ON-CONDITION MAINTENANCE FOR NON-MODULAR JET ENGINES - AN EXPERIENCE

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Abstract

Using updated knowledge and gained experience in engine control and maintenance a specific on-condition maintenance concept of RD-33 engines installed on Yugoslav Air Force MiG-29s was developed in the middle of the 1990s.

The concept included two components: on-condition maintenance and periodic partial engine disassembling in order to establish mechanical condition of parts that had been affected by more serious problems in earlier operation.

1 Introduction

In most Air Forces, which have aircraft of the second and the third generation within their arms, predominant maintenance concept is the one in accordance with to fixed prescribed service life (hard time between overhauls-TBO). Upon expiration of TBO, engine and/or aircraft is forwarded to overhaul plant in order to be overhauled in accordance with prescribed technological operations. Such preventive maintenance procedure is the result of long-term estimation of non-failure operation of components and systems that essentially effect the flight safety (of value more hundred hours of running time or more years of operation), but without considering actual mechanical and thermal loads of individual engine/aircraft during operation. With certain safety margin, regardless of being necessary or not, aircraft and engines of the same type are overhauled after expiration of prescribed TBO.

However, continuous price increase of new fighters and their engines, spare parts, maintenance and usage, as well as the high prices of kerosene have generated modification of existing maintenance systems, as well as the development and the application of new maintenance concepts with application of aircraft and engine diagnostic systems. As known, a major problem in designing, development, establishing or modification of maintenance systems for applying to a high-speed jet fighter and its power plant is sudden change of operating conditions and operating environment, primarily temperature and vibrations levels, especially at low altitude flight. In order to establish effective system of aircraft and engine maintenance, it is necessary to provide sufficient relevant information on their status through application of appropriate diagnostic system.

In the middle of the 1990s, the concept of specific on-condition maintenance of RD-33 jet engines for MiG-29 fighters was developed and applied in Yugoslav Air Force due to expiration of prescribed TBO, which included two components: on-condition maintenance with discrete check of parameters condition and periodic partial engine disassembling in order to establish mechanical condition of parts that had been effected by more serious problems in earlier operation. Two benefits were realized by this: earlier maintenance system was changed and engine service life extending was performed.

2 Approach to problem

After thorough theoretical consideration of fatigue, crack origination and propagation, as well as the analysis of earlier experiences in aircraft engine maintenance [1], and in order to maximize the utilization of effective service life of RD-33 engine, former concept of fixed service life maintenance started to be replaced with on-condition maintenance. The following key theoretical-experiential criterion was established: to analyze possibilities and to define condition for continuous inspection and check of actual condition of engine systems, parts and elements, which would supply accurate and reliable information on their technical condition, on possible damage, on fatigue indications, on wear level, and other factors which might indicate probable failure in future period of operation, before new inspection was due.

Aforementioned criterion imposed the performance of the following:

- Analysis of foreign experiences in defining overhaul life and life of jet engines;
- Comparison of structural concept of modern Western engines and RD-33 engine;
- Analysis of own experiences in extending life of jet engines (defining equivalent testing cycle and total accumulated cycle of engine in a combat assignment function type);
- Analysis of all earlier failures and results of repairs before expiration of RD-33 engine operation life;
- Establishing the most critical parts and their effect to reliable engine operation, and establishing the most critical automation elements;
- Forming engine total accumulated cycle based on annual running times and the type of assignments performed by aircraft;
- Establishing relation between limitations imposed by manufacturer and TAC, i.e. hour operation life and number of TACs;
- Analysis of rationality of RD-33 engine earlier utilization from the aspect of consumption of set limitation;
- Defining type and content of inspection and needed equipment;
- Determining acceptable level of flow system elements damage and deviations of engine operation parameters;
- Defining program of engine operation check on test bed and test flight;
- Establishing time interval of due inspection and creation of appropriate technical documentation;
- Presenting the concept to competent level of decision making and obtaining official approval of concept application;
- Presenting concept to direct participants and operators;
- Continuous control of applied concept on concrete engines and its refinement.

3 Applied methodology and acquired experiences

Comparison of structure and comparative analysis of existing diagnostic equipment and applied procedures of maintenance of RD-33, RB-199, PW1120 and F-404 engines were performed as initial element of estimation of possible application of RD-33 engine on-condition maintenance. During aforementioned analysis, it was established that RD-33 engine, from technical-technological aspect, satisfied in large-scale prerequisites for establishing on-condition maintenance concept [1].

The basic problem was the lack of information on character and the number of allowed TACs during the life. Instead of them, the manufacturer introduced the following basic limitations in defining TBO:

- allowed hour operation in air Δ_1;
- allowed number of engine starting Δ_2;
- allowed hour operation on "maximal" and "reheat" ratings: Δ_3;
- allowed hour operation on "special" rating with increased temperatures: Δ_4;
- approved service life of accessories Δ_5.

By thorough operation analysis of each individual engine, it was established that, in spite of utilization of hour service life, prescribed limitations Δ_2 - Δ_4 were utilized in average of 65%, which explicitly indicated the conclusion that engines had certain reserve of usable service life.

Although RD-33 engine is not entirely of modular structure, as the one applied on Western engines, it was proved in practice applications that it could be conditionally divided into 8 modules, which are interchangeable without additional testing. This enabled introducing of differential life for engine modules and accessories, which is related to either hour service life or number of TACs.

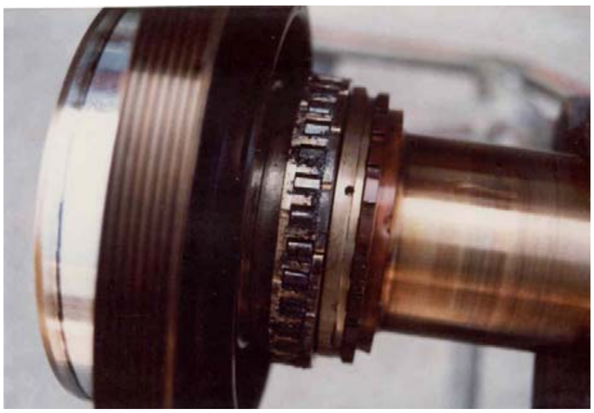

Fig. 1: An example of fourth bearing jamming.

When considering experiences in operation, as the most complex problems regarding RD-33 engines were identified those regarding multiple jamming of fourth bearing (Fig. 1), to which rests high pressure turbine, and those regarding burning of stator vanes (Fig. 2).

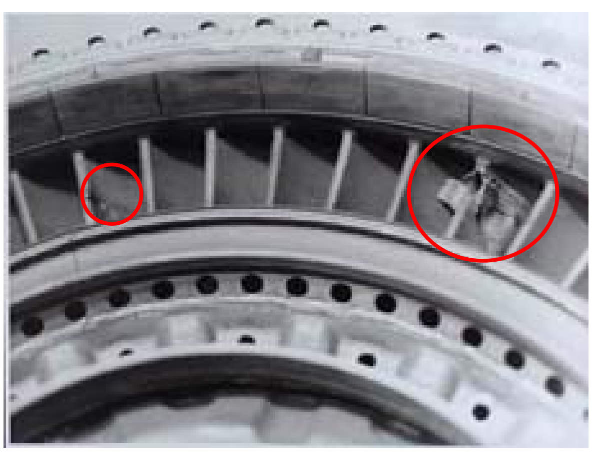

Fig. 2: Turbine stator vanes burns.

Regardless of complexity and seriousness of jamming of fourth bearing, it was decided to continue engine operation under condition that reliable mechanism of monitoring its condition was provided. It was estimated that the way of failure creation was not critical for flight safety, because it was of gradual character and could be controlled, and was characterized with the following indications: color change and higher oil consumption, increase of iron and graphite concentration in oil and shorter time of compressor rotor stoppage. The conclusion was reached that, by introducing new maintenance concept, in which bearing condition was monitored through introducing spectrochemical oil analysis, measuring vibrations and noise, the above-mentioned characteristics could be timely discovered and filed.

One of the main problems in turbine blades life prediction is a blade root crack initiation due to low-cycle fatigue. A formula that relates the low-cycle fatigue (LCF) damage to localized stress range is given in the following form:

$$Nf1_L = \frac{1}{2}\left(\sigma_L(\text{true}) - \sigma(\text{mean})\right)^{\frac{1}{(n-c)}} K^{\frac{1}{(n-c)}} Ef^{\left(-\frac{1}{c}\right)} \qquad (1)$$

where:

$Nf1_L$ - low-cycle fatigue life for blade (L), that is mean number of cycles to blade root crack initiation;

$\sigma_{L(true)}$ - localized true plastic stress amplitude at a blade root;

n - cyclic strain hardening exponent

c - fatigue ductility exponent

K - cyclic strength coefficient

Ef - fatigue ductility coefficient

The damage accumulated due to LCF may be given by a non-linear damage accumulation rule suggested by Gary Halford at NASA Langley 1996. [8]:

$$\text{Damage} = \left(\frac{n_1}{Nf1_L}\right)^{r_1} \qquad (2)$$

where:

n_1 - number of cycles experienced;

r_1 - non-linear damage exponent;

Nf1 - number of cycles to crack initiation.

The blade root crack initiation due to low-cycle fatigue is only one segment of the turbine blade prognostic. The complete turbine blade prognostic model must further account for the other failure modes at other critical locations on the blade, and introduction of TACs could be a good experimental substitute for such model.

3.1 Introduction of total accumulated cycle

In accordance with main principles of TAC calculation and limitations of RD-33 engine operation introduced by manufacturer, the procedure for defining TAC for RD-33 engine was started. Regarding that data on exact TAC and realized profiles of aircraft flights were not available at this time, it was decided to perform, in cooperation with pilots, complete analysis of annual training of MiG-29 aircraft pilots, and to convert all training elements of pilots into appropriate flight profiles into throttle lever shifting function. For this purpose, complete training was divided into 5 training elements:

- the first group included the assignments of interception and air-to-ground tasks;
- the second group included aerobatics;
- the third group included navigation flights, overflights, weather reconnaissance, and school circles;
- the fourth group included technical trials, accelerations and ceiling;
- the fifth group included air combat.

The following elements were defined for each group of exercise elements: number of exercise, total number of flights per exercise, percentage share of concrete exercise in total number of flights, total flights duration time per concrete exercise, percentage share of total exercise duration time in total running time, average flight duration, average number of TAC cycles per flight, total number of TAC cycles per exercise and average number of TAC per hour of flight. Based on these elements, a graphical presentation of flight profile in throttle lever shifting function was made for each exercise group. After acquisition of all data related to planned annual running time under defined groups of exercise elements, the most complex exercises were selected from each group of elements, and the analysis of 5 real flights for each of them was performed (using flight data recorder), and based upon which the conclusion was reached that deviations between planned exercises and real flights were within acceptable limits of 5%. In order to cover all possible deviations between planned and actually performed flights in each exercise, the calculation of TAC cycles [2] was performed including elementary type IV cycle:

$$\mathrm{TAC} = \mathrm{n\ x\ TAC\ Type\ I} + \mathrm{n\ x}\ \frac{\mathrm{TAC\ Type\ III}}{4} + \mathrm{n\ x}\ \frac{\mathrm{TAC\ Type\ IV}}{40} \qquad (3)$$

As the result, data were obtained for the following:

- average time of flight duration;
- average number of TAC cycles per flight;
- average number of elementary type IV cycles per flight;
- average number of TAC cycles per groups of exercise elements;
- share of elementary type IV cycle in engine TAC cycle;
- average number of TAC cycles per hour of flight, with and without elementary
- type IV cycles.

So obtained TAC of RD-33 engine clearly showed that the most intensive load of engine occurred in two training and flight stages: air combat (Fig. 3) and aerobatics. Regarding that in the moment of researching the possibility of expanding TBO the procedure for mastering overhaul of RD-33 engine in own overhaul works was initiated, valuable knowledge was reached regarding weak points of the engine flow system, as well as that of acceptable damage values, especially turbine stator vanes. It was concluded that engines on maximal operation rates are very loaded and the result of this was burning of turbine stator vanes, which additionally loaded operating blades and caused exfoliation of their coatings and initiation of cracks. For this reason, the decision was taken to reduce turbine temperature of all RD-33 engines by 20^{o}C by adjusting T4 temperature channel on the engine electronic control unit. This was one of the key factors, which enabled

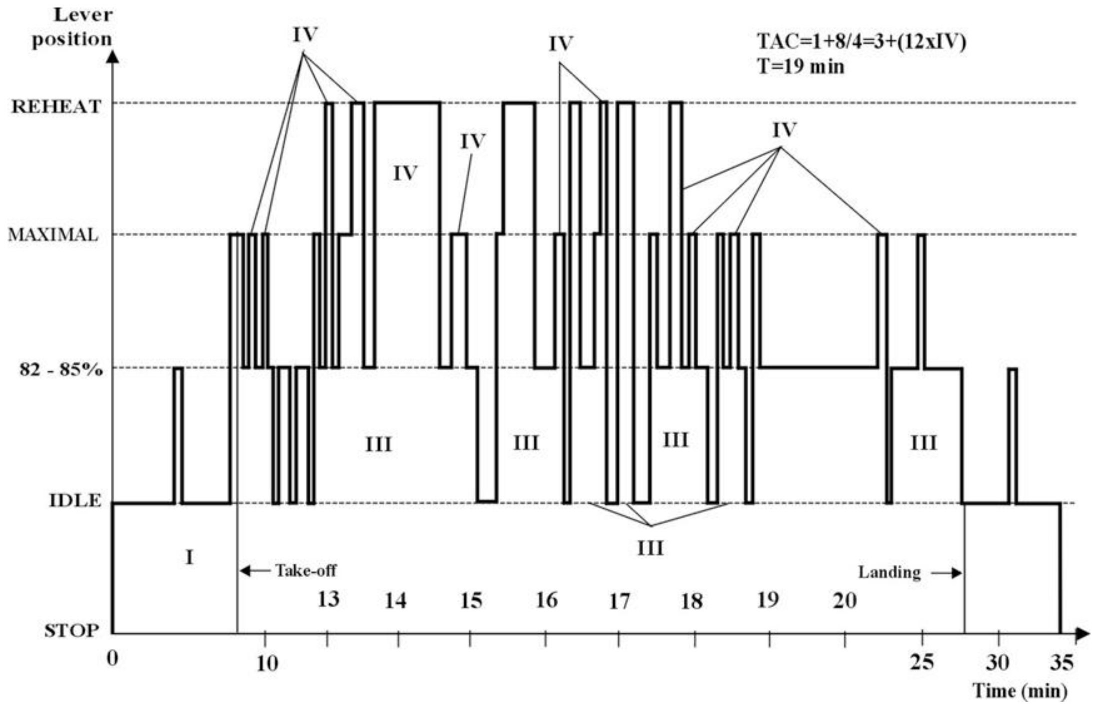

Fig. 3: An example of TAC representation for air-combat exercise.

turbine thermal unloading, and enabled further engine on-condition operation. Estimations and experimental confirmations on aircraft confirmed that the thrust was reduced by 3-4%, which created negligible (acceptable) effect to aircraft performances.

By integration into TAC of basic limitations prescribed by manufacturer, targeted engine service life, expressed in number of running hours function and in possible TAC numbers function, which was corrected against actual TAC of each engine separately, was defined. Such definition of targeted service life is necessary for planning annual running time of aircraft, load calculation of aircraft workshop capacity, and calculation of effective service life residue. The correction of targeted service life is performed in accordance with the following criteria: for each hour of saving prescribed operation on "maximal + reheat" ratings, targeted service life is extended by additional "n" hours, and for each hour of saving increased temperature ratings, targeted service life is extended by additional "m" hours [9]:

$$T_N\,[h] = T_P + \Delta T = T_P + [\Delta T(n) + \Delta T(m)] = T_P + [\Delta_{3\ rez}\,\delta_1 + \Delta_{4\ rez}\,\delta_2] \qquad (4)$$

Where: T_N – target TBO; T_P – prescribed TBO by manufacturer; ΔT – increased life; $\Delta_{3\ rez}$ – part of unused prescribed work at “maximal + reheat” regimes; $\Delta_{4\ rez}$ - part of unused prescribed work at the “Elevated Temperatures” regime; δ_1 and δ_2 - weight factors.

It should be noted that the engine service lives are not fixed any more, but a check of condition and evaluation of technical condition and parameters of engine operation is performed after utilization of 60 TAC (equivalent to 20-30 hours of engine operation), and based on performed analysis, further effective service life of 60 TAC is approved. At this, information on maximum possible effective service life residue of engine is always available to the user.

3.2 Importance of spectrochemical oil analysis

Spectrochemical oil analysis has very important role in diagnostics of engine condition [3]. Regarding that rotation of compressor rotor is running on oil film in thickness of 10 μm, oil should be of adequate quality, pure, and free of humidity. Experiences have proved that engine oil indicates engine appropriateness, and spectrochemical oil analysis converts the indications into valuable information, which help in making correct decisions on engine operation and maintenance procedures. An insight into the wear intensity of bearings, gears, filters and accessory box in engine oil system may be acquired, i.e. abnormal operation of some parts may be preventively discovered. During the on-condition maintenance concept implementation spectrochemical oil analysis contributed to the saving of 5 engines. Namely, the observable peaks of iron content, followed by increased zinc and nickel content and dirt undoubtedly indicated that the bearings of these engines approached the limit of safe use and that their jamming was unequivocal if operation continued. The engines were removed from aircraft by which more serious transmission damage was prevented and thus the costs of repair were considerably reduced. Experiences proved that standard form of spectrochemical oil analysis in laboratories that are distant from aviation base location in some cases do not provide satisfactory results. Namely, in practice, more problems occur in relation with inappropriate and non-timely oil sampling, and in more cases spectrochemical oil analysis had to be repeated, or the sampling interval had to be shortened.

In general, allowable limits of six key elements content in oil were established: iron, copper, nickel, zinc, chromium, and magnesium. Spectrochemical analysis has been proven as very effective method in engine condition monitoring, because its results timely indicate when the operating performance of components in lubricating system is degraded, and that appropriate procedures or maintenance procedures should be applied at certain level of metallic debris content.

3.3 The role of remote visual inspection

The most serious problem, when elaborating the concept and considering the possibilities of monitoring RD-33 engine condition, was how to provide reliable inspection of flow system – compressor, main combustion chamber, fuel injectors, and turbine, i.e. how to detect cracks, damage, exfoliation of protective coatings, vanes and blades burns, or corrosion traces, their actual sizes and the speed of their propagation on inaccessible components of engine flow system. In order to solve this problem, new modern remote visual inspection (RVI) equipment was purchased (videoimagescopes with CCD image sensor mounted in the end of the flexible probe and computerized video analyzer with inspection manager software). From CCD image sensor a picture is transferred to special liquid crystal display, or to special display mounted on the head of an inspector (Head Mount LCD), or to PC monitor, and at this, the picture may be zoomed, frozen and kept for subsequent analyses. It is also possible to enter numerical grid of stator vanes and rotor blades, which may be integrated with the picture from CCD "camera" and so measure actual length of detected cracks or damage. In this way, it is possible to establish the condition of engine flow system with high precision and reliability, detect cracks or damage on the bottom limit of detectability, monitor cracks propagation speed, forecast service life residue and timely undertake optimal maintenance procedures. The modern RVI equipment with CCD cameras provided objective inspection of the engine flow system condition, because it was enabled that: a few experts simultaneously watched inspected surfaces on the monitor; the condition of inspected surfaces was documented in a computer video-record format, subsequent thorough analysis of the condition of suspicious cracks or damage was performed, cracks lengths or other types of detected damage were measured. There are 13 bores that are used for the inspection of engine interior: 5 on low pressure compressor casing, 4 on high pressure compressor casing, 2 on combustion chamber, and 2 on turbine. For all parts of engine flow system, allowable limits are defined for crack size based on which further schedule of engine utilization is approved.

3.4 Integration of applied methodology

In order to monitor engine condition more reliably, distributed expert system consisting of three participants was introduced: Flight Unit,

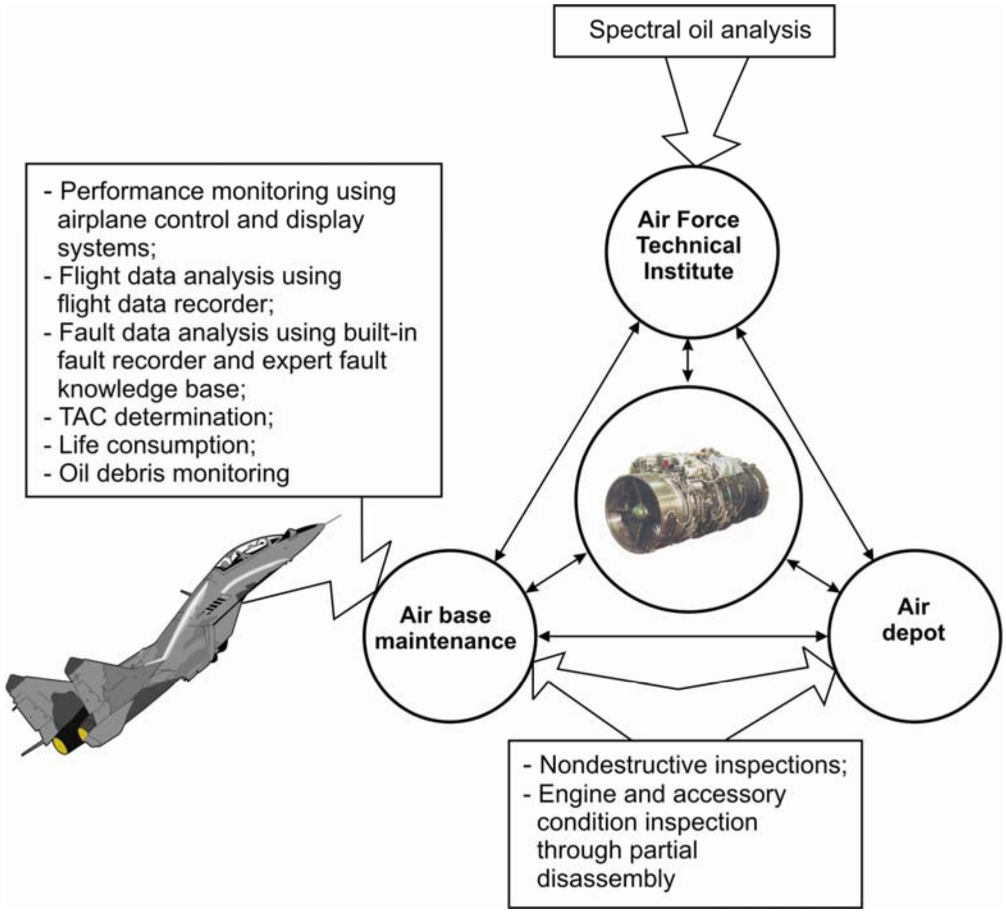

Fig. 4: Established distributed expert system for engine condition monitoring.

Air Depot, and Air Force Technical Institute (Fig. 4 and Fig. 5). Each of above-mentioned participants has precisely defined assignments and decision-making competence. Flight Unit performs continuous monitoring of engine condition parameters, additional RVI of main combustion chamber and high pressure turbine and updating of TAC; Air Depot performs inspection of engine condition with partial disassembling (RVI + other types of non-destructive testing) and evaluation of residual service life; Military Technical Institute performs spectrochemical oil analysis. On-line information exchange between members of distributed expert system is realized.

Key role in decision making on further engine serviceability has the expert knowledge base of typical failures, their symptoms and consequences, as well as data base of allowed length of cracks at turbine and compressor blades.

3.5 Preparation and training of personnel

Before initial application of on-condition maintenance concept of RD-33 engines, it was necessary to have professional discussion with pilots and aviation-technical staff, during which the concept postulation, possible risks, and responsibility of all participants in consistent implementation of all inspections, checks and monitoring of engine operation parameters were presented. At the same time, it was necessary to carry out the training of direct participants in the maintenance of RD-33 engine, to establish precise coordination of joint work of personnel from the first level of maintenance and Air Depot in performing inspection of engine condition, to provide conditions for comprehensive and undisturbed work of experts for the flight data analysis and planned performance of spectrochemical oil analysis. It

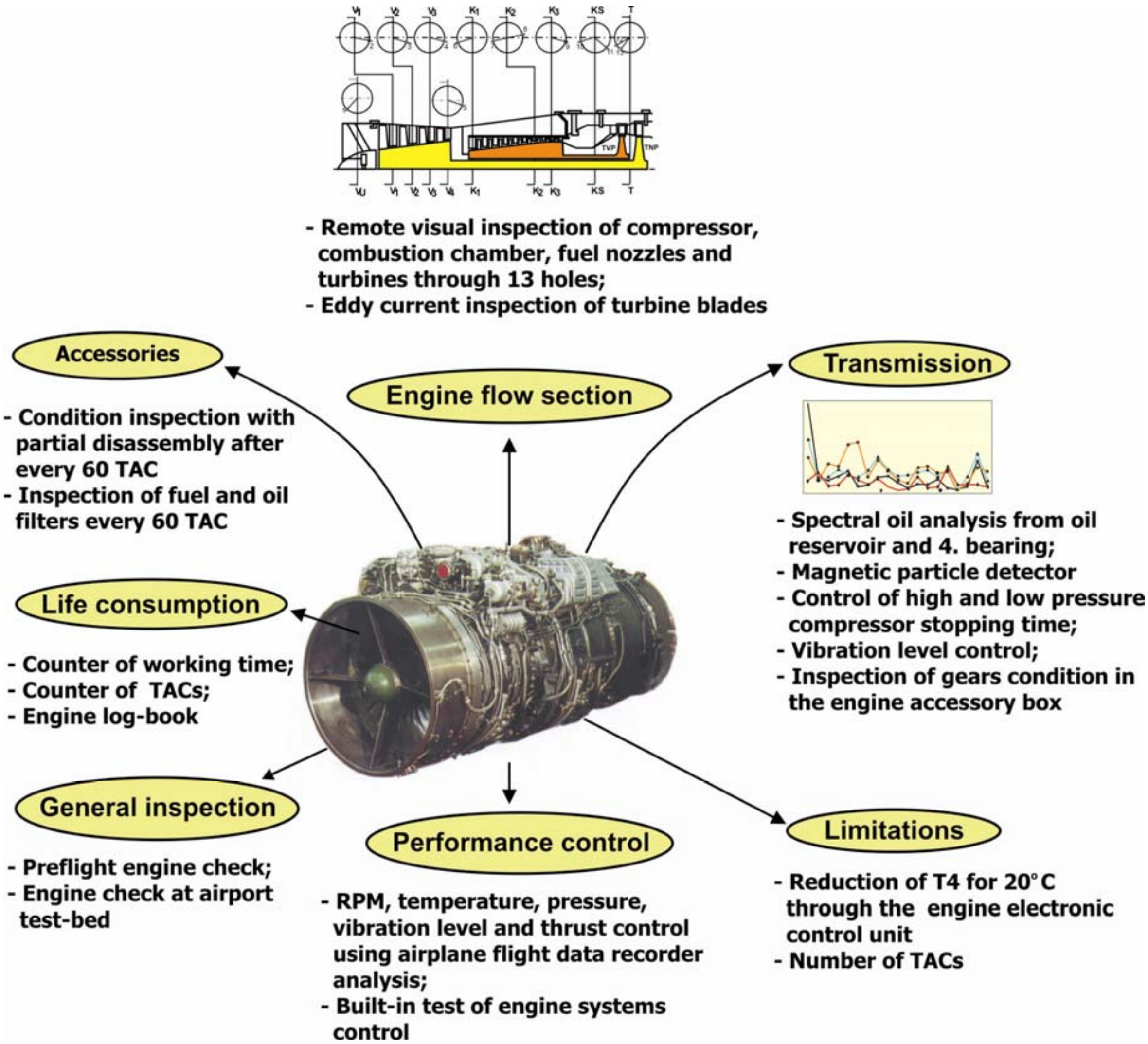

Fig. 5: Content of the engine on-condition maintenance procedure.

was decided that the leader of spectrochemical oil analysis were the laboratory of Air Force Technical Institute, which had available necessary equipment, experts for spectro-chemical oil analysis, and methods needed for evaluation of analyzed oil samples and for adjusting oil sampling schedule. The coordination of implementation of whole project was carried out at the highest level of aviation-technical service.

The analysis of flight parameters from aircraft flight parameter register is performed in two steps. The first step or so-called express analysis of parameters is performed by lap-top computer immediately after aircraft landing, between two flights, in order to check possible exceeding the values of engine running key parameters. The second step or detail analysis of flight parameters is performed after completion of flight day, and filing of necessary data and needed correction of TAC is performed during this.

Regarding unknown risk level in forecasting of the condition of parts and the reliability of correct choice of time intervals for inspection of engine hot parts, which existed when implementing on-condition maintenance concept of RD-33, it was decided to introduce additional safety reserve until final approval of the concept, which included fitting in redistribution of engine, i.e. the principle of combining one engine with extended service life and one with originally prescribed service life on aircraft was introduced.

4 Conclusion

Established on-condition maintenance concept of RD-33 engines with its diagnostic system satisfied its original purpose – it prevented disastrous failures and provided extending of engine service life. This concept has clearly demonstrated following advantages of the on-condition maintenance approach: controlled usage of engine life, introduction of life algorithm based on total accumulated cycles instead of hours, extension of earlier prescribed engine life by 50-60% and considerable savings.

Key role in its application had distributed expert system established in relation fighter regiment - Air Depot – Air Force Technical Institute. By introducing the algorithm of RD-33 engine service life, based on actual TAC instead of hour operation life, the extension of service life maintaining the same safety margin, valid evaluation of effective service life residue, and considerable maintenance cost reducing were enabled. One of significant deficiencies of aforementioned diagnostic system is limited forecasting capability of future condition of engine components, which is presently implemented based on experience rates. For this reason, it is necessary to upgrade existing diagnostic system by intelligent algorithm [4-7], which would be capable of recognizing failure modes automatically.

References

[1] Siladic M., Komljenovic D., and Milosavljevic D., Introduction of on-Condition Maintenance Concept for Turbofan Engine of Combat Airplane. *Proc International Aerospace Congress*, Belgrade, pp 22-27, 1995.

[2] Proposal for PW1120Y for Yugoslavia's Supersonic, Multipurpose, High Performance Combat Aircraft Program, U.T. Pratt & Whitney Aircraft, FP 84-614, 1984.

[3] Mishra C., and Muncherji S., Expert System for Wear Debris Analysis - a Powerful Tool for Condition Monitoring, Trends in NDE Science & Technology; *Proc 14th World Conference on Non-Destructive Testing*, New Delhi, pp 103-115, 1996.

[4] Tumer Y. I., Bajwa A., A Survey of Aircraft Engine Health Monitoring Systems, AIAA-99-2528, American Institute of Aeronautics and Astronautics, Inc., 1999.

[5] Siladic M., Pokorni S., and Rasuo B., Possibilities of Jet Engine Diagnostic Improvement by Using Neural Networks, *Proc XLVII Conference of ETRAN*, CD-Rom, Herceg Novi, 2003.

[6] Roemer J. M., Kacprzynski J. G., Advanced Diagnostic and Prognostic for Gas Turbine Engine. Risk Assessment, IGTI/ASME Turbo Expo, Munich, Germany, 2000.

[7] Zhernakov V. S., 2000, Diagnostics and Checking of Gas-Turbine Engines Parameters with Hybrid Expert Systems, *Proc Workshop on Computer Science and Information Technologies CSIT 2000*, Ufa, Russia, pp 227-234, 2000.

[8] Halford G.: Cumulative Fatigue Damage Modeling - Crack Nucleation and Early Growth, First International Conference on Fatigue Damage, 1996.

[9] Siladic M., *Life Management of Aircraft and Engines*, 1st edition, BB-Soft, Belgrade, 2007. (in Serbian)

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