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Turbojet engine maintenance systems

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This paper deals with maintenance systems of turbojet engines applied in military and commercial aircraft. In addition to traditional maintenance procedures applied for decades, a today's generally accepted on-condition maintenance concept is explained. The advantages of this concept based on engine parameters monitoring during flight are pointed out in particular.

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

Introduction

AN initial concept of maintenance of aircraft turbojet engines was a concept, generally accepted, from the period of airplane piston engines. It was a so-called, hard time concept with precisely defined repair and revision tasks after a number of flight hours. However, with time, accumulated experience concerning operational use of turbojet engines as well as some modifications performed on engines and their modules influenced the extention of life of engine components and engine life as well. In the late 60s and early 70s, owing to new materials and new technologies, the existing maintenance concept became considerably uneconomical and inflexible.

At the beginning of the 70s, with a new generation of large turbojet engines in wide body airplanes (*Boing 747, Mc Donnell Douglas DC-10, Lockheed tristar*), appeared a new maintenance philosophy. For the engines which were for the first time modularly designed, reliability and accurate methods have been developed for monitoring engine health. Efforts have been directed to up-to-date existing methods for monitoring vibration, temperature, pressure, quality and oil consumption, metal debris, etc. Special progress has been made by using a fiber-optic instrument called boroscope. Thanks to the boroscope there was no need any more for periodic engine removing for inspection of the 'warm' parts: combustion chamber and high pressure turbine vanes. Furthermore, a hardware-software system for acquisition, processing and analyzing engine performances in the flight, has been developed and on the basis of these performances it was possible to monitor engine health with accuracy without removing and disassembling it in workshop. Thus, the old hard-time maintenance system has been replaced with a new, on-condition maintenance concept.

On-condition maintenance concept

There are essential differences between turbojet engines of civil aircraft and turbojet engines of military aircraft, 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 regimes suddenly change in flight. Their use, expressed by flight hours, is much less frequent than their use in civil aircraft, which can be over 5000 hours a year. According to data dating from several years ago, world's average is between 2.700 and 3.500 hours.

Because of existing diferences between engines of civil and military aircraft, there are different requirements concering monitoring of some parameters during flight. For engines of military aircraft different heterogeneous data of frequent occurence during the whole, relatively short flight, are collected while for engines of commercial aircraft some parameters in particular regimes are shortly recorded during a long flight. Data collection is performed automati-cally 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 the aircraft lands or before a next flight.

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

As for the parameters monitoring during flight, it is necessary to say that processing possibilities and quantity of processing data are permanently increased. The reasons for that are electronics development and computer technology as well as applied software development over the last ten years. Different parameters are collected generally including flight altitude and velocity, exterior temperature, mass of aircraft, engine revolution per minute, 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

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acquired data are processed using computer programs and the results are in the form of numerical values and diagrams showing a particular engine performance status.

The initial software for engine status monitoring has been developed for large computer systems. However, with 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 in flight, the second one for performance modular monitoring in flight, and the third one for engine test analysis on the stand. However, with development of new engine types with specific requirements and software extensions, it was concluded that further development of the existing programs would be higly complicated and inflexible. It was a reason to develop new software programs with more detailed data bases. New programs enable the monitoring and the analysis of engine vibrations, they contain expert systems with elements of artificial intelligence and, on the basis of built-in data and experience from the service life, they can suggest a decision to be made on some of corrective actions.

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

Example of engine maintenance for civil aircraft

The CFM56-3 engine, produced by France and the USA in a joint-venture company of *Snecma* and *General Electric* for large civil aircraft, will be used as an example of a part of the on-condition maintenance procedure. The engine is modularly designed and developed from the maintainability point of view. It consists of four modules: fan booster, core engine, low pressure turbine and accessory drives (Fig.1).

Magnetic chip detectors

A simplified scheme of the engine bearings disposition is given in Fig.2 and the oil system scheme is given in Fig.3.

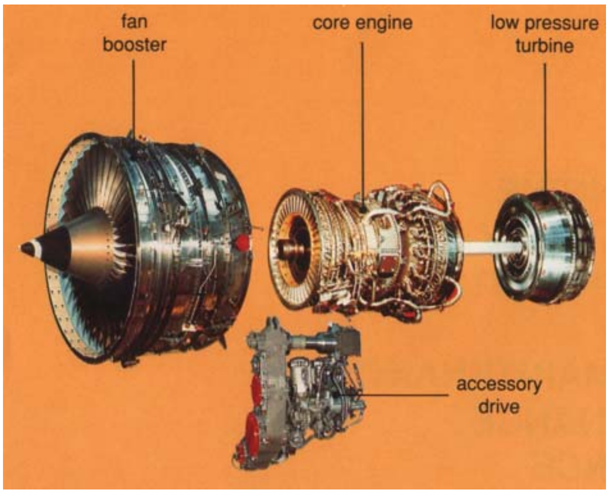

Figure 1. Modular design of the CFM56-3 engine

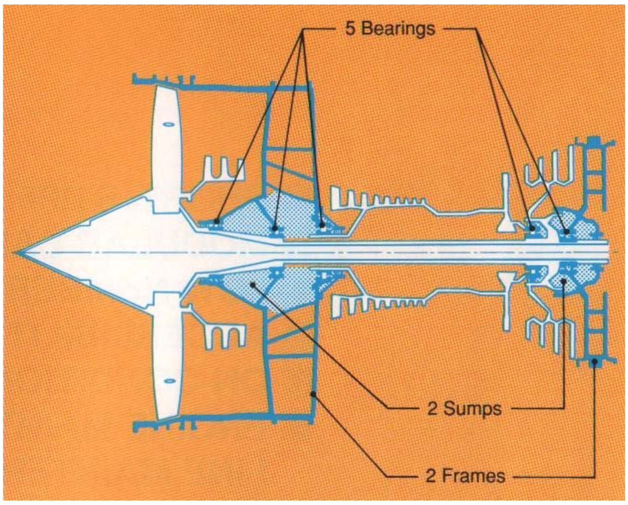

Figure 2. Simplified scheme of the engine bearings disposition

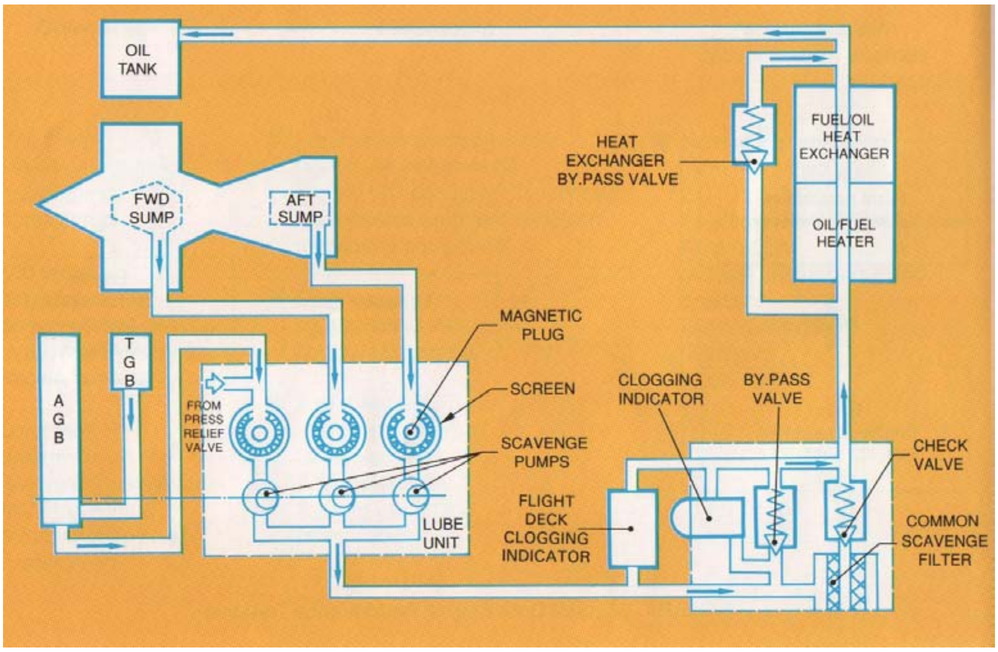

Figure 3. Simplified scheme of the engine oil system

The system is so designed that three front bearings are connected to the first magnetic detector, two rear bearings are connected to the second one and the bearings of the accessory drive are connected to the third magnetic detector. The accessory drive consists of the accessory gearbox - AGB and the transfer gearbox – TGB. The chip detector assembly is presented in Fig.4, and the scheme of the magnetic plug and the filter is presented in Fig.5.

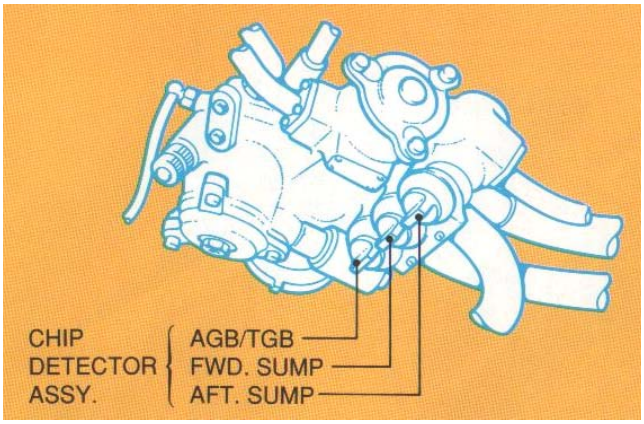

Figure 4. Chip detector assembly

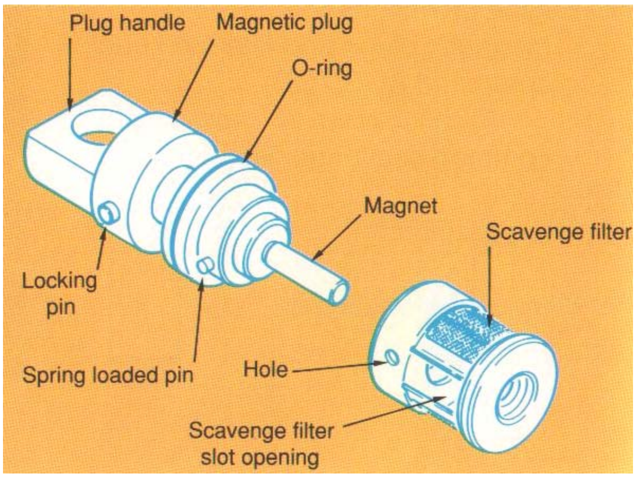

Figure 5. Magnetic plug and filter

The detector allows faults detection and isolation on the basis of metal debris (magnetic and non-magnetic) in the lubrication system. The identification and classification of the particles is performed in two steps. The first step contains a visual and microscopic inspection to determine magnetic or non-magnetic particles. In the second step, the particles are sent to a lab for analysis. If required, an engine inspection is performed. There is no engine removal if oil contains silver slivers, black colored debris carbon deposits and aluminium shims. If all detectors detect bearings material, the engine is removed. The module replacement is performed if the detectors AGB and TGB detect bearings cage wear.

Spectrographic analysis of oil

Spectrographic analysis of oil is used for detecting any wear of rotating parts which can cause a failure. The analysis is based on the nature and concentration of particles, total operating time, operating time since last oil sampling (evolution of concentrations), oil type and brand, and oil consumption. The extraction of a sample of 60 cc of hot oil is performed as soon as possible after the engine shutdown (15 to 30 min at the latest). The analysis determines any excessive concentration of material wear (Table 1).

Table 1. Materials contained in oil

Iron (Fe)	Most significant metals
Titanium (Ti)	
Copper (Cu)	
Aluminium (Al)	
Nickel (Ni)	Secondary identifiers of worn-out parts
Zinc (Zn)	
Chromium (Cr)	
Silver (Ag)	
Phosphorous (P)	
Silicon (Si)	Oil contamination indicator
Magnesium (Mg)	

Borescopic inspection

The borescopic inspection detects failures or damages of inaccessible, internal parts without disassembling the engine. A schematic review of the position and the number of the ports for the borescopic inspection is presented in Fig.6. The review of the borescopic ports diameters is presented in Fig.7. All borescopic ports are accessible without removing any other hardware. The most of the ports are 10 mm in diameter and are intended for rigid borescopes. The ports of diameter 6 mm are used for flexible and the ports with 8 mm diameters for rigid/flexible borescopes.

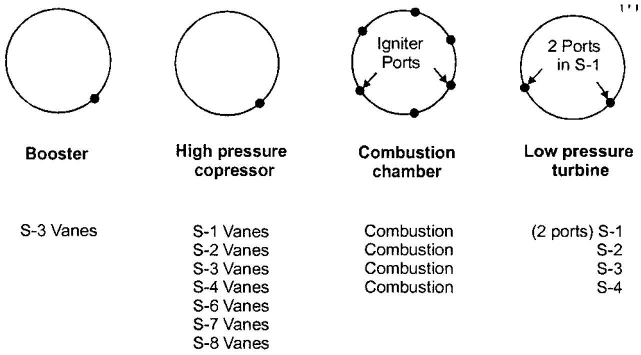

Figure 6. Schematic review of the position and the number of the ports for the engine borescopic inspection

Vibration monitoring

The aim of vibration monitoring is early warning about engine unbalance and locating its cause. Vibrations can occur due to turbine or compressor blade damage, rotating parts failure in one of the engine mounted accessories, bearing damage, etc. Early warning should help in undertaking a corrective action.

The engine CFM56-3 pick-up vibration locations are presented in Fig.8.

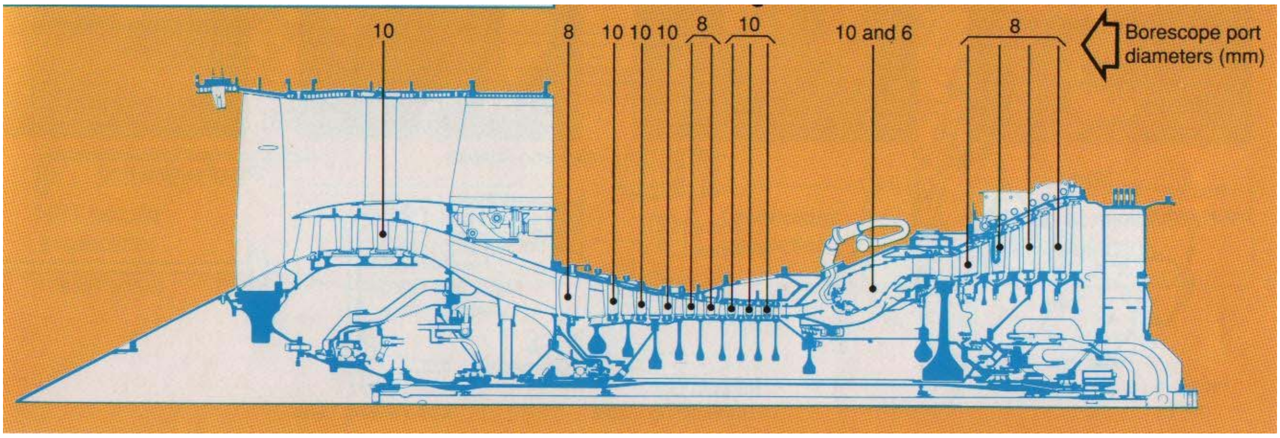

Figure 7. Review of the borescopic ports diameters

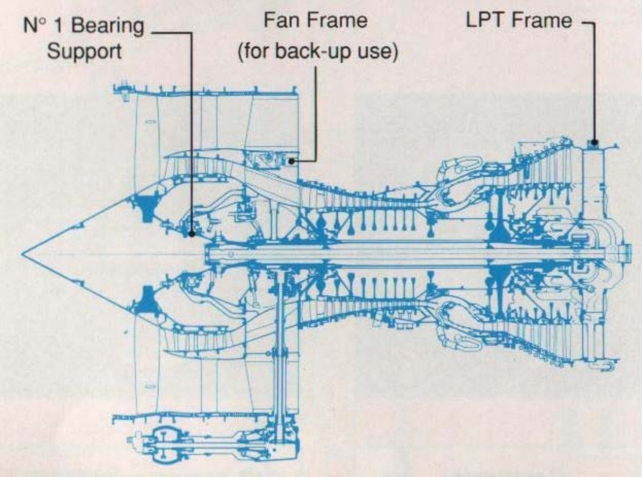

Figure 8. Engine vibration pick-up locations

Radiography- Gamma Ray

Radiography detects an internal part failure or damage without disassembling the engine. The procedure is based on the capability of x-rays to pass through different materials. During penetration through a material x-rays are absorbed, i.e. the become weak. This decrement is lower if rays come across failures and inhomogeneities, i.e. absorption is reduced then.

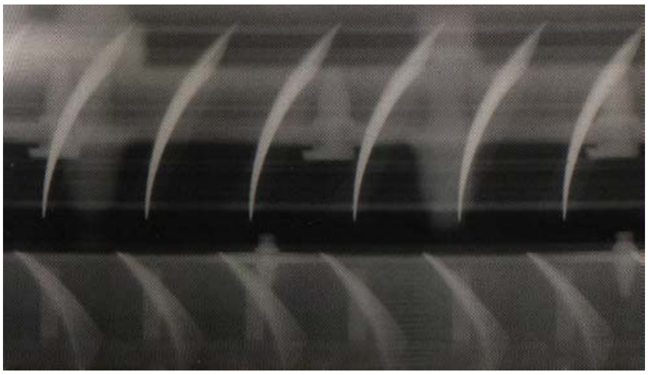

Figure 9. Radiogram of the engine fan

Gammagraphy is a procedure of investigation by gamma rays having the same features as x-rays. They also penetrate through the material where they are more or less absorbed depending on the homogeneity of the material. But their wave length (10^{-10} to 10^{-11}cm) is less than the wave length of x-rays. Because of that, gamma rays have greater penetration power. One fan radiogram is shown in Fig.9. The total number of engine inspection positions is 22:4 in the fan, 10 in the high-pressure compressor, 3 in the combustion chamber, 5 in the high and low pressure turbine.

Line maintenance

In order to detect failure in civil aircraft a common monitoring of cockpit instrumentation and on-wing recommended inspections are performed. Visual routine checks in specific parts, drain and oil quantity level checks are performed on wings daily. Table 2 presents inspection type and time intervals. Line maintenance contains: fan blades replacement, quick unit replacement, fan and low pressure turbine balancing, quick engine replacement, etc.

Table 2. Inspection types and time intervals

Inspection type	*Inspection interval*
Visual inspection of parts/oil	Daily
Magnetic plugs, Oil filters indicators	375 effective flight hours
Borescope inspection of the high pressure turbine	750 effective flight hours
Borescope inspection of the combustion chamber	1500 effective flight hours
Fuel filter, oil filter replacement	3000 effective flight hours

Maintenance of turbojet engines of military aircraft and helicopters

Maintenance of turbojet engines has been for a long time performed, and is still performed, in older engine generations, according to a fixed prescribed number of working hours. After the prescribed period expires, engines are sent to the repair department for a repair according to a prescribed technology. This preventive procedure does not take into account real thermal and other loads during service. Thus, engines are repaired for safety, no matter there is a real need for it or not.

At the beginning of the 80 s of the last century, significant changes occured in maintenance of turbojet engines of fighters. As in engines for commercial flights, the changes introduced a new concept of preventive maintenance, an on--condition maintenance concept, in modern engines of western production. We shall mention only some characteristic applications. This concept was applied for the first time in the RB199 engine of *Tornado* aircraft, which has been in use since August 1986. It was a very serious project of design, development and production. This engine was a product of three leading European turbo engine producers: English *Rolls-Royce*, German *Motoren-und-Turbinen-Union* and Italian *Fiat Aviazione.* Up to 1988 over 1900 engines were manufactured in *Turbo-Union,* a consortium of the mentioned companies. The on-condition maintenance concept provides low costs and module replacement enables quick engine return to service and considerably minimizes spares stock. Line maintenance provides easy access to engine for daily maintenance, easy accessories change, and fast engine change (45 minutes).

Eurojet EJ200, in service from 1995, belongs to a new generation of turbo jet engines. The engine is of modular design, and it represents an example of on-condition maintenance with build-in equipment for testing and monitoring. In this engine a complete digital control system with failures diagnosis is applied.

In the 80s of the last century, *Rolls-Royce* and *Turbomeca* developed the *Adour* RT172-56 engine family for the *Hawk* aircraft and the version RT172-58 with afterburning for the *Jaguar* aircraft. The engine is of modular design, equipped with magnetic chip detectors for early warning of bearing or gear failures, as well as with the equipment for vibration pickup. Using the borescope, through the existing borescope ports, we perform the inspection of intake inlet pipe and the low and high pressure compressor casing to detect damage by a foreign object.

In the field of helicopter engine development *Rolls-Royce* and *Turbomeca* cooperated for more years and in late eightes of the last century they developed a family of the RTM322 engine with the power range: 1345 – 1945 kW. The engines were of modular design with digital electronic control and on-condition maintenance. The engines were available for future helicopter projects including the Anglo--Italian EH101 multipurpose, *Westland* 30 transport helicopter, and other helicopters from 7 to 15 tones.

New maintenance philosophy required, even in the aircraft design phase, building-in of corresponding diagnostic equipment for monitoring component states, for device self–testing. It also required registrators for all engine operating regimes, ports for inspection of warm parts, modular engine design, fast and easy access to parts.

Taking into account the differences in operating regimes between turbojet engines of military and civil aircraft it is clear that the determination of their life is different. Namely, the life of a turbojet engine of military aircraft depends very much on aircraft mission. The life of modern turbo jet engines of fighters is determined on the basis of the total accumulated cycle which presents a sum of specific movements of the throttle lever during fighter task performing. During transient regimes, temperature gradients, especially in cold turbine parts, can lead to enormous tension skip due to local unequal dilatation. This phenomenon is known as thermal or low cyclic fatigue and it influences most the life of warm parts in high-temperature engines. The *Rolls-Royce* has analyzed movements of the throttle lever in military aircraft and has come to data about the number of cycles per hour: for an acrobatic flight 10-14, for a training flight 5-10, for a hunting-bombing flight 5, etc. Approximately, for one flight hour the engine spent 2 cycles.

Taking into account that engine manufacturers have developed a procedure for calculating cycle numbers during service, life of some engine components, in addition to working hours, can be expressed in cycles. A new generation of engines has a built-in register for measuring cyclic life, so that, at any moment, technical personnel at airports knows a real engine life after every flight.

As for engines in civil aircraft, this on-condition maintenance concept uses spectrographic oil analysis, endoscopic equipment and equipment for vibration pick-up. Table 3 presents the results of the engine oil spectrographic analysis for four engines, with equal number of working hours in service. It is obvious from the table that in Engine 4 abnormal operating conditions has occurred and that the wearing process has started.

Table 3. Results of the engine oil spectrographic analysis

Elements content	**Engine 1**	**Engine 2**	**Engine 3**	**Engine 4**
Content of insoluble materials in organic solvents %	16.8	32.1	11.2	140.4
Copper [μg/g]	4.4	6.7	5.5	x
Iron [μg/g]	2.7	3.0	2.5	x
Lead [μg/g]	0.7	< 0.5	< 0.5	x
Nickel [μg/g]	< 0.5	0.5	0.5	x
Chromium [μg/g]	0.5	0.5	0.5	x
Zinc [μg/g]	0.6	0.7	0.7	x

In order to detect and correct faults periodical inspections are performed after a fixed number of flight hours or a usage time period. Periodical inspections are performed after 50+5 aircraft flight hours and after 6 months if an aircraft is not in use. Periodical inspections on the basis of the flight hours number or the usage time period are totally equal and are performed depending on which condition is fulfiled first. While using aircraft in conditions of intensive humidity, dust, etc, or while performing special tasks (higher number of landings, more frequent arms usage, etc), additional periodical inspections can be performed on aircraft or some accessories and systems.

Expert systems and neural networks in maintenance

The expert systems technology widely used today in airforce is capable of solving complex problems in the domain of: signal processing, image recognizing, data acquisition from different sensors, training, diagnostics, etc. For example, copilot expert systems are used for a pilot load decreasing in critical phases. Expert systems are engaged in non-fighting activities as well as in aircraft state, monitoring, communication, navigation, trajectory planning, aims recognizing, emergency analysis, faults diagnosis. In this way, copilot expert systems help the pilot to concentrate on essential tactical and strategic aims.

Neural networks studing, especially in the last decade of the last century, traced a new direction of expert systems development, towards the integration of neural networks and conventional expert systems in order to obtain more effective systems which would be more resistant to errors and incomplete data, adaptable to system enlargement. This integration of expert systems and neural networks led to the development of hybrid intelligent systems widely applied for solving different problems imposed by modern technological development, as well as for tasks monitoring, state predicting, planning, etc.

The development of reliable helicopter gear state monitoring was a subject of large research work last twenty years. The research aim was to develop a system which would lead to a considerable resource increasing and to a drastic reduction of helicopter maintenance costs. The solution was found in the monitoring based on neural networks. A hybrid (digital/analogical) neural system as exceptionally exact off-line monitoring for reducing maintenance costs was proposed. Furthermore, an analog neural network was proposed as a monitor for helicopter gear fault detecting in real time.

The helicopter state in flight is followed by the monitoring system, and then a computer on the ground performs an analysis of the measured data. Because of a large number of data recorded during flight, an automatic intelligent system is used for its scanning.

The developed intelligent control system can extract and identify samples pointing out to a fault, from a large number data recorded during flight. It can point out to abnormality due to an unknown cause and give an estimate regarding further helicopter usage.

In order to achieve this, non-supervision studing is applied as a process which should classify samples without previous knowledge. By oil analysing, as we have seen, intensity of wear of oil wetted parts can be identified. The investigations showed that the applied hybrid intelligent monitoring system on the basis of neural networks enables discovery and removae of incorrect components before fatal failures.

Conclusion

The traditional maintenance concept applied for decades and based on periodical inspections after a fixed flight hour number or a time period of aircraft usage, withdraws more and more before of a modern, generally accepted, on-state maintenence concept. This concept has been applied since the 80s with a new modular engine design providing fast and simple access to engine parts and significant usage of diagnostic equipment for state monitoring.

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

Development of neural networks, especially in the last decade of the past century, as well as further development of expert systems, has led to the application of hybrid intelligent systems in airforce maintenance. There is no doubt that the future of modern maintenance belongs to them.

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Sistemi održavanja turbomlaznih motora

Razmatraju se sistemi održavanja turbomlaznih motora vojnih i civilnih vazduhoplova. Pored tradicionalnih višedecenijskih procedura koje su doživele svoj puni razvoj i primenu, objašnjen je savremeniji, danas opšte prihvaćen koncept održavanja prema stanju. Posebno su istaknute prednosti ovog koncepta, koji se bazira na stalnom praćenju određenih parametara tokom leta.

Ključne reči: **vazduhoplovi, turbomlazni motor, dijagnostika, održavanje.**

Systèmes de l’entretien du turbo-réacteur de l’aéronef

Les systèmes de l’entretion des turbo-réacteurs chez les aéronefs militaires et civils sont traités. A part des procédures traditionelles, utilisées pendant les décennies, une conception plus moderne de l’entretien selon la condition est décrite. Les avantages de cette conception basés sur la surveillance des parametres de turbo-réacteur en vol sont montrés en particulier.

Mots-clés: **aéronefs, turbo-réacteur, diagnostic, entretien.**