LOOK ACADEMIC PUBLISHERS
OPEN ACCESS

INTERNATIONAL JOURNAL OF ENVIRONMENTAL & SCIENCE EDUCATION
2016, VOL. 11, NO. 4, 3832-3846

Cycle Counting Methods of the Aircraft Engine

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ABSTRACT

The concept of condition-based gas turbine-powered aircraft operation is realized all over the world, which implementation requires knowledge of the end-of-life information related to components of aircraft engines in service. This research proposes an algorithm for estimating the equivalent cyclical running hours. This article provides analysis of the existing methods of cycle counting and suggests a new original method. It implies consideration of two cycles related to the chain of extrema "max - min – max". The first is the main simple loading cycle; another cycle is the additional from the minimum to the lowest extrema. It is assumed that the "global" minimum is known. The authors developed the algorithm aiming at allocation of separate simple loading cycles in a complex life cycle, implemented by using Visual Basic for Applications and Excel'97. The paper also provided the method of bad records rejection and evaluation of the stress-strain behavior of the main engine components – drive shafts, discs and blades based on regular measurements of temperature and pressure in the gas stream. These methods allow calculating the accumulation of damage on a real-time basis. The developed algorithms laid the foundation for an automated diagnostic system of an aircraft engine.

KEYWORDS
Aircraft gas-turbine engine, loading cycle counting, condition-based operation, cyclical running hours, diagnostic system

ARTICLE HISTORY
Received 21 April 2016
Revised 14 June 2016
Accepted 22 June 2016

Introduction

Operation of gas-turbine engines (GTE) in aviation or industry is carried out in various modes and under different external conditions determined by the region, season, life cycle etc.

The main factor affecting the loading and, accordingly, the end-of-life of the main GTE components, is its operation mode, which is characterized by the power output for industrial gas turbines or thrust development for GTE. Considering the typical profile of civil aircraft, it includes a number of "binding" modes, which are shown in Figure 1.

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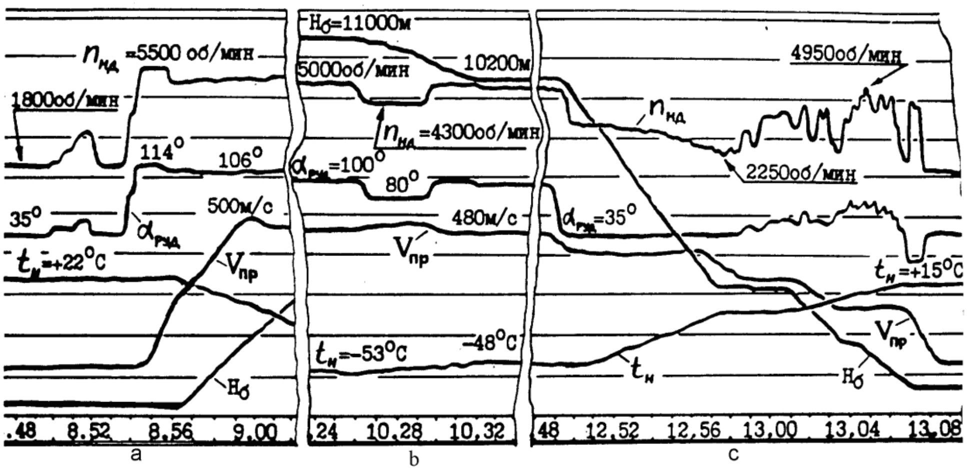

Figure 1. Typical changes in civil aircraft engine modes in flight: a - takeoff taxiing; takeoff; climb; b - en route cruise; c – descent operation, landing approach, landing, reverse thrust.

Most of the GTE components work under multi-mode and multi-component loading (Krivenyuk, 1990; Aronson, 1990). Typically, they work under the impact of prolonged static loading of centrifugal and gas forces, often at high temperatures, and the low cycle loading. This is determined by the start, stop or change in the operating mode described above.

In the condition-based operation, all GTEs should be equipped with automated diagnostic systems (ADS), which provide verification of their technical state. In general, the operation structure of the ADS GTE complex can be described by the scheme presented in Table 1.

Table 1. ADS GTE operation scheme

The operation structure of ADS GTE complex			
Inspections and regulations, including non-destructive methods of control	Built-in control sensors	Automated GTE bench-run tests	End-of-life assessment of the main details

One of the ADS components is presented by the automated end-of-life control systems in relation to the main parts of the engine.

With the increase in engine life, more emphasis is laid on the low-cycle loading resistance, associated with the cycles: start and stop of the engine, changes in the operation mode during its life cycle. In addition, each loading cycle is different and is characterized by its stress level, depending on the GTE operating conditions, the asymmetry of cycles, temperature, duration of the maximum loads, the level of vibration loads (Tzeytlin & Fedorchenko, 1980; Kuznetsov, 1989).

The engine life is also determined by its dynamic loading, which largely depends on various designs of the dampers. The study (Falaleev, Chaadaev & Diligenskiy, 2014) provides a method of selecting the required type of damper for the rotor, and the research (Novikov, 2014) proposed a method for calculating the fluid flow in the damper.

Literature Review

In the modern world, special attention is paid to improving the technical level of gas turbine engines and machines, their efficiency, reliability, and mean time between failures (Herrera, Yepifanov & Loboda, 2011). The extension of the operational life of gas turbine engines is a relevant problem, as is the accurate assessment of the technical state by the data provided by the registration of thermogas dynamic and vibrational parameters during operation (Varadan & Varadan, 1999; Kudva, Grage & Roberts, 1999). Modern studies focus on improving the strategies of gas turbine engine resource management, including the problems of building adequate diagnostic models and methods for assessing the changes in the parameters of gas turbine engines, etc. (Hached, 2014; Harvey, 2015).

The experimental assessment of low-cycle endurance in laboratory conditions was carried out mostly with “simple” cycles – symmetric and repeating-stress. Therefore, in order to assess the end-of-life of parts that operate under complex strain programs, it is necessary previously to schematize the complex operating cycle with a set of simple symmetric and asymmetric cycles.

There are very few methods for reducing a complex cycle of strain change to an equivalent sequence of simple symmetric and asymmetric cycles (Baklacioglu, Onder & Hakan, 2015). With that, different schematization methods can produce significantly different results if the total accumulated damage is assessed by fatigue exhaustion with random strain.

The use of maximum method implies definition of the simple cycle stress amplitude by all positive maximums of the “complex” stress change cycle (Birger, 1984). It is assumed that the initial cycle is symmetrical with respect to some medium level. The mean stress value σ_m may be regarded as guideline value or defined as $\sigma_m = \sigma_{\max} / 2$, where $\sigma_{\max}$ – maximum stress value. Maximum method can provide substantially higher values of the cycle range, which accordingly will lead to the unreasonable over-estimation as regards predicted value of the running hours.

The use of the level crossing method implies definition of the simple cycle stress amplitude as the largest extremum between the two medium-level intersections (Kogayev & Drozdov, 1991). This method does not take into account the asymmetric cycles, which are fully above or below the medium-level loading, which can lead to underestimation of the equivalent cyclical running hours.

Using the amplitude method implies definition of the “simple cycle” amplitude as half of the increment between adjacent extrema of the "complex" loading cycle (Mouhat, Khamlichi & Limam, 2015). It does not take into account the medium-level loadings of the "simple" cycle. Its disadvantage is that in some cases, for example in the case of a "sawtooth" or a "steplike" increase in loading, or in the case when one or more intermediate cycles are performed before switching the take-off mode, this method does not allocate the loading cycle from a "global" life cycle minimum to its "global" maximum. However, this method can more accurately consider insufficient changes in the engine operating conditions.

Using the full cycle method (Vronsky, 2004), implies definition of the "simple" cycle amplitude as half of the increment of the "complex" cycle between two adjacent extremes (minimum and maximum of the process) with a gradual elimination of intermediate cycles with increasingly higher values of stress amplitudes. The amplitudes and the number of excluded cycles are recorded. Medium stresses in cycles are not considered.

Using the full cycle method implies definition of the "simple" cycle amplitude, which is similar to the full cycle method, with regard to the medium-level stresses of "simple" cycles (Yepifanov et al., 2013).

Using the half-sum and half-difference method (range-pair-range count with regard to the medium stresses) method implies definition of the "simple" cycle amplitude, which is similar to the amplitude method, with regard to the medium-level stresses of the cycles (Wiseman & Guo, 2001).

Method of extended range-pair-range count method implies calculation and comparison between the damaging effect of the «simple" cycle defined by the method of intersection, and the aggregate of intermediate "simple" cycles defined by the amplitude method (Bartelds, 1997). After comparison, the option having greater damaging effect is selected.

The "rain" method (Cowan & Winer, 1999) and the full cycle method (Kulyk, Kucher & Miltsov, 2011) most thoroughly consider "simple" cycles. Both of these methods give almost identical results. The disadvantage of both methods is that their application requires knowledge of the entire history of loading. Therefore, the "rain" method and the full cycle method can be used only for post-flight information processing, recorded during the flight or operating cycle, and may not provide assessment of equivalent running hours on a real-time basis.

The end-of-life assessment systems operate on a real-time basis, therefore, it is advisable that more practical methods providing allocation of simple cycles be used, for example, the half-sum and half-difference method. This method is simple and requires a minimum amount of memory for data storage. However, the half-sum and half-difference method has the same disadvantages as the amplitude method - it cannot identify the main loading cycle from the "global" minimum to the "global" maximum, which causes the main defect of a complex life cycle - its share usually exceeds 50 % of the equivalent low-cycle running hours during the flight. This can happen when one or more intermediate cycles are performed before coming to takeoff power. This happens virtually every time when the pilot uses main engines during takeoff taxiing.

Nowadays, there exist all the prerequisites – methodological, algorithmic, and software support, to improve the accuracy of assessment of the technical state of aviation and industrial gas turbine engines.

This can be achieved by improving the diagnostics techniques, which should include the diagnostic models of gas turbine engines, obtained from the data of bench tests and operation, and modern methods of trend analysis. The technical means of the automatic diagnostics system enable using improved algorithmic and software support based on universal and certified software. Considering the drawbacks of existing methods for schematizing the complex operating system with a system of simple cycles and, consequently, assessing the equivalent cyclic life during operation in real time, the improvement of respective techniques based on experimental data and the development of applied software becomes especially relevant, which outlines the prospects for further research.

Aim of the Study

The aim of this study is to develop a method of schematization of the operating cycle of strain change, with a view to assessing the life of gas turbine engines during operation by their technical state.

Research questions

Development of an algorithm for assessing the equivalent cyclic life using the schematization of complex operating cycles, the parameters whereof are recorded in real time. The development of an algorithm for distinguishing individual simple strain cycles in the complex operating cycle.

Method

The End-of-Life Control Systems in Operation

Possible methods of the end-of-life control over the GTE parts in operation are shown in Table 2. Each of these methods has its advantages, disadvantages and applications. The common drawback is their high cost and low durability. Most often, these methods are still in the pilot production stage.

Table 2. The end-of-life control systems in operation

The end-of-life control systems in operation			
Damage sensors	Systems measuring the change in the physical characteristics of the material	Systems registering working conditions of components	Systems registering changes in propulsion parameters

Therefore, their use in the operating conditions is limited, and they are used primarily in factory production control.

Having regard to the above, the calculation methods for the end-of-life assessment of the engine components based on registration of operating conditions are of particular importance (Astafiev, Fedorchenko & Tzypkaikin, 1996).

The complex of automated end-of-life assessment can be developed with regard to the assessment of cyclical running hours of basic engine components and its comparison with the permissible values, verified through experiment. The assessment of the equivalent cyclical running hours should be carried out with regard to the fact that each operating loading cycle has its maximum level of stress and multicomponent values of the real loading: the temperature effect; cycle asymmetry; maximum stress duration; applied vibrational load (Coffin, 1976).

The approximate assessment algorithm of the equivalent cyclical running hours is given (Fedorchenko, 2014). This process starts with measuring engine parameters (step 1), rejection of bad parameters (step 2), and concludes with identifying the equivalent cyclical running hours (step 7).

The assessment algorithm of the equivalent cyclical running hours:

1. Checking sensors of propulsion parameters.

2. Rejection of bad propulsion parameters.

3. Isolation of elementary loading cycles from the complex life cycle.

4. Determination of the minimum and maximum temperatures of design section of components – t_{min}, t_{max} in the cycle extrema.

5. Determination of design section stress – σ_{Σ} in the cycle extrema.

6. Determination of the temperature and asymmetry coefficients of the i-cycle: $K_z^i = \sigma_{max}^i / \sigma_b^t$, $r^i = \sigma_{min}^i / \sigma_{max}^i$, where r^i - cycle asymmetry influence coefficient, σ_{max}^i - maximum stress in the cycle, σ_{min}^i - minimum stress in the cycle, σ_b^t - long-term strength at the i-cycle temperature (this value is defined by the results of statistical analysis of the operating conditions of the fleet of engines).

7. Summation of equivalent cyclic running hours - $Z_{ECT} = \Sigma Z_i$

This algorithm involves the end-of-life assessment of the engine components through the influence coefficients of the low-cycle temperature durability, maximal stress duration and the asymmetry of cycles (Fedorchenko, 2015).

The value of maximum permissible running hours in operation could be determined by the value of cyclic running hours, verified in terms of relevant assurance coefficients during engine rig tests: $[Z]_{EXPL} = Z_{ECT} / K_z$, where Z_{ECT} – the equivalent low-cycle running hours during engine rig tests.

The above algorithm for assessing the equivalent running hours in operation experience in operation is not unique. There are other algorithms for assessment of equivalent GTE running hours based on its measured operating parameters.

Data, Analysis, and Results

Isolation of the elementary loading cycles from the complex operational cycle

Experimental evaluation of the low-cycle durability in vitro is generally carried out with regard to the "simple" form of cycles - symmetric or to the zero-to-tension stress cycle. Therefore, in order to carry out end-of-life evaluation of components operating at complex loading programs, one should first schematize the complex life-cycle by the sequence of simple symmetric or asymmetric cycles. This could be performed through cycle counting methods in relation to complex operating cycles.

These methods aim at replacing the "complex" life cycle of stress changes by a certain amount of "simple" cycles, determining their amplitude, loading frequency and the degree of damage according to the criterion of the low-cycle durability exhaustion. The "simple" cycle in this regard refers to the loading cycle, the damage from which can be estimated by the results of standard tests for low-cycle fatigue, and the degree of the life-cycle damage accumulation can be determined upon the hypothesis of damage summation. Different cycle counting methods may give significantly different results in the case of estimating the total accumulated damage with regard to the exhaustion fatigue provided random loading.

Therefore, the GTE cycle counting method should reflect specificity of its work, providing objective data in relation to the degree of low-cycle durability exhaustion of the engine components and should provide the possibility of using the computer. In this regard is seems expedient that realization of this method be carried out on a real-time basis.

Rejection of bad values of the measured parameters

The parameter values obtained directly from the measuring sensors may be bad for a number of reasons, which may lead to errors in the calculations. Therefore, rejection of bad values is important in the implementation of the said algorithms. In order to save computing resources rejection of bad parameter values must be carried out prior to the calculation of stress and thermal state of the component and its equivalent running hours.

The simplest and the most effective method used for rejection of bad values is the method of sample censoring.

Selection of the number of measurements in the sample requires consideration of the following limitations:

- small N value increases the likelihood that the sample will include more than $N/2$ bad values;

- large N value increases the likelihood of extremum "smoothing" in the sample, which will result in the underestimated value of equivalent running hours.

In practice, the N value is selected in such a way that the sample size does not exceed half-time of the engine thrust response. For typical thrust response values of the GTE engine (6…10 s.), report rate - 0.1…0.5s., the N value is chosen within the interval of 5…10 values. Such sampling size does not introduce errors in the assessment of the equivalent cyclic running hours and reliably rejects the random peak errors of parameter measurements.

Table 3 shows the calculation results of the equivalent cyclical running hours during landing in real flight operation of the engine with different number of measured points of the N sample - (report time - 1s, thrust response time - 10 s.).

The data presented in Table 3 show that the sample size has significant impact on the value of the equivalent cyclic running hours, and the optimal sample size makes half-time of the engine thrust response pickup.

Table 3. The results of processing the real flight engine cycle

Sample size N	1	3	5	7	10
Value of equivalent cyclic running hours Z	0.574	0.545	0.543	0.470	0.493

Assessment of stress and thermal state of turbine blades

As a rule, the GTE operational life is determined by the rotor parts: blades and disks of compressors and turbines, therefore, registration of their working conditions require setting special sensors and current collectors. Such systems have short life time and their setting for serial production of the engine is not always possible. Therefore, it is particularly preferable to use systems, which give the possibility to determine stress and temperature status of engine components through the measured engine parameters and to assess running hours with regard to these parameters. As regard turbine blade, the formula for determining stresses in the most loaded point can be generally presented in the following form:

$$\sigma = \sigma_{tens} + \sigma_b + \sigma_c + \sigma_t \quad (1)$$

where σ_{tens} - tensile stress from centrifugal forces; σ_b bending stress of the gas and the centrifugal forces; σ_c torque stress arising in section of a twisted rod in the area of centrifugal and gas forces; σ_t thermal stresses from uneven temperature field in blade sections, respectively. The proposed calculation formula (1) is based on the blade strength calculation method, based on the theory of flexible twisted rods developed by I.A. Birger (1984).

Figure 2 shows the results of a static strain measurement of the cooled rotor blades of the blade wheel during its testing on acceleration bench and the calculation results of their strain pursuant to the theory of naturally twisted "rods"; Table 4 shows stress values. It is evident that the "rod" theory provides fairly accurate results in the root sections of the blade. Comparison of the calculated stresses in turbine blades according to the "rod" theory with finite element method (FEM) also shows good convergence of results.

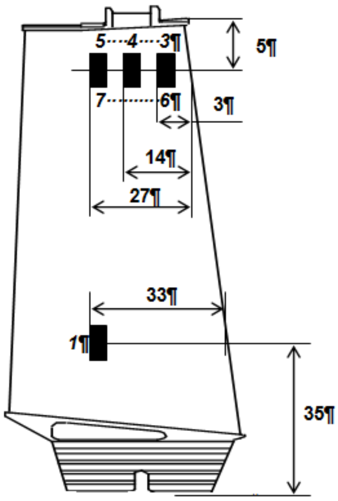

Figure 2. Comparison of the calculated and measured stress in the cooled working blade during tests on acceleration bench. Strain sensors 1, 3, 4, 5 are located on suction side; strain sensors 6 and 7 – on the pressure side.

Table 4. Stress values in the blade shown in Figure 2

Stresses at n=10000 rpm

Strain sensor No.	calculated σ_{calc}, MPa	measured, $\sigma_{measured}$, MPa	$\varepsilon = \frac{\sigma_{calc}}{\sigma_{measured}}$
1	233	275	0,84
3	75	-5	15,0
4	145	63	2,3
5	84	150	0,56
6	84	275	0,31
7	93	240	0,39

The specific section of a working blade determined by the equation (1), can be also expressed as follows:

$$\sigma = b_1 n^2 + (b_2 P_2 + b_3 n^4) + b_4 (t_{\max} - t_{\min}) \quad (2)$$

where n - rotation, P_2-pressure behind the compressor, $t_{\max}$, $t_{\min}$ - maximum and minimum temperature in the considered blade section; b_1, b_2, b_3, b_4 - constant coefficients, determined by approximation of a number of exact solutions of the blade stress state for all operating conditions of the engine.

Exact solutions of the blade stress state can be provided by FEM or by the theory of naturally twisted rods used in the calculation of the normalized operation life of the blades.

The temperature in the design section of the turbine parts can be measured with regard to the measured parameters of the engine by means of simple computational and experimental dependencies, based on a thermodynamic model of the engine. As regards engines with a cooled turbine, one should consider possible changes in the cooling conditions in the modes which imply the "full" and "partial" cooling.

For example, as regards the cooled parts, the authors can offer an interpolation formula for determining their temperature as follows:

$$t_{\partial} = T_4 k_1 k_2 \Theta_1 - k_3 \Theta_2 T_2 \quad (3)$$

where k_1, k_2, k_3 - coefficients taking into account the temperature in the nozzle diaphragm of the first turbine stage or at the previous turbine stages, the difference of the local gas temperature from the bulk temperature, the difference between the cooling air from the air temperature behind the compressor, respectively; Θ_1, Θ_2 - heat transfer coefficients from air or gas to the engine component; T_4 – gas bulk temperature before the turbine; T_2 – air temperature behind the compressor.

Measuring the gas temperature directly before the turbine causes a number of problems associated with the performance and durability of thermocouples in high-speed gas flow with high temperature and pressure. Therefore, it is advisable that the total gas temperature before the turbine $-T_4^*$ be determined by the calculation method based on a thermodynamic model of the engine, by measuring the gas temperature behind the turbine, the temperature in the atmosphere and the flight speed by using relatively simple computational and experimental formulas, namely:

$$T_4^* = T_4(t_a, M, t_6) \qquad (4)$$

where t_a - ambient air temperature; M – flight Mach number; t_6 - measured gas temperature behind the turbine.

According to the known gas temperature behind the turbine and air temperature behind the compressor (ambient gas temperature and cooling air temperature), it is possible to determine the temperature of almost all GTE components by using formulas such as (3) and (4).

The dependencies (2), (3) and (4), which determine stress in the elements of the engine with regard to the main parameters of its operation, in conjunction with the developed methods of loading cycle counting and rejection of bad results gave the possibility to create an automated system. This system detects the end-of-life of the engine components in real time operation and, therefore, this diagnostic system, increases operational reliability of aircraft engines.

Development of the cycle counting method of a complex life cycle by using a system of simple cycles

Given the drawbacks of the known cycle counting methods of a complex life cycle by using a system of "simple" cycles and relevant assessment of the equivalent cyclical running hours on a real-time basis, the study offers description of the developed method of GTE life cycle counting by using the sequence of "simple" cycles, based on the half-sum and half-difference method, which is implemented on a real-time basis.

In the proposed method, the simple loading cycle is taken as change in loading from the minimum to the subsequent maximum, with regard to the minimum and maximum cycle stress.

Loading cycle counting is shown in Figure 3, where n_a - amplitude rotation, t -time indicated by figures 1, 2,…5 – rotation maxima, 1', 2,…5' – rotation minima.

In addition, each "simple" loading cycle is characterized by its temperature, duration of exposures to maximum stresses, minimum and maximum stress level, and the value of applied vibration load.

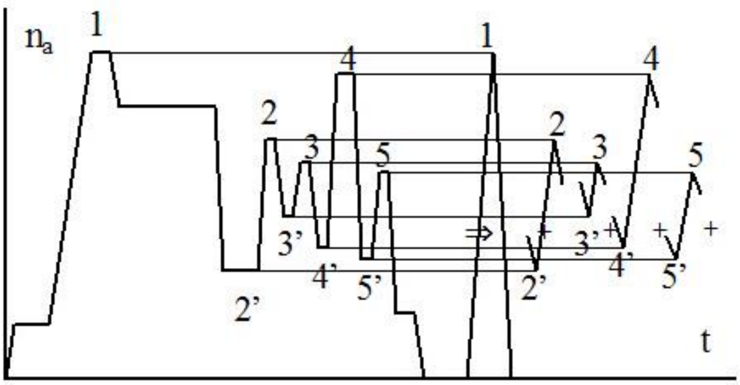

Figure 3. GTE loading cycle counting using the system of simple loading cycles

The main point of the proposed method lies in the fact that using the information on three consecutive extrema of a random process (two maxima and one minimum), i.e., on the two potential "simple" cycles, and a known value of a "global" minimum, one can reliably determine the main loading cycle and the sequence of other "simple" cycles.

Selection of the main and additional simple loading cycles with regard to the sequence of three extrema is shown in Figure 4. Damages in the selected cycles are calculated, added to the already accumulated damage, and this information is "forgotten".

Control-flow chart showing allocation of separate simple loading cycles in the complex life cycle with regard to the proposed method is shown in Figure 5, where N_i indicates rotation, which corresponds to the i^{th} moment of time. Indices 1, 2, 3 refer to the appropriate modes: maximum, minimum, and again maximum. Testing of this method shows that it reliably identifies the "global" maximum and the results of calculations by this method almost always coincide with the calculations made with regard to the "rain" method.

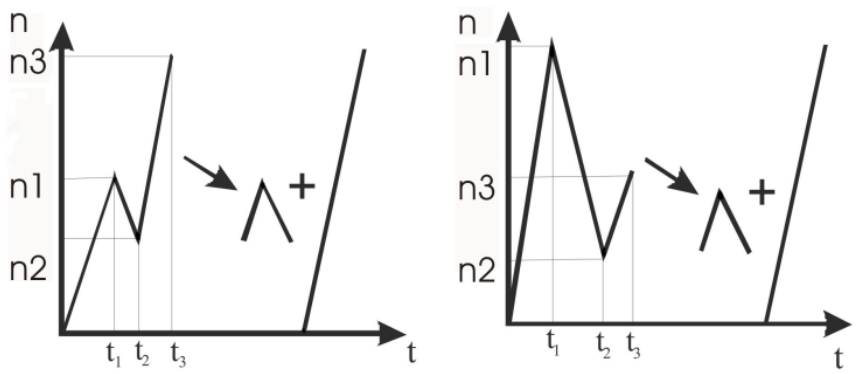

Figure 4. Possible allocation of the main and additional simple loading cycles with regard to the sequence of three extrema

The proposed method, in contrast to the "rain" method does not require information on the entire life cycle and, therefore, allows the selection of "simple" cycles on a real-time basis.

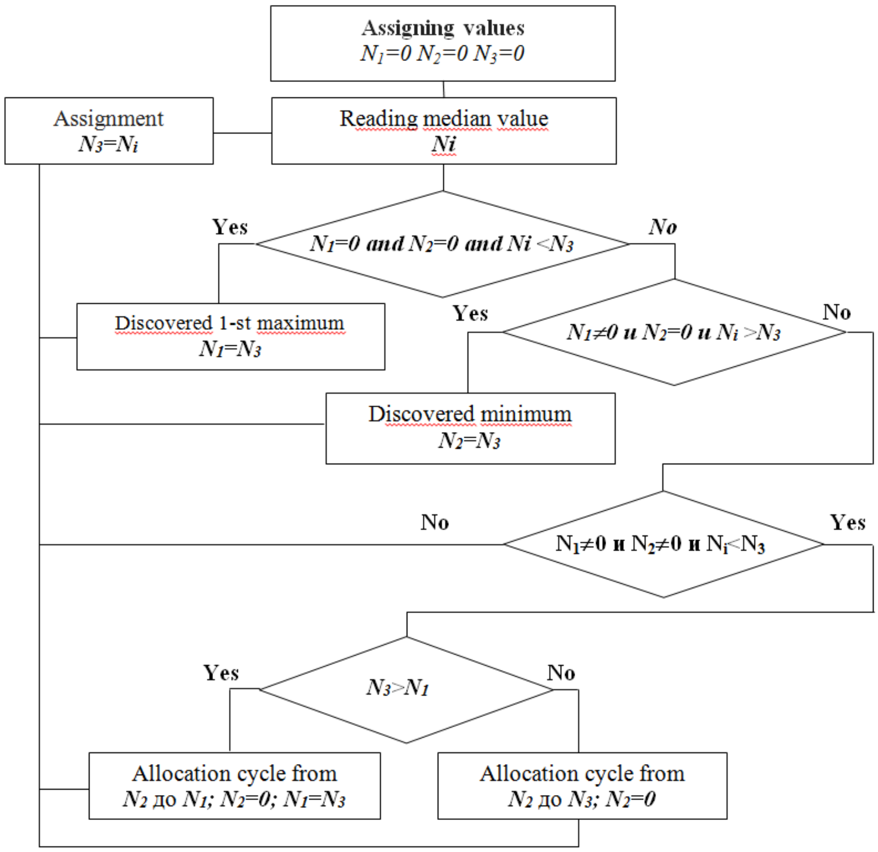

Figure 5. Flowchart of the algorithm for distinguishing "simple" cycles

Discussion and Conclusion

Currently, the countries producing aviation equipment, are actively developing and using ADS of aircraft engines (Herrera, Yepifanov & Loboda, 2011; Hached, 2014; Harvey, 2015; Baklacioglu, Onder & Hakan, 2015). Considering the drawbacks of existing methods for schematizing the complex operating system with a system of simple cycles and, consequently, assessing the equivalent cyclic life during operation in real time, this research offered a description of the development technique for schematizing the operating cycle of a gas turbine engine with a sequence of "simple" cycles, based on the real time semi-sum-semi-difference method.

The obtained results provided the development of aircraft engine ADS, which structure is shown in Table 1. The developed system has a number of specific features. The developed cycle counting algorithm in conjunction with rejection of random variations in the measurements is the basis of the end-of-life assessment complex and provides the possibility to count the number of stress change cycles.

The developed techniques for calculating the stress-strain state of the main engine components blades, drive shafts, and wheels based on measurements of the engine parameters and the approximation of the numerical results of calculation by polynomials, depending on temperature, pressure and rotation are verified by relevant experiments. These techniques provide calculations of damage accumulation on a real-time basis.

The civil aircraft engine ADS was created on the basis of relevant developments. In this system, flight information recorded by multi-channel aircraft recorders is processed on the ground (in the diagnostic laboratory) in the course of turnaround analysis.

Modern aircraft are equipped with airborne monitoring and control (AMC), which solve a number of diagnostic problems of diagnosis directly in the flight mode. These systems provide the information on the current state of the engine and on arrival at the airport of location one can take a prompt decision on the flight tolerance of the aircraft. Currently, the system of monitoring and diagnostics of the modern promising engine, has been developed, which is based on the use of AMC and the ground-based ADS.

Implications and Recommendations

This paper showed advisability of using more economically efficient methods of simple load cycles allocation in the end-of-life assessment systems operating on a real-time basis.

The authors analyzed the existing cycle counting methods and suggested a new original method. It implies allocation of two cycles from a “max - min – max” sequence of extrema. One of these cycles is a simple loading cycle. Another cycle is the additional cycle from the minimum to the lower of the two maxima. It is assumed that the "global" minimum is known.

The developed method does not require information regarding the entire operation cycle and allows selecting the "simple" cycles on a real-time basis. It also provides the possibility to carry out separate summation with regard to the main and additional simple cycles, which is determined for a number of engines.

The study provides techniques for calculation of the stress-strain state of the main engine components - blades, drive shafts, and wheels based on the measured engine parameters and the approximation of the numerical results of calculation by polynomials, depending on temperature, pressure and rotation verified by relevant experiments.

The obtained techniques give the possibility to determine the "equivalent" running hours of GTE in operation, which provides a more objective approach to their technical condition assessment and, consequently, increases reliability, and life cycle for the specific engines.

The developed cycle counting methods and techniques of the stress-strain state calculation in conjunction with the methods of bad values rejection provided ADS development for the aircraft engine being in operation. These methods and techniques laid the foundation of the ADS development for the new promising engines for civil aircraft and terrestrial power plants.

Disclosure statement

No potential conflict of interest was reported by the authors.

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