UDC: 629.7.036.3(047.3)=20
COSATI: 21-05

Sophisticated diagnostic systems in aircraft engines

Dragoljub Vujić, PhD (Eng)[1)]

Modern diagnostic systems and their application in state and failure predicting at aircraft engines are considered. A special attention is paid to the oil debris monitoring and failure detection logic. Some practical experiences gained during the monitoring system realization on the military combat aircraft engine are exposed. A special diagnostic system of reasoning based on past experiences from the aircraft engine maintenance domain is shortly presented.

Key words: **aircraft engines, condition-based maintenance, magnetic detector, monitoring system, sophisticated diagnostic systems, failure detection.**

Introduction

AT the beginning of the 1980s significant changes occurred in turbojet engine maintenance, in combat aircraft engines as well as in engines of civil aircrafts for commercial flights. Instead of maintenance based on precisely defined number of flight hours [1] a new maintenance concept based on condition appeared. This concept was first applied to the RB199 engine of the *Tornado* aircraft [2], which has been in use since August 1986. It was a very serious design, development and production project. This engine was a product of three leading European aircraft engine producers: English *Rolls-Royce*, German *Motoren-und--Turbinen-Union* and Italian *Fiat Aviazione.*

In the 1980s, *Rolls-Royce* and *Turbomeca* developed the *Adour* RT172-56 engine for the *Hawk* aircraft and the RT172-58 version with afterburning for the *Jaguar* aircraft. The engine is of modular design, equipped with magnetic chip detectors for an early detection of bearing and gear failures, as well as with vibration pickups. In the late 1980s *Rolls-Royce* and *Turbomeca* developed a family of RTM322 helicopter engines with the 1345-1943 kW power range with digital electronic control and on-condition maintenance.

The *Eurojet* EJ200 engine of the European hunter which entered in use in 1995 also belongs to a new generation of turbojet engines. The engine is of modular design, and it represents an example of on-condition maintenance with built-in equipment for testing and monitoring.

The emphasized increase in reliability and maintainability of engines, especially in the USA aviation, and a need that aircraft delivered from the base operates without failures, require sophisticated maintenance systems and expensive diagnostic equipment. Such systems have to provide reliable, consistent state diagnosis and to minimize requirements for maintenance personnel training. These requirements can be satisfied only by the diagnostic systems based on knowledge, so-called *knowledge-based systems.*

In the developed world, great attention is paid to maintenance problems. „Maintenance 2000”, a meeting held in the USA in January 1992 with the main purpose to consider new requirements which would appear in aviation aids maintenance in the following decade contributes to this fact. On that occasion it was found that the aircraft complexity would increase and more sophisticated aircrafts would be introduced into use.

Owing to sensors integrated into the aircraft structure [3], the propagation of the crack is monitored in aviation constructions. The constructions are made of so-called smart materials, especially composite materials, which have been used much more recently. In this way, the service life of constructions is longer and the costs are significantly reduced. It is particularly important for military fighters which are exposed to greater loads than airplanes during commercial flights. One of the main problems in this case is the processing of signals from sensors. The sensors need a central device or distributed networks for processing. Based on incoming results, this device decides about necessary preventive actions. Many researches are performed in domains of artifical intelligence, expert systems, fuzzy logic and pattern recognition. Artificial neural networks are expected to give the best results in the domain of effective pattern recognition for a damage detection. In recent years significant progress has been achieved in determing the optimal number and the sensor position for the location of damage. Different optimization techniques are developed. New development in this area includes the application of genetic algorithm.

Technological development of the turbojet engine

The technological development of aircraft engines during the last forty years of the 20th century is shown in Table 1. Only the most important characteristics of the engine development are presented through the use of new materials/processes, design tools and technologies.

[1)] Military Technical Institute (VTI), Katanićeva 15, 11000 Beograd

Table 1. Technological development of the engine

YEAR	MATERIALS/PROCESSES	DESIGN TOOLS	ENGINE TECHNOLOGIES
1960s	• Super alloys • Nickel-based alloys • Titanium-based alloys	• Fracture mechanics	• Variable stator geometry • Blade cooling • Canannular combustors • Vertical short/takeoff and landing nozzles • Afterburning turbofans
1970s	• Low-temperature composites • Powder metallurgy • Nondestructive inspection techniques	• Component optimization	• Annular combustors • Modular design • High-bypass turbofans
1980s	• Single crystals • Thermal barrier coatings • Computerized numerical control machining • Automated vacuum welding	• Computer-added design (CAD) • Computer-added manufacturing (CAM) • Finite element analysis • Computational fluid dynamics • Damage tolerance	• **Diagnostics** • **Digital electronic control** • Low-emission combustors • Low-observable inlets and nozzles
1990s	• Intermetallics • Advanced coatings • Ceramics for low-stress parts	• Rapid prototyping • **Advanced sensors**	• Blisks • Two-stage combustors • Variable engine cycles • 2-dimension vectoring nozzles • Rotating spools counter
2000s	• High-temperature composites • High-cycle fatigue reduction • **Automatic prognostics and health management**	• Metal prototyping • Engine testing integrated with aircraft simulators • Complete engine computational fluid dynamics (CFD) modeling	• Integrated flight and propulsion controls • Multipoint fuel injectors • High-temperature fuels • Integral starter generator

It is obvious that the use of diagnostic systems and digital electronic control systems started in the early 1980s. More important sensor applications are characteristic for the 90s but the automatic health prognostics appeared in 2000.

Electric control systems

The flight control of modern aircrafts is based on electric, so-called fly-by-wire systems [4]. Owing to fast development of the microprocesor technology, storage elements, integral electronic circuits as well as other electronic components, the development of electric systems became especially intensive after the 1970s. Although the previously used conventional hydromechanical control, based on components developed for a long time, was very reliable, it could satisfy only the requirements regarding performance increase, especially in military supersonic aircrafts.

The engines of modern aircrafts have a compressor with variable geometry of stator vanes. Nowadays, the trust vector control is applied. Also, there is a general trend of reducing dimensions and masses. These requirements increased the number of inlet and outlet parameters, for the control of which a powerful digital computer was necessary. The experience with multiple inlets and outlets, with so-called multiple variable systems has shown that the realization of a complete hydraulic control system is impossible. Only the realization of the electrical control system in digital technology enables the fulfillment of all requirements for today's and future aircrafts. This control system is produced by only a few producers in the world. The most important producers are *Pratt&Whitney* and *General Electric*.

Automatic diagnostic systems

The diagnostic system developed by American firm *Pratt&Whitney* [5] relies on the electronic digital control, uses its data and sensors and requires only a minimum of additional special sensors. The system continuously monitors the engine state in real time and records critical events. In this way the pilot does not have to follow engine parameters. If the system detects a failure, the modular system design enables the replacement of the inoperable modul with a new one and the return of the engine to operational use. The malfunction of the block which has to be replaced is detected automatically using the program located in the memory of the control system. Information about detected failures, blocks and modules are given to personnel in digital form, as an easily accessible outlet. Data from the diagnostic system can be read using ground support equipment or, if it is required, transmitted directly to the aircraft.

It should be mentioned that an integral monitoring will have a very important role in future diagnostic systems. In that sense, many efforts are adressed to the development of applied technologies for integration into engines of today's and future aircrafts. This is the sensor technology that will considerably reduce the costs of the engine service life. The sensors will be built in engine components, lubrication and fuel feed systems. The technologies are in different phases of the development. Some technologies are at the concept level and the others are at the prototype level.

Engine health monitoring on the basis of oil debris monitoring

A traditional method of quantitative measurement and analysis of worn-out particles of parts contained within the lubricating oil [6] is used for determining health conditions of aircraft engines. Based on the analysis of these particles, in terms of quantity, size, shape, colour and material, a conclusion about the source and kind of the incipient failure can be drawn. The main purpose of this method is to detect failures before they produce secondary damages and become evident by means of other methods such as measuring vibrations, high oil themperatures, etc. *On-line* and *off-line* methods with different accuracy and effectiveness are used for failure detection.

The *off-line* technology based on testing in laboratory conditions comprises spectral, ferrographic, colorimetric analysis, etc. It is a conceptually simple procedure that provides relatively accurate results. However, laboratory analyses require time and adequate equipment, and affect the aircraft availability. Another major drawback is that there are no automatic rules for failure determing based on the analysis results and the conclusion has to be drawn from case to case. This means that the experience of operators plays a major role in the assessment. This approach requires a significant maintenance burden due to frequent inspections performed each 10-20 engine running hours, as well as to the necessary time for analysis.

For this reason, great efforts have been made to develop a more requested monitoring system able to automatically detect the beginning of a failure.

Historically, the first „intelligent" system was the electric chip detector, arisen as a result of the magnetic plug development. It consists of a collective magnet with two electric contacts, acting as a switch. The switch is closed when the collected debris fill the gap between the contacts, thus providing electrical indication about the amount of collected particles. Although this is a good method of avoiding scheduled inspection, the accuracy of the resulting information and related prognostic capabilities are questionable. The main question here is that of the gap size which should be specified in order to enable detecting the minimum gap size that is deemed critical. Normal sizes are anyway in the order of 2 mm.

The electric chip detector finds its major application in helicopter gearboxes, where the generation of large amount of fine particles is not considered critical for engine operation, while the occurrence of chucks has to be promptly detected. More sophisticated versions of the electrical chip detector provide the capability of measuring the resistance across the gap. This feature enables the monitoring of the debris accumulation and differentiating between critical and non-critical conditions. Nevertheless, a systematic attempt to correlate between the resistance changes, debris type and quantity is quite difficult. A further improvement of the same approach is to quantify the size of bridging particles from the energy required to destroy them. When the gap is closed, a series of sparks is generated to reopen the gap. The energy required to destroy the particle is then related to the particle size. Although this system can detect micron range debris, the major drawback is a possible hazard related to the electrical discharge within hot oil. For that reason, it is necessary to provide an appropriate protection system.

Nowadays, a significant role in the failure detection belongs to closed monitoring systems providing mass indication of all particles accumulated on the magnetic sensor. Also, great efforts are made to define an appropriate logic which should provide an alarm for maintenance personnel whenever critical conditions for engine operation are detected. Therefore, it is necessary to define the rules related to particle generation. Number of particles, their mass and/or size and the rate of debris generation are the parameters used in this exercise. As a rule, more detailed and accurate measuring of particles can be used for the design of more complex and reliable detection system. Reviewing the development and validation activity of existing systems, it can be concluded that there is no common understanding about debris generation profile and failure progress nor about the exact relationship between the type of debris and engine failure modes. In that sense, several interesting efforts have been made, but they still have not provided satisfactory results. Moreover, there is no general approach to the definition of system requirements, such as type of output and measurement accuracy. The approach to the validation task has not been standardized yet. Although several interesting trials have been performed (laboratory investigations, rig tests, engine data collection), defining criteria of correct system operation assessment is left to the system supplier. For those reasons, the development of the specified devices cannot be considered completely finished. There are still certain difficulties for the system designer to choose a technology for a particular engine application. The extensive flight testings are currently performed on military fighter engines.

Realization of the monitoring system

During the realization of the monitoring system it was assumed that all types of ferromagnetic particles, whatever their size was, were significant for identifying failure onset, and that the mass accumulation rate is the key parameter for engine health monitoring. Therefore, the first goal was to ensure sufficiently high capture efficiency, which would be achieved by the collective device, in order to base the analysis on the greatest possible debris quantity. This was obtained by using the centrifugal separator within the scavenge line.

A photo of the sensor tip, about 2 cm in diameter, completely covered by particles following a gearbox breakdown is presented in Fig.1. Distinguishing significant events, i.e. high debris generation rates, from environmental noise is the major problem during the system validation. Besides, difficulties arise from high temperatures in the scavenge line. Therefore, the thermal compensation based on oil temperature measurements is introduced. In addition, as debris accumulation is a long-term phenomenon, this compensation should cope with slow thermal changes. The thermal compensated output (oscillated line) from the monitoring system is presented in Fig.2.

Figure 1. Sensor for debris collection

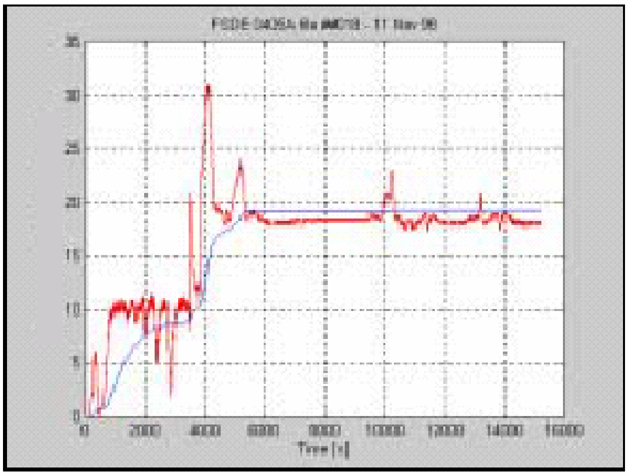

Figure 2. Debris accumulation during the bearing destruction test

An autput signal from the system after its filtration is presented by a relatively smooth line. The essential information related to the mass accumulation is extracted from the background noise and can be used to identify sudden variation due to debris accumulation.

Besides numerous technical difficulties, the major problem is the defining of failure detection logic. In that sense, it is a question of defining a warning threshold. The problem is solved by means of a bearing dectruction test. Rig simulating the operating conditions of shaft bearing on the engine was used in the test. The bearing was damaged before the start of the test, in order to induce a failure. The monitoring system was fitted onto the scavenge line in order to collect produced debris. The bearing failed after 105-hour testing. Fig.3 shows the results obtained from data processing. It can be easily concluded that the highest debris accumulation mass rate, as an upper warning limit, is plotted a few hours before the bearing breakdown. This electrical signal, similar to the warning of the electrical chip detector is a signal for the maintenance service.

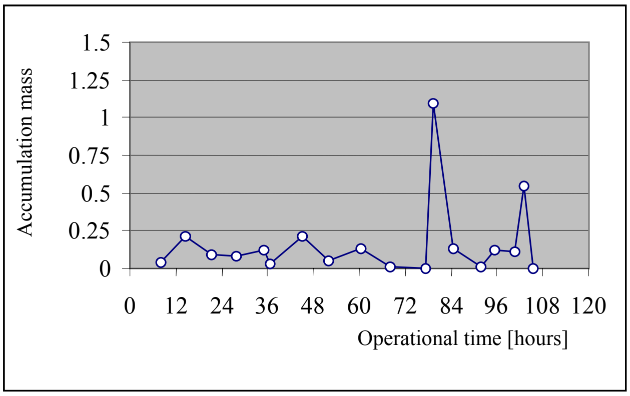

Figure 3. Mass accumulation

The experience gained during the rig testing is very useful in defining and assessing the method on the engine. Also, it has been stated that the system validation can be done after a long period of monitoring normal engine operation, data collection and analysis. The background for defining some guidelines for the monitoring system is obtained from laboratory testings. These guidelines are to be checked during the engine development testing. The traditional oil debris monitoring via magnetic chip detector is used parallelly to this system in order to avoid undetected failures. Engine failures, although undesirable, would help a lot in the validation process. When sufficient confidence in the automatic oil debris monitoring function is achieved, it will be possible to abandon traditional inspection techniques and rely on the oil debris monitoring function alone.

As mentioned, the goal of the presented debris monitoring approach is to provide a simple and reliable warning to maintenance personnel about critical conditions for the engine operation. This will induce all additional investigations required and analyses which can be better performed off-line in laboratory environment. Due to relatively infrequent arising of failures detectable via debris generation, false warnings and unnecessary maintenance actions should be avoided. The maintenance personnel at the first line should only be informed whether the engine is safe to continue to operate or not. Of course, it is a great challenge to pass from a relatively safe approach, based on regular checks, onto a new on-condition warning system. Therefore, the reliability of the failure detection logic has to be well checked and proven through a series of back-to-back testings using current methods.

Until that time the magnetic chip detectors, despite all their limitations, will have an irreplaceable role on most service engines.

Based on the previous considerations, it can be concluded that the proposed oil debris monitoring function, supporting engine on-condition maintenance, will be composed of: an automatic *on-line* device for quantitative measurement and indication of the amount of debris, an *on-line* failure detection logic as well as of additional methods for *off-line* and *on-line* oil debris analyses.

Aircraft fuel supply monitoring systems

Significant progress has been achieved in the area of oil debris monitoring systems applied on aircraft engines. Therefore, it was suggested that this technology should be applied to an in-line aircraft fuel supply system. The monitoring system should provide continuous inspection of sediment and water content and warn when contaminant amounts exceed maximum prescribed levels. This system should reduce operational costs, especially during the aircraft fuel transfer and storage on the aircraft carriers. The costs can be reduced through fewer inspections and shorter laboratory testing time. The sensors will be placed on each fuel transfer line, on filters and in storage tanks. Several types of sensors are selected in order to indicate levels of solid contaminants and water. Sensor data is transmitted to a central control panel that displays both contaminant levels at each location as well as alert when nonpermitted contamination is detected.

Vibration monitoring

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

The concept of the diagnostic system is defined based on requirements identified during the inspection of typical failures appearing at the engine rotor. Those are failures arised due to rotor unbalance, rotor bevelling (wrong assembling), friction, increased support flexibility and accessories vibration. The diagnostic system is connected with the data acquisition system and is successfully used for diagnosing all failures due to engine vibration.

Case-based reasoning

The Canadian firm *Tricom Technologies* has developed a case-based reasoning system [14]. This technology belongs to a branch of artificial intelligence that reasons about new problems based on past experiences. The idea for generating this system is to record and save experiences of technicians who have worked on aircraft maintenance or its subsystems and systems. In this way, their precious experience, gained during a long professional career, would be accessible even after their retiring. They started from the well known concept of human knowledge disappearance during the time and that machine memory technique complements technicians' capabilities in maintaining activities and state predicting. Using data bases, the *SpotLight* system is capable to compare the symptoms of actual failures, with those from previous failures and to make a conclusion about it. The system can be successfully used for a training course.

Conclusion

The real time engine health monitoring and diagnostic systems enable the optimization of maintenance procedures and prevent fatal failures. Those systems can significantly reduce engine life costs and whole aircraft costs. In that sense, the sensor technology for integration into engines of current and future aircrafts develops rapidly. Great efforts are addressed to integral monitoring development which presents a future technology.

At oil debris monitoring systems, problems of the failure detection logic and warning threshold question of oil debris indicating failures have not been solved yet. After flight testings that are currently ongoing and the validation of monitoring systems, precious on-condition maintenance tools will be obtained. Until then, magnetic chip detectors will have an irreplaceable role on most service engines.

References

[1] VUJIĆ,D. Tehnička dijagnostika i njena primena u vazduhoplovstvu, *Kumulativna naučnotehnička informacija*, no.12, Vojnotehnički institut, Beograd, 2003.

[2] BERGAGLIO,L., TORTAROLO,F. RB199 *Maintenance Recorder: an application of "on condition maintenance methods" to jet engines, Condition-based maintenance for highly engineered systems.* Universita' degli Studi di Pisa, Pisa, Italy, September 25-27, 2000.

[3] BOLLER,C., STASZEWSKI,W., WORDEN,K., MANSON,G., TOMLINSON,G. *Structure Integrated Sensing and Related Signal Processing For Condition-Based Maintenance, Condition-based maintenance for highly engineered systems.* Universita' degli Studi di Pisa, Pisa, Italy, September 25-27, 2000.

[4] VUJIĆ,D. Osnovni koncept sistema elektronskog upravljanja turbomlaznim motorima, *Naučnotehnički pregled*, 1998, vol.XLVIII, no.5, pp.39-44.

[5] VUJIĆ,D. Dijagnostički sistem turbomlaznog motora. *Tehnnička dijagnostika*, no.2, 2002.

[6] VUJIĆ,D. Dijagnostika stanja vazduhoplovnih motora na bazi monitoringa ulja za podmazivanje. *Tehnnička dijagnostika*, 2004, no.2,.

[7] VUJIĆ,D. Maintenance systems of powerplant in aircraft. *Naučnotehnički pregled*, 2003, vol.LIII, no.2.

[8] VUJIĆ,D. Sistemi održavanja u vazduhoplovstvu. *Zbornik radova, XXVI majski skup održavalaca*, Niška Banja, 28-29. maja 2003, pp.17-28.

[9] VUJIĆ,D. Sofisticirani dijagnostički sistemi i njihova primena kod vazduhoplovnih motora, *Zbornik radova, XXIX naučno-stručni skup HIPNEF 2004*, Vrnjačka Banja, 18-21. maj 2004.

[10] AZZAM,H., ANDREW,M. A modular intelligent data administration approach for helicopter health and usage monitoring systems. *Proc. Insts Mech Engrs,* ImechE 1995, vol. 209.

[11] MONSEN,P.T., DZWONCZYK,M., MANOLOKAS,E.S. Analog neural network-based helicopter gearbox health monitoring, *The Journal of the Acoustical Society of America*, Dec 1995, vol 98, pp.3235-49.

[12] CONTE,S., TORTAROLO,F. *Oil Debris Monitoring as a technique for Engine Health Monitoring and Condition-Based Maintenance: the EJ200 experience, Condition-based maintenance for highly engineered systems.* Universita' degli Studi di Pisa, Pisa, Italy, September 25-27, 2000.

[13] ADAMOVIĆ, Ž. *Tehnička dijagnostika*, OMO, Beograd, 2001.

[14] HASTINGS,B., D'EON,P. Cloning Your Best Aircraft Technicians, *Journal of the National Training Systems Association.* Issue 2/2001 of MS&T.

Received: 1.10.2004

Sofisticirani dijagnostički sistemi i njihova primena kod vazduhoplovnih motora

Razmatraju se savremeni dijagnostički sistemi i njihova primena za predviđanje stanja i otkaza vazduhoplovnih motora. Posebna pažnja je posvećena monitoringu kontaminacije ulja za podmazivanje i logici za detekciju otkaza. Izložena su neka praktična iskustva stečena pri realizaciji monitoring sistema na motoru vojnog borbenog aviona. Ukratko je predstavljen i poseban dijagnostički sistem logičkog zaključivanja na osnovu prethodnih iskustava iz domena održavanja vazduhoplovnih motora.

Ključne reči: **vazduhoplovni motori, održavanje prema stanju, magnetni detektor, monitoring sistem, sofisticirani dijagnostički sistemi, detekcija otkaza.**

Systèmes diagnostiques sophistiqués et leur application chez les moteurs d’aéronefs

Les systèmes diagnostiques moderns sont traités aussi bien que leur application pour la prévision de l’état et la défaillance chez les moteurs d’aéronefs. L’accent est mis sur le monitoring de la contamination de l’huile lubrifiante et sur la détection de la défaillance. Quleques expériences pratiques en réalisation d’un système de monitoring sur le moteur d’un avion de combat sont données. Un système diagnostique spécial du raisonnement logique basé sur l’expérience préalable dans le domaine de l’entretien des moteurs d’aéronefs est brièvement présenté.

Mots-clés: **moteurs d’aéronefs, entretien selon l’état, détecteur magnetique, système de monitoring, systèmes diagnostiques sophistiqués, détection de la défaillance.**