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LIFE VALIDATION STRATEGY

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Abstract

The features of existing aero engine (or its major components) life assignment strategies are discussed: terms of application, advantages and disadvantages of each strategy. The attention is also given to the matters of special qualification of PD-14 engine materials, resulting in creation of materials mechanical properties Data Base.

PD-14 engine that is being extensively developed by OJSC "Aviadvigatel" in cooperation with other enterprises of OJSC "UEC" must pass the certification in Aviation Register of Interstate Aviation Committee in accordance with Russian Aviation Rules AP-33 [1] and then EASA validation in accordance with European normative documentation CS-E. Russian AP-33 are harmonized with European (and American) regulatory basis. The aero engine certification procedure is mandatory and is intended to ensure the required high level of aircraft flight reliability.

One of the essential provisions needed to achieving high level of flight reliability is to validate and to assign engine life and engine components life ensuring reliability of its operation.

During the operation the engine components are subject to factors such as loads and increased temperature, causing "damage accumulation" in components material. The term "damage accumulation" in this case means not forming of some defects like local cracking, peening or contacting surfaces wear. This term is used to designate the process of gradual loss of the component's ability to resist the effects of operational factors as the operation life extends.

Operational loads and temperature are characterized by change of their intensity during a flight, different time of duration in different flight legs and repeatability from flight to flight, i.e. the cyclicality of their effect. These features of loads application determine the process of damage accumulation in the components material. Besides, the determining mechanism of damage accumulation turns out to be different for different parts. Thus, for parts working under high loads and moderate temperatures – these are shafts and engine rotor disks – the cyclicality of load is the most important, which causes low-cycle fatigue of material due to its repeated cyclic elasto-plastic strain.

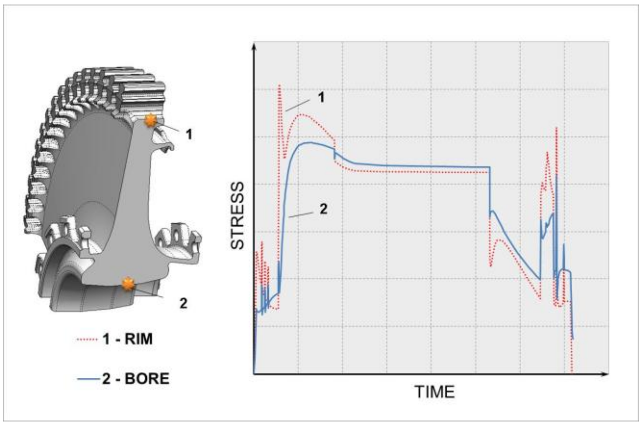

Fig. 1. Stresses in PD-14 engine turbine disk during flight cycle.

Life utilization of such parts is characterized by their "damage resistance" for one loading cycle, i.e. for one flight. Respectively, in this case life is assigned in cycles or permissible number of flights.

In parts working under high temperatures – these are the parts of engine "hot" section, mainly, turbine blades, – the material creep phenomenon appears under the effect of applied load, i.e. the accumulation of nonelastic strain in the course of operation.

Life utilization of such parts is characterized by their static or continuous "damage resistance" for one hour of operation. Respectively, the life of these parts is assigned in hours. The cases are possible when it is necessary to consider both of the above mentioned damage accumulation mechanisms in the material and to assign life both in hours and in cycles.

Life monitoring strategy includes the method of validation and assignment of engine reliable life and operation mode during this life. To date three life monitoring strategies are known [2].

The first life monitoring strategy was historically the first to be set and was applied to engines of earlier generations (for example, D-30, D-30KU/KP engines designed by OJSC "Aviadvigatel") having poor engine health monitoring and control systems. According to this strategy life was assigned to the complete engine taken as a whole. To validate life, endurance tests of a full-scale engine were carried out according to operation or equivalent-cyclic program. The engine was operated by phases with a fixed time between overhauls.

The economic failure of such approach under current conditions is obvious. First, the necessity to perform expensive endurance tests of a full-scale engine dictated unacceptably slow improvement of validated life. This affects adversely the life performance of the engine fleet and leads to slow growth of operation rate. Secondly, with fixed time between overhauls sometimes it is required to remove those engines which can be still operated if there is enough diagnostic data about its technical condition, which is economically unsound.

When the second life validation strategy was developed life validation costs and engine operation costs were significantly reduced. According to this strategy neither life nor fixed time between overhauls is assigned to the complete engine taken as a whole. Instead of that life is assigned to engine major components and engine operating time is limited only by the shortest life of any of its major components. The engine is removed for overhaul only based on readings of its health monitoring and diagnostic system. The life of engine major components is validated through their endurance tests at special-purpose stand-alone benches for separate components testing which are order of magnitude cheaper than the whole engine testing.

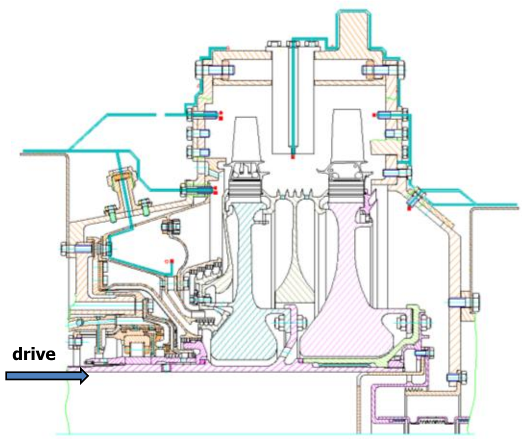

Fig. 2. Stand-alone bench for rotor testing.

Stand-alone bench tests are organized so that damage resistance of the components was reproduced, corresponding to their damage resistance under engine flight operating conditions. Endurance tests of a full-scale engine are substantially reduced in amounts and are carried out mostly to verify the workability of the design as such, i.e. rather to reduce risks at the initial stage of engine operation, than to validate its life.

The second life monitoring strategy is successfully applied for 4th generation engines (for example, for PS-90A engine designed by OJSC "Aviadvigatel" and its modifications). To make use of economic advantages of the second strategy it was necessary to fulfill a number of conditions that influence the flights reliability. First, PS-90A engine was equipped with a health monitoring and diagnostic system and in basis airports diagnostic laboratories were established to process flight data which is necessary to take decisions about the engine allowance for the next flight. Secondly, parts and components operating environment was thoroughly analyzed, secondary flows models were built and identified as well as models of engine parts and components transient thermal condition and models of parts stress-strain state kinetics during the flight cycle. Then, during life validation, these models were taken as a basis for endurance test procedures to simulate major parts stress at stand-alone benches separately from the engine. Finally, thirdly, a manufacturing company monitors major parts operating time; and in OJSC "Aviadvigatel" the plan of engine life monitoring was developed, according to which a number of high-time major parts is taken out of service for comprehensive study, when they worked a part of assigned life.

However, despite the advantages, the second strategy has also drawbacks. For PD-14 advanced engine being developed it is necessary to ensure the life of major components at the level of 20000…40000 cycles. In case of using the second strategy the question will arise not only about the time of verification the components' life, but also about the life of test benches themselves, because operating hours up to 100000 cycles and more will be required. Such big number of bench tests requires substantial costs and it will prevent intensification and extension of the engines operation. We see the way out in transition to the third life monitoring strategy.

In the scope of the *third strategy* life is also assigned only to major parts and engines are operated without fixed time between overhauls. The difference from the second strategy is that major parts assigned lives are established by so-called calculation method – without endurance tests. Thus, all the advantages of the second strategy remain, and it becomes possible to achieve high assigned life within a shorter period of time. But having validation based at calculations, flights reliability is achieved by meeting additional conditions.

Firstly, it is required to meet all the conditions of the second strategy application as related to the engine health monitoring and diagnostics, considering major parts operating time. Also it is necessary to develop three Life Monitoring Plans.

- Engineering and technical plan which stipulates the methods of life assignment for major components, determines "characteristic features" of each major component that influence life, and also specifies the required scope of development and certification testing;
- Production plan of manufacturing, which sets the process parameters influencing the life, and also stipulates which methods will ensure the reproduction of "characteristic features" established in the engineering and technical plan, during production of major components;
- Operation monitoring plan, which stipulates the means of control, the periodicity of technical analysis of operation results and gained experience, and also stipulates which measures will ensure the maintenance of condition of "characteristic features" established in the engineering and technical plan, during operation.

Secondly, it is needed to have complete statistically substantiated list of mechanical properties of every material used for major parts manufacture that is a data base of material properties defined at samples. It is worth noting that samples must be cut out of engine components' blanks, mass produced at the manufacturing enterprise supplying blanks for mass production engine. The most important part of this base, needed for life validation procedure, includes LFC curves and cyclic curves of material strain.

These characteristics must be defined at heavy loading of samples (cycle strain range monitoring) as this mode of loading is the most close to actual conditions of material application in parts critical areas. At present actually there are no such specifications for modern materials used in Russian aero-engine-building (including the materials of PD-14 engine being developed) and this gap is to be filled up.

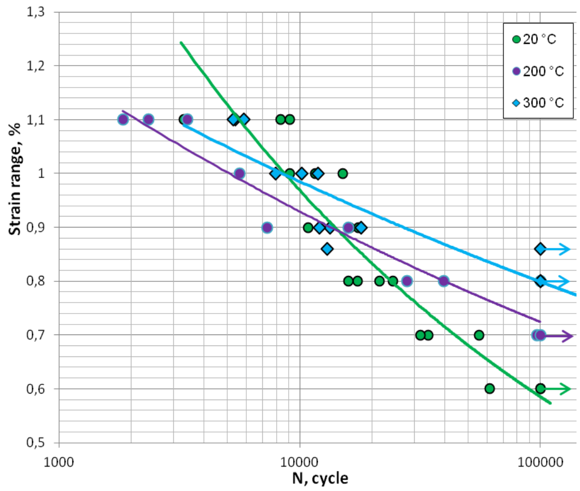

Fig. 3. Low-cycle fatigue curves of a titanium alloy.

It is necessary to note that the procedure of special qualification of materials both of major and critical engine components, resulting in creation of the Data Base, in accordance with harmonized Aviation Rules AP-33, is mandatory irrespective of life monitoring strategy applied. In this regard the works were commenced under the guidance of OJSC "Aviadvigatel" on special qualification of materials of PD-14 engine being developed. In the course of special qualification the following sample tests are carried out [3, 4]:

- tensile strength test (with determination of strain curve and short-time strength response);
- long-term strength and creep test;
- low-cycle fatigue test (with determination of LCF curves);
- high-cycle fatigue test (with determination of HCF curves, this characteristic is essentially important for compressor blades and engine turbines materials);
- fatigue crack growth rate test.

The full scope of material strength characteristics may be received based on the results of testing big number of samples, enough for obtaining statistically valid values of material structural strength characteristics. Namely, for each of materials of PD-14 engine "hot" section disks: the last stages of high pressure compressor and turbine, - approximately 1000 samples; for single-crystal alloy used for manufacturing of HPT blades – more than 1 600 samples. Considering that for PD-14 engine 22 materials are subject to qualification, used for manufacturing of 42 dimension types of blanks, it becomes clear that creation of the Data Base is a quite long, expensive and labor-intensive process.

An important moment in Data Base creation is ensuring persistently high quality of samples manufacturing which determines to a large extent the effectiveness of qualification tests and which is necessary to obtain minimum scatter of materials structural strength response being determined. For this purpose in Aviadvigatel an unique robotic cell was put into service which ensures, beside high quality of samples, their manufacturing in amount of 600-900 samples per month. It is this number which is necessary for Data Base creation for PD-14 engine within the target time frame.

At present the testing of PD-14 engine materials samples is in full swing in laboratories of OJSC "Aviadvigatel", FSUE "CIAM named after P.I. Baranov" and FSUE "VIAM" within the scope of the first stage of special qualification.

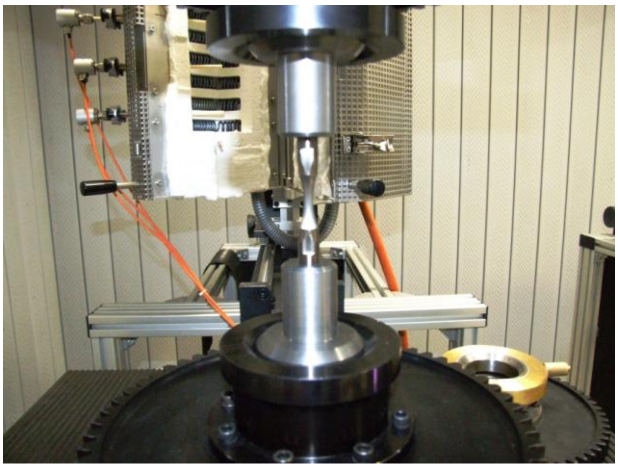

Fig. 4. High-cycle fatigue tests in the laboratory of OJSC "Aviadvigatel".

Returning to necessary conditions of using the third life monitoring strategy, we will name the last and a very important condition: experimental validation of life determination method must be performed. I.e. it must be shown that the calculation method allows to determine life correctly. To achieve this goal it is required to significantly improve the quality of simulating components stress-strain condition (SSC) kinetics during a typical engine flight cycle. The matter concerns the degree of confidence of all the data which take part in the final analysis of the part stress-strain state, namely: expected operating conditions (generic flight cycle parameters), thermodynamic model of an engine, aerodynamic and thermal models of parts and components, stress-strain state calculation models and material behaviour models. The feature is that in the second strategy the analysis of stress-strain state kinetics has a relative nature: calculations for flight cycle conditions always correlate with calculations for test cycle conditions. Meanwhile it was allowed to use simplified models of materials behavior, for example, to exclude materials strain curve dependence on cyclic operating time etc. It was acceptable because material properties are changed more or less similarly during the engine operation and during the component endurance tests on a stand-alone bench. For the third strategy such simplifications are not acceptable as it is required to consider actual variation of material properties depending on its operating time because those should be absolute calculations. It is also necessary to verify models of thermodynamic, aerodynamic, thermal and strength calculations. Validation of analytical models quality and substantiation of life determination methods are based on extensive use of results achieved during endurance tests carried out for the second strategy implementation.

Summarizing the review of life monitoring strategies as applied to PD-14 engine, it is necessary to note the following. Taking into account the tight schedule of development and certification of PD-14 engine and the time required for creation of materials mechanical properties Data Base in full, the only right decision on engine major components life validation strategy appears to be the following:

- at the engine certification stage use the second life monitoring strategy, based on equivalent-cyclic tests of major components on test installations and spin rigs;

- at the full-blown operation stage, as the Data Base is filled with necessary amount of material properties and as the level of confidence of calculation models, by which the assigned life value is determined via the third strategy, increases, pass to the third life monitoring strategy.

Considered all, adoption of the third strategy is connected with sufficient expenditures for purchasing test machines fleet, creation of materials mechanical properties data base and experimental substantiation of life determination strategy. But perhaps it is the only way, having reasonable time spending, to validate huge life values required for modern engines. According to the available experience, sufficiently complete special qualification of one material takes near two years (in case of developed samples manufacturing), and it gives the opportunity to confirm at once life of all the components manufactured from this grade of material and from a single dimension type blanks. This will significantly reduce the costs associated with endurance tests of components. The third strategy application will make it possible to extend engines operation more rapidly.

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