event.

Obviously frequent false triggering of the surge detection is nearly inevitable, unless the sensitivity is chosen to be much lower for this particular combination of engine and CS. This supports the requirement that IMFs have to be supplied with sufficient information about engine and CS configuration, as different standards are used within an aircraft fleet in parallel, which have to be monitored using adapted limits or even different algorithms.

The occurrence of such an event makes borescope inspection of all compressor stages necessary, which requires two specialists working for one hour. Therefore, it is quite clear that an operator is not willing to tolerate many false alarms. On the other hand, there have been transient surge events reported by the aircraft crew, but the affected engine could not be identified. If only this information could be provided by the IMF, it would eliminate the need for inspecting both engines.

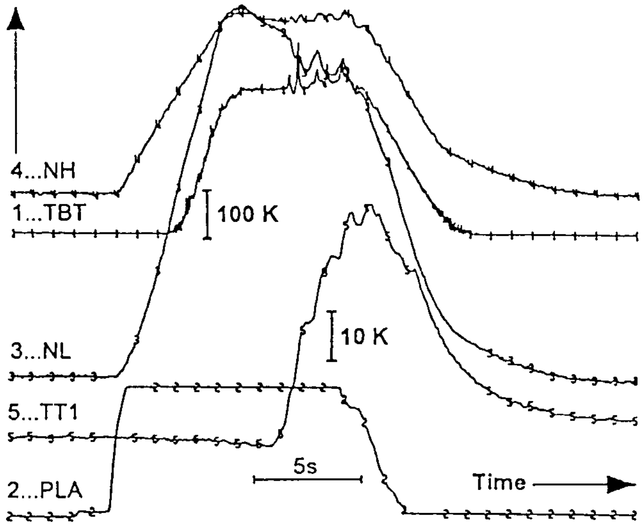

Figure 5: Hot Gas Ingestion during Thrust Reverse

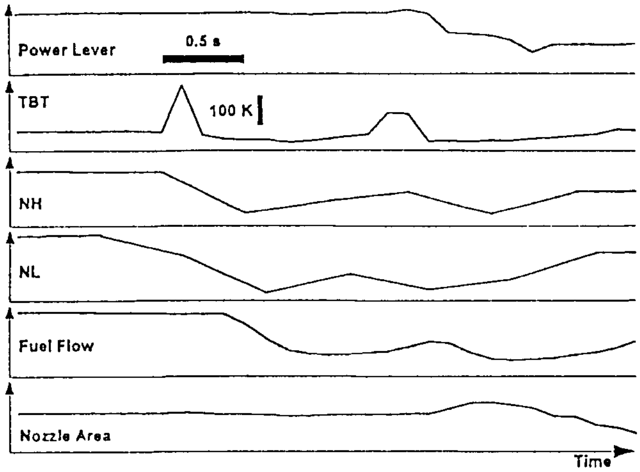

Figure 6: Surge Event Displayed on Ground Station

There are also situations where even with optimal signal quality and a digital CS the distinction between regular and disturbed engine operation is quite difficult to implement into a detection algorithm. Fig. 5 shows a plot of the engine behaviour during thrust reverse immediately after landing. As can be seen from the rise of inlet temperature TT1, hot exhaust gas is ingested into the engine intake followed by oscillations of TBT and NL. In contrast to the surge situation, the missing drop of NH can be used as a distinction criterion.

The current policy of the GAF is to use the results of the surge detection function only in those cases when a corresponding incident is reported by the pilot. On the basis of the recorded snapshot data a decision is made on the necessity of an engine inspection.

The results of a surge incident detected during normal flight operation is shown in Fig. 6 in a format similar to the one displayed on the OLMOS ground station. Before the event, the engine is operated at reheat conditions (afterburner operating). The first occurrence of a TBT spike is followed by a drop of both spool speeds; a short recovery is terminated by a second TBT spike. After deselection of the afterburner by the pilot the nozzle starts to move towards its "dry" position and spool speeds start to increase again.

8. Interaction between Monitoring Functions

The behaviour of an ageing engine cannot be exactly predicted when the engine is designed or even at EIS. At best some experience from engines of similar design is available. It is therefore useful to adjust the parameters of the IMF algorithms using the results of other monitoring functions. Usage spectrum monitoring can provide statistical information about the frequency of certain operating conditions or about frequent operation near certain monitored limitations. Some faults will also not manifest themselves in a single event, but rather in a changed relationship between measured parameters, which persist for a whole engine run or leads to a slow drift over a long time period. Such faults, e.g. leakages, malfunction of bleed valves, fouling or erosion of compressor blades are normally not detected by an IMF, but are likely candidates for the application of gas path analysis or automated procedures for power or thrust monitoring at fixed quasi-static operating conditions.

9. Development Process of Incident Monitoring Functions

The development of an EMS is a long-term step by step process (Fig. 7). For a newly developed engine, especially for military engines, where a detailed requirement document is provided, this document only contains very general requirements for engine monitoring, such as detection

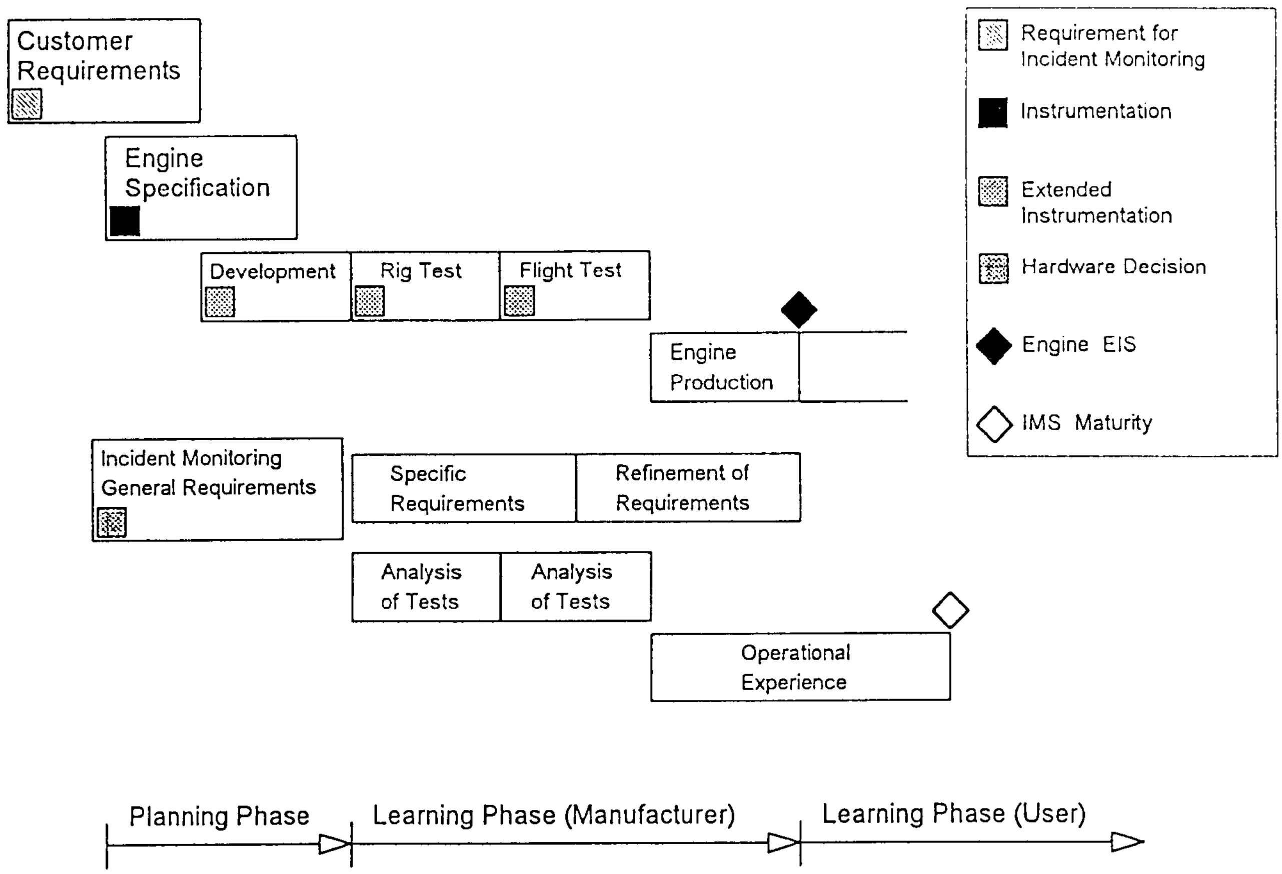

Figure 7: Development of an Incident Monitoring System

rates for certain faults or demanded maintenance or repair times (see e.g. [6]). In the following planning phase a simultaneous and coordinated decision has to be made concerning engine instrumentation and EMS hardware. The processing capacity of the EMS hardware is often dominated by the requirements of a single function. In current EMSs the required processing capacity of vibration monitoring exceeds that of other monitoring functions by an order of magnitude, unless this function is assigned to a specially customized dedicated processor system.

The decision on engine instrumentation has far-reaching consequences, not least owing to the technical and economic difficulties of a hardware change after production start or even after EIS. Some evidence may be derived from experience with comparable engines or from a detailed analysis of foreseeable fault modes. Similar difficulties arise in the decision on the hardware and system architecture of the EMS. Due to long development times for on-board hardware and contractual obligations to a hardware manufacturer wrong decisions may lead to very high consequential costs and long delays in the development process.

The real development of IMFs starts only after the decision on engine instrumentation and EMS hardware. Inherent weaknesses of operational performance of the future engine often show up only during engine tests or even after delivery to the customer. The major part of the knowledge about engine performance is acquired during tests first on engine test beds and later in flight trials. In this phase comprehensive instrumentation and high speed high capacity recording devices are available. Most of the algorithms to be used later for the detection of engine malfunctions are based on results acquired during development testing of the engines. The parameters of these algorithms have to be adjusted afterwards to the characteristics of the production engines and their instrumentation (e.g. changed frequency response, increased signal noise levels, reduced sampling rates).

Usually an IMF will not have reached its final state when the first production engines are delivered, especially since the interaction with the operating environment of the customer has to be included into the EMS. Our experience shows that operational usage of an engine by the customer differs from the very beginning from that laid down in the engine specification and also from the usage during flight trials. The inclusion of actual experience at least from the first phase of usage is therefore urgently needed to optimize the functionality of IMFs. The creation and maintenance of a data base of IMF results accessible by service personnel and also by industry may facilitate a fast adaptation of IMFs to user needs.

When planning interfaces to the ground support system, one has to bear in mind that an EMS has to be kept operational for a very long time. In-service times of 20 to 30 years will be the rule for such systems. To be on the safe side, changes of the involved computer hardware and also of operating systems have to be envisaged. Therefore, interfaces should be kept simple and as independent as possible from operating systems and specialized hardware. A typical example is the decision to use a commercial database system for the management of logistic data. Highly sophisticated access methods tend to be the least portable ones and may require a large amount of effort to replace at later system changes.

Existing engines undergo component replacements during their lifetime and it is common practice that changed or improved components are used for this purpose. Before the introduction of updated engine versions, flight trials are carried out. Obviously any change of engine behaviour may also affect the function of an EMS tuned for the old engine version. To acquire knowledge about necessary adaptations of monitoring functions it is very desirable to have the actual version of the EMS in aircraft equipped with prototype engines when flight tests for this new or modified engines are performed.

If a shift of the adaptation phase of monitoring functions to the customer is inevitable, comprehensive support has to be supplied to the involved personnel to avoid frustration or incorrect reactions following unexpected EMS performance.

10. Lessons Learned

The IMF was always well accepted by the customer, when clearly defined inspections or maintenance actions could be derived from the IMF results. Displaying an event without further information about necessary measures leads to a negative attitude from the side of the maintenance personnel.

Warning limits should not be set too low. If a certain event is frequently indicated with a required subsequent inspection (e.g. check for deformation or cracks), and the result is always negative, confidence in the necessity begins to disappear with the service personnel and the risk of carelessness with the indicated fault begins to grow. It is important in this context, that the maintenance manual should acknowledge and reference the existence of an EMS and that the data produced in the EMS should be taken into consideration when maintenance actions are planned.

Existing maintenance documentation has to be checked carefully for consistent and full coverage of the EMS outputs. Missing or contradictory information in the written reference documentation usually leads to poor acceptance of the EMS and frustration of the involved personnel.

If possible, limits used in IMFs should match those released in the relevant technical documentation. Otherwise the service personnel runs into a conflict such as: EMS indicates exceedance of limit X, documentation says inspection to be performed following exceedance of limit Y.

11. Survey of Existing and Planned IMFs

- DAU/OLMOS for the RB199 Engine

MTU has gained most of its IMF experience with the OLMOS system installed in the GAF Tornado fleet. OLMOS is a comprehensive system ranging from onboard equipment to the central logistic planning system of the GAF. The on-board part is installed in the DAU-1C and consists of 3 processors. There are two engine processors whose main task is life usage monitoring. The engine processors receive data from the interface processor whose original task was the data conditioning for the crash recorder. Taking into account that development dates back to 1985, there is a fairly advanced IMF implemented on this processor. Fig. 8, reproduced from [7], illustrates the IMF design, which has been described in detail in the cited reference. The event monitoring function within the DAU in the Tornado aircraft excels by a fairly modern and flexible design, its practical application is however hampered by a very small memory (17kB) for the storage of snapshots and by the missing on-board programmability of the monitoring software.

The event monitoring function consists of 8 fixed detection algorithms and 8 relations between arbitrary parameters, which can be programmed by the user. As mentioned earlier there is only one engine related fixed algorithm (surge detection), whereas the other fixed algorithms deal with incidents affecting the aircraft structure (e.g. hard landing, load exceedances at certain flight conditions).

A modification to eliminate some of the known shortcomings of the GAF OLMOS system is currently under investigation. It will include a replacement of the old tape based crash recorder by a solid state memory with increased storage capacity, which will also serve as storage for time histories of parameters of the event detection function. Further improvements will be an increased capacity of the working memory and the accessibility of program memory by a software loading function.

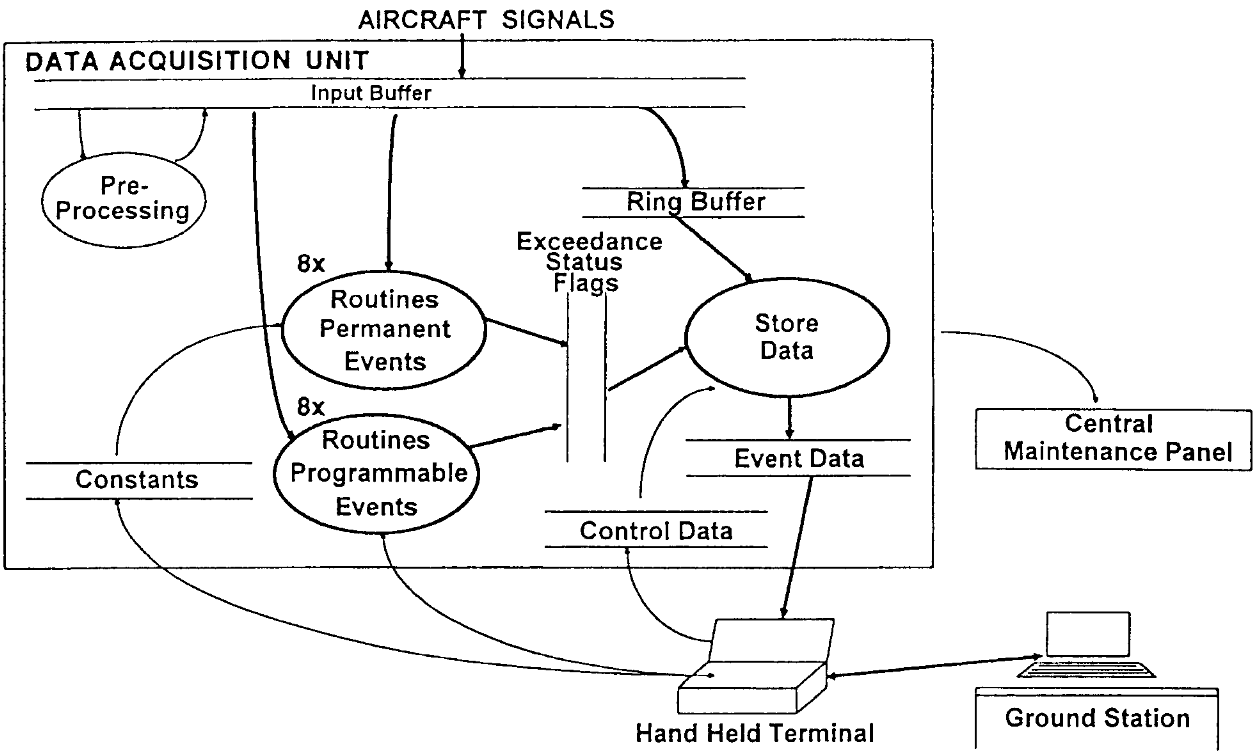

Figure 8: Data Flow of OLMOS Event Monitoring

- EMS for the MTR390

The monitoring system [8] of the MTR390 turboshaft engine, which powers the TIGER helicopter, is integrated with the CS in a common plug-in unit. There is a strict functional separation between the CS processor and another processor, which performs the computationally demanding life usage monitoring function. Engine performance check and limit exceedance monitoring are carried out by the CS processor.

The limit exceedance function checks the observance of operating limits for spool speeds, torque and high pressure turbine outlet temperature dependent on the power rating level released by the pilot. An exceedance event is triggered, if the engine operates continuously above the released limits for more than the corresponding allowed time. Exceedance of the limits associated with the highest defined power rating is signalled to the pilot. The following information is stored: Longest consecutive and accumulated times at the different defined high power levels, maximum values of spool speeds, torque and turbine temperature, status indicating type and severity of exceedances. There are no separate protocol entries for multiple events. A snapshot function is not implemented.

- EMS for the EJ200.

The planned EMS [6] for the EJ200 military jet engine includes life usage monitoring for all critical parts, advanced vibration monitoring and also a comprehensive IMF. The EMS is located in a separate box, receiving most of its data from the electronic CS.

Events are classified into 4 categories:

1. Limit exceedances of continuously measured input signals
2. Logical signals (incident indications created by CS)
3. Incidents detected at end of flight (e.g. released life limits of parts reached)
4. Incidents detected by the vibration monitoring function

Diagnostics are provided in the form of incident summaries and snapshots. Summaries are stored and, if necessary, overwritten based on an overall incident intensity, which is computed by adding up individual weights which are either fixed numbers or computed for category 1 incidents using a logic already illustrated in Fig. 2.

A number of incidents requiring immediate corrective action or influencing the performance of the CS are detected by incident detection algorithms integrated into the electronic CS. CS-detected failure incidents are signalled to the EMS, where further processing, such as storage and snapshooting of parameters is performed. Examples of such incidents are: Engine flame out, jet pipe resonance transducer signal above limit (Buzz, Screech), nozzle sticking detection during afterburner selection and deselection, occurrence of pop surge and locked stall.

A positive result of certain checks performed by the CS during ground idle conditions is also transmitted to the EMS as "Engine Health Ground Warning", e.g. triggered by NL outside expected range w.r.t. NH, fuel flow outside expected range, inability of the CS to reach closed loop control, actuator failures, double input signal failures of essential signals. By an analysis of the triggered data snapshot a quick recognition of the underlying engine or CS defect is expected.

The outlined IMF potentially will greatly simplify the troubleshooting of the EJ200 engine. As flight trials are just beginning, we are looking forward to a fruitful learning phase which will hopefully lead to a widely accepted system significantly contributing to the ease of maintenance.

12. Future Outlook

In the long term most existing monitoring systems will undergo far-reaching modernization with respect to processing power and memory capacity. It is very unlikely, that in a time where a standard home user's personal computer has a minimum of 8 Mb RAM, on-board systems will be limited to storage capacities of a few 100kb, even if one takes into account the requirements for high reliability under severe environmental conditions.

A typical future incident monitoring system will combine on-board detection algorithms with a high capacity (e.g. solid state) storage device capable of storing all parameters of interest continuously over the complete flight. Snapshots will be restricted to high frequency data (e.g. time domain raw vibration data). Incident summaries will contain time tags identifying the absolute time of occurrence. All required information for an in-depth ground-based analysis can then be recovered from the stored flight data at arbitrary points in time.

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