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Diagnostic systems in aircraft engines maintenance

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This paper presents a modern maintenance concept of aircraft engines relying significantly on diagnostic equipment and diagnostic systems. The maintenance concept is applied on engines of combat aircraft and as well as civil aircraft.

Key words: **aircraft, aircraft engine, turbojet engines, maintenance, diagnostics.**

THE maintenance of the aircraft engines has been performed for the long time using the concept of a prescribed fixed number of working hours. This concept is still applied, especially on the engines of the old generation. After the prescribed time period the engines are sent into overhaul depot for overhaul according to the prescribed technology. Such preventive procedure does not take into account real thermal and other operational loads during service. Therefore, the engines are overhauled in order to increase their safety, weather a real necessary for that exists or not.

At the beginning of the 1980s significant changes occurred in aircraft engine maintenance, in combat aircraft engines as well as in engines of civil aircraft for commercial flights. Instead of maintenance based on precisely defined number of flights number [1] a new maintenance concept based on aircraft condition appeared. This concept was first applied on the RB199 engine of the Tornado aircraft [9], which has been in use since August 1986. The design, development and production in this project was very serious. The fact that this engine was a product of three leading European aircraft engine producers: English *Rolls-Royce*, German *Motoren-und-Turbinen-Union* and Italian *Fiat Avizione*, speaks for itself.

This new maintenance concept requires expensive diagnostic equipment and sophisticated diagnostic systems. These systems have to provide reliable, consistent state diagnosis and to minimize requirements for maintenance personnel training. The use of diagnostic systems and systems of digital electronic engine control started in the early 1980s. More important sensor applications are characteristic for the 1990s, but automatic health prognostics appeared in 2000.

Engine state monitoring

There are essential differences between turbojet engines of civil aircraft and turbojet engines of military aircraft and particularly turbojet engines of fighters. A low load level characterizes engines of civil aircraft. In civil passenger or cargo traffic, engines usually operate five minutes at a maximum power during taking off, then at reduced power during lifting and finally at a lower power during cruising which can last for 12 or more hours.

Turbojet engines of military aircraft operate at regimes very close to maximum constraints and regime suddenly changes during flight. Their use, expressed in flight hours, is much less frequent than their use in civil aircraft, which can be over 5000 hours a year. According to data from several years ago, world average is 2.700 and 3.500 hours.

Due to the existing differences between engines of civil and military aircraft, there are different requirements concerning monitoring of some parameters during flight. For engines of military aircraft different heterogeneous data of frequent occurrence during the whole, relatively short flight, are collected, while for the engines of commercial aircraft some parameters are shortly recorded in particular regimes during a long flight. Data collection is performed automatically through the systems of sensors thus enabling everyday monitoring of a real engine status and making a decision to undertake a prompt action, if necessary, after aircraft lands or before the next flight.

The main aim of engine state monitoring is to increase maintenance efficiency, flight reliability and security. Owing to the state monitoring concept it is possible to prevent unscheduled engine moving which increases operational costs considerably. This is especially important when removing the engine block from the home basis when maintenance costs increase considerably due to the high prices of engine transportation.

As for the monitoring of the parameters during a flight, it is important to note that processing possibilities and the quantity of processed data are permanently increasing. The reason is electronics and computer technology development as well as applied software development over the last ten years. Depending on the engine manufacturers different parameters are collected, generally including flight altitude and velocity, exterior temperature, mass of aircraft, engine speed, turbine exhaust temperature, fuel flow, oil pressure and temperature, engine vibrations, etc. Modern versions contain significant number of monitored parameters which present a more complete image of the engine status. Thus acquired data is processed using computer programs and the results are in the form of numerical values and diagrams showing a particular engine performance state.

Initial software for engine status monitoring has been developed for large computer systems. However, with the

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development of microcomputer technology, applications are made for personal computers. Three well known engine manufacturers: *General Electric*, *Pratt &Whitney* and *Rolls - Royce* had three separate systems of computer programs. The first one was used for performance monitoring during flight, the second one for performance modular monitoring during flight, and the third one for engine test analysis on the stand. However, with the development of the new engines types with specific requirements and software extensions, it was concluded that further development of the existing programs would be highly complicated and inflexible. For that reason new software programs with more detailed data bases were developed. New programs enable the monitoring and analysis of the engine vibrations, they contain expert systems with elements artificial intelligence and on the basis of built-in data and experience from the service life, they can suggest made on some corrective actions.

Apart from the monitoring of engine status parameters, other standard procedures used for decades in the on-condition maintenance concept should be mentioned. These are, firstly, the analysis of oil consumption and quality, inspection of the metal debris in oil using magnetic chip detectors [4], as well as periodical inspections and tests in line maintenance [5].

Monitoring the operational engine capability

Fifteen years ago, as mentioned above, monitoring the operational engine capability often called monitoring of the „spent engine life" was performed according to the engine running time. However, the life of rotating components of the aircraft engines such as turbine and compressor discs, shafts, etc. depends significantly on aircraft missions.

In transport type aircraft, the movement of the throttle handle is not as impulsive as in fighters. The engines of fighters are subjected to more heavy operational conditions during training than during normal usage of the fighters. For that reason the producer has to specify the engine reliable life for engine missions specified in the agreement, at engine delivery. The deviation of real missions from agreement concept increases the risk of unexpected malfunction.

Modern technologies are based on monitoring the real engine life during service. The movement of the throttle handle in range scale of the engine speed 0-100%-0 can be expressed in terms of the so called load equivalent cycles. *Rolls-Royce* has analyzed the throttle handle movements from in service experience for aircraft used in different operational roles and obtained the following approximate cyclic rates presented in the Table 1.

Table 1. Number of equivalent cycles

Ordinal number	Mission profiles	Number of equivalent cycles per hour
1.	Formation acrobatics	10 – 14
2.	Training	5 – 10
3.	Bombing and gun firing missions	5
4.	Ground support	3.8
5.	Reconnaissance	3.5

Rolls-Royce predicted a safety life for particular engine parts produced by them or the testing of which they monitor. Engine parts are identified as group A and group B parts. Group A parts consist of parts with limited life whose failure could cause the unacceptable aircraft damage. Group B parts are other parts which have a life limitation. Parts from the A group have life cycles. The user has to monitor the life expiration and to stop using it on time. When the engine is passed on to another user, the data on the life cycles expiration has also to be passed on. Therefore, the user is responsible for engine spent life during his exploitation. When the engine is delivered to the overhaul depot, the user must indicate in adequate documents the total service time and the number of equivalent cycles. The overhaul depot is responsible for further system maintenance of each part from the A group, whether it is located in the storage or in the engine. This record on engine spent life is very important and must be updated constantly. The record has to be organized according the part name, marker and serial number in order to enable quick fining of all of the parts.

Influence on the life of engine rotating components

The centrifugal force is a major source of stress in engine rotating components. The stress analysis in rotating components is performed as a function of engine speed variety. For example, the centrifugal acceleration rate is 28.460 g ($g = 9.81\ m/s^2$) in engine vanes at 13.760 min^{-1} engine speed with 134.6 mm center of mass, approximately. However, there are other influences on the life of rotating components such as:

- Stress due to moment of bending which appears as effect of pressure difference on the disk
- Stress due to vibrations when vanes go to the uniform flow
- Flatter of vanes and disks is aero elastic phenomena where eigen values spontaneous by excite due to gas flow energy
- Torsion stresses are inescapable during power transition (driving torque) from turbine to the compressor
- Temperature gradients, in cold turbine parts especially, can significant by increase the stress due to local different dilatations. It is evident especially during transient regimes. These thermal stresses lead to low cycle fatigue which is evidently the biggest life consumer of engine warm parts of the fighters.
- There are a lot causes which lead to local stress concentration. In the plastic deformation they can double the stress rate. These are holes, grooves, external and internal angles, contact of coating and basic material, trace of machine process, cracks, etc.
- Stroke or damage caused from an outer body or on own part have to be taken into account during design phase. A typical example is the design of vanes fan resistant to the impact of birds. For this reason light non-metal materials have not been used over thirty years.
- During manoevre the engine is influenced by other forces for like inertial and gyroscopic forces.
- Furthermore, there are some chemical influences such as well as erosion, corrosion and creep.

Engine life computer

The 0700 series engine life computer of the Smiths Industries firm (Fig.1) can take up to 12 input signals (analog and digital), it performs different real-time calculating operations using customer's software, it stores results into its memory and shows them on display for both engine parameters:

- Engine speed (comparison of the engine speed with cockpit gauge of 0.1% resolution)

- Total engine life from low cycle fatigue
- Ten latest exceedances of the engine speed (exceedance of the prescribed values between 100 % and 110% of the engine speed is registered). The data on exceedance of the engine speed contains the number of engine starts, duration time of the exceedance and max. registered engine speed in the exceedance.
- Sudden changes of the engine speed
- Total number of engine starts (the engine is considered to be running when the engine shaft is above 30%)
- Acceleration and deceleration time
- Built in test for engine state check.

Figure 1. Engine life computer

Dimensions of the engine life computer are: 84mm height, 58mm width, and 319mm length. The weight is 1.8kg. The engine life computer is located in the case mounted in the space for aircraft electronic equipment. It consists of three modules: energizing and signal acception modulus from rear side, display from the front side, electronic modulus (microprocessor and memory) in the central part of the computer. The engine life computer operates from the nominal 28 V dc aircraft supply. The computer accepts one signal input from tacho generators for each of the two engines. 100% engine speed is equivalent to 70 Hz frequency. Sampling of the input signals take place at least ten times per second under all operating conditions. The operator reads data from computer at particular intervals (after each flight, each day, etc.), depending on the user request. Data are obtained manually, using a switch for channel selection and read on the display or automatically by data retrieval unit. The readings are then recorded in forms previously agreed on or entered automatically into the data base.

Engine monitoring system

The TR473 engine monitoring system of England *Negretti aviation* firm consists of two units: the Engine Monitoring Unit (EMU) and Data Retrieval Unit (DRU) (Fig.2). One DRU is capable of handling data from several airborne systems. The recorded and processed data are used to determine the condition of the engine in question. The results are stored for post-flight extraction with the use of the DRU and subsequently to a ground processing facility. This facility can be a simple printer for tabulation of the results or computing system for data base management and further data processing of the data if required. The DRU permits access the EMU memories so that these may be reset to zero or to operator selected values, as required by either EMU or engine change. The EMU accepts input signals from the following sources: two tachogenerators, two reheat select switches and Data Retrieval Unit.

The EMU performs the following functions:

- Acquires data from two gas turbine engines and two cockpit mounted switches
- Monitors the input data for pre-defined abnormal conditions of the engine data
- Calculates the low cycle fatigue for each engine
- Accumulates a number of engine starts and engine running time
- Monitors for exceedances of the input speed for each engine
- Stores the speed profile for both engines in non-volatile memory
- Accepts input signals from reheat selector switches
- Detects the presence of a slam acceleration
- Provides the required data interfaces (for the DRU and the integral BITE indicator)

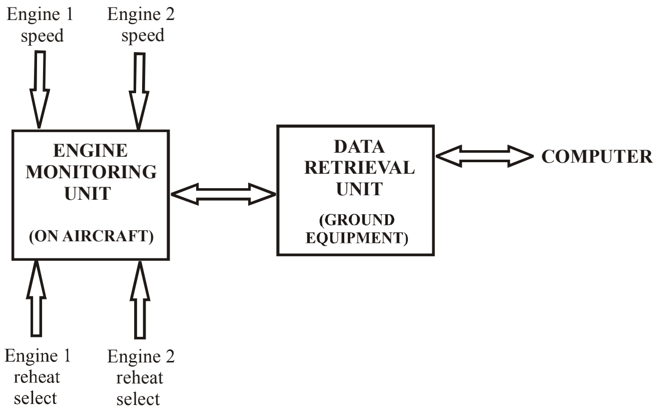

Figure 2. Engine monitoring system configuration

The minimum recordable engine speed is 12%. Below these values all speeds are set to 0%. Recorded engine parameters are stored in non-volatile memory every 5 minutes of engine run time, immediately after the engine start. The maximum number of samples is 16 per second for engine speed (per engine). When the speed input signal increases from 60% ± 2% to 73% ± 2% within a period of 1 second, a slam acceleration condition is identified. Data store is reset to zero before engine start. The EMU calculates in real time and periodically records in non-volatile memory, the following data for each engine:

- Accumulated number of starts
- Total accumulated engine run times
- Total accumulated time over engine speed exceedance (each engine)
- Accumulated counts of the low cycle fatigue

The EMU is capable of accumulating low cycle fatigue damage counts for a large number of individual components on up to 3 shafts of each engine. In this installation, the low cycle fatigue is calculated for the 3rd stage compressor of each engine. The low cycle fatigue is calculated by computing a stress-strain signal using shaft speed tacho generator inputs. This stress-strain time history is broken up into a series of cycles of varying amplitude. These cycles are stored in memory as they occur and are extracted from the signal history by a cycle extraction routine. This routine only extracts minor cycles. The major cycles cannot be identified until the engine is shut down (normally at the end of the flight). The minor cycles are therefore processed and their contribution to the fatigue damage is accumulated and stored whilst the major cycle is retained, non-processed, until complete. The EMU outputs are accessed through the use of a DRU. The following parameters are output from the DRU:

- Aircraft serial number
- Engine serial number
- Number of starts (cumulative engine starts)
- Running time (engine times)
- Excess duration of the engine speed
- Maximum excess of the engine speed
- Accumulated counts of the low cycle fatigue.

The *Smiths Industries* is a leading English firm for design and production of the monitoring systems applied both in military and civil aircraft. The systems of the *Smiths Industries* have been calculating in real time the low cycle fatigue of the *Hunter, Harrier, Jaguar, Trident, Tristar, Buccaneer, Tornado*, etc. aircraft, over the last thirty years. *Smiths Industries* has been designing and producing the sensors and transducers for engines, transmission, and airframe and flight parameters, for nearly eighty years. Fig.3 presents, in a symbolic way, the way that a monitoring system monitors aircraft engines, just like a stethoscope.

Figure 3. Monitoring system applied in civil aircraft

Fig.4 presents an airborne monitoring system applied in civil aircraft. The data from the computer are used, through the DRU, for the first and second maintenance line.

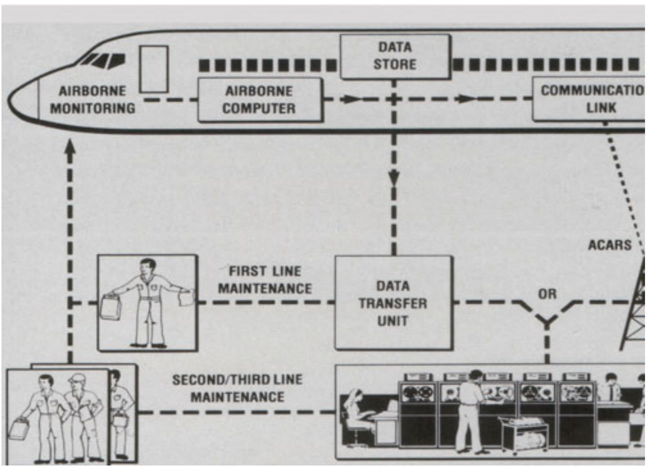

Figure 4. Using monitoring system in aircraft maintenance

Conclusion

The traditional maintenance concept applied for decades and based on periodical inspections after a set number of flight hours or time period of the aircraft usage, is being replaced by a modern, generally accepted, maintenance concept according to the condition. This concept has been applied since the 1980s with a new modular engine design providing fast and simple access to engine parts and significant use of diagnostic equipment for state monitoring.

This concept has led to the increase in maintenance efficiency, reliability and flight safety. Using this concept it is possible to prevent unscheduled engine removals which considerably increase operational costs. This is especially important in case of engine removal from the home base which considerably increases maintenance costs due to high prices of engine transportation.

Concerning airborne parameters monitoring applied more than twenty years ago, it is necessary to say that the possibilities and the quantity of the processed data are continually increasing. The development of the electronics and computer technology, as well as applied software development, in the last ten years has evidently contributed to this. Depending on the engine manufacturers, the following parameters are collected: altitude and velocity of the flight, external temperature, aircraft mass, engine speed, turbine exhaust gases temperature, fuel flow, oil pressure and temperature, engine vibration, etc. The modern versions contain several monitoring parameters and they give a more complete picture of the engine state. The collected data is processed using computing program for numerical values and diagrams of the engine performance state.

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Dijagnostički sistemi u održavanju vazduhoplovnih motora

Prikazan je savremeni koncept održavanja avionskih motora, zasnovan na značajnom korišćenju dijagnostičke opreme i sofisticiranih dijagnostičkih sistema. Koncept je primenjen kako na motorima borbenih aviona, tako i na motorima civilnih aviona za komercijalne letove.

Ključne reči: **avion, avinski motor, turbomlazni motori, održavanje, dijagnostika.**

Les systèmes diagnostiques dans l'entretien des moteurs

Ce papier démontre un concept moderne dans l'entretien des moteurs d'avion. Ce concept se base sur une grande utilisation d'équipement diagnostique et des systèmes diagnostiques sophistiqués. Le concept est appliqué tant chez les moteurs d'avions de combat que chez les moteurs d'avions de passagers pour les vols commerciaux.

Mots clés: **avion, moteur d'avion, turboréacteur, entretien, diagnostic**

Диагностические системы в техническом обслуживании и ремонте авиационных двигателей

В этой работе показан современный черновой набросок технического обслуживания и ремонта авиационных двигателей, обоснован на значительном пользовании диагностического оборудования и софистицированных диагностических систем. Черновой набросок применён как на двигателях боевых самолётов, так и на двигателях гражданских самолётов для коммерческих полётов.

Ключевые слова: самолёт, авиационный двигатель, турбореактивный двигатель, техническое обслуживание и ремонт, диагностика