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# METHODS OF COUNTING AIRCRAFT TURBINE ENGINES OPERATING CYCLES

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Abstract

*The issue of low-cycle fatigue is very important in terms of operational safety of aircraft turbine engines. This paper discusses methods, which are used in US aviation industry to determine boundary cycle counts, as well as methods of counting turbine engine operating cycles allowing to determine the residual safe operation time (hard time), expressed in cycles. Methods are discussed, which are used for both older types of engines as well as for present-day ones.*

*In the paper titled „Zmęczenie niskocyklowe konstrukcji i jego minimalizacja" (Low-cycle structural fatigue and its minimization), published in volume no. 199/2009 of Prace Instytutu Lotnictwa (Proceedings of the Institute of Aviation) contains a schematic presentation of loads acting on components in the „hot section" of an aircraft turbine engine, as well as loads' operational dependencies on engines' operating conditions and operating ranges affecting their low-cycle structural fatigue. The paper pointed out that findings related to this type of loads had caused engine safe operation times to be expressed both in hours as well as in cycles. Methods for determining the number of cycles „utilized" by main engine modules and their important parts affecting operational safety, as well as maximum limits of operational cycle which if exceeded should require replacement of respective modules or individual parts had been imposed on operators by engine manufacturers. They are initially determined basing on fatigue tests performed on standard specimens of structural material and then based on fatigue tests of production parts and tests of complete engines. This paper is a further development of these previously discussed topics.*

*Keywords: aircraft engine, turbine engine, low-cycle fatigue, cycles number*

## 1. METHODS OF THE BOUNDARY CYCLE COUNT DETERMINATION

In US aviation industry, tests are performed of passenger aircraft engines, during which at least 1.000 typical engine operation cycles are simulated under normal operation conditions. During each cycle the engine must run for a specific time in the takeoff range, in the reversed thrust range as well as in the idle (cooling) range prior its shut-down (see fig. 1).

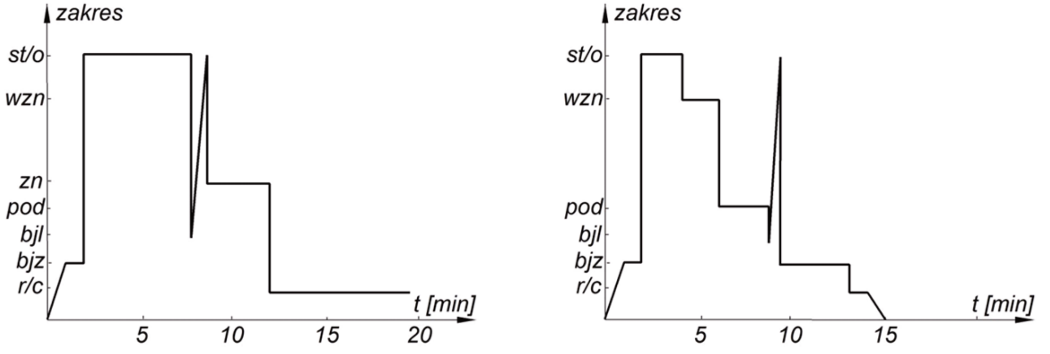



Fig. 1. Sample passenger aircraft engine operating cycles recreated during tests (each test consisting of 1000 cycles) in order to simulate typical operating cycles during engine's operation under standard conditions. Engine running ranges are identified as: *r/c*–start-up or cool-down, *bjz*–ground idle, *bjl* – flight idle, *pod*– approach, *zn*–descent, *wzn*–climb, *st/o*–max. takeoff or thrust reverser mode

In case of engines of multipurpose combat aircraft, in order to determine the limit number of cycles, currently tests based on engine operation conditions typical for military missions are begin used. At the same time, in order to reduce duration of tests, engines are being run during these tests only within these ranges, which are significant for the fatigue wear process, i.e. periods of engine operation in the idle and cruise range, which occur during each mission, are accordingly reduced (Fig. 2).

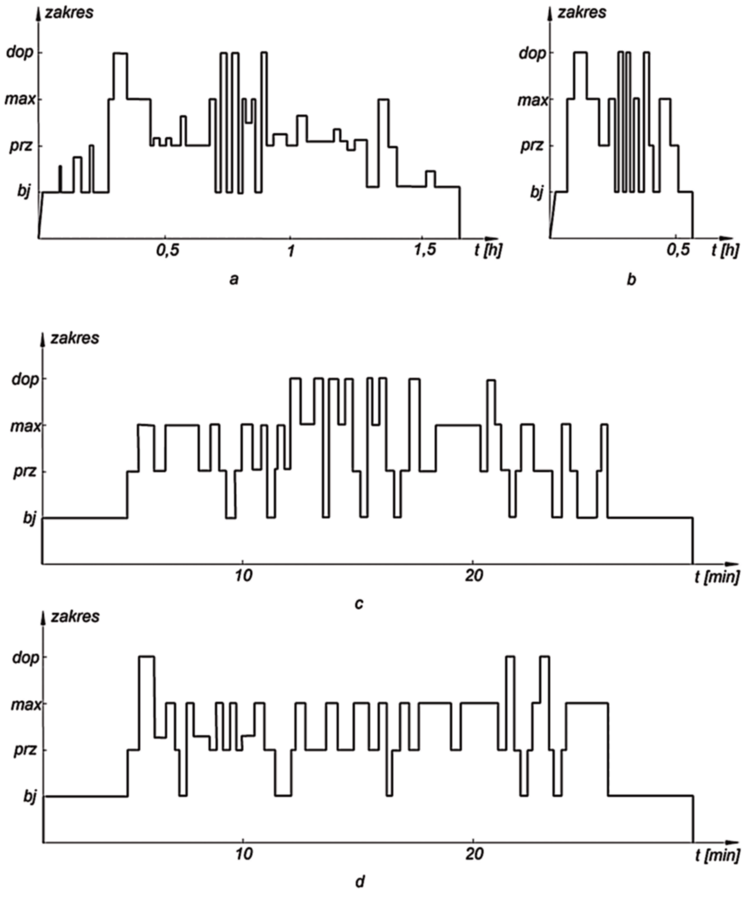
In case of propeller engines and helicopter engines, in order to determine their low-cycle fatigue life, instead of such shortened tests based on analysis of missions, special-purpose tests with individual cycle durations of 15 minutes, according to the program presented in tab. 1 [3] are being performed.

Tab. 1. Steps of a low-cycle test of propeller engines and helicopter engines used in US Aviation

| Engine operating range | Duration [s] |
|---|---|
| **Start-up** | **30** |
| **Idling** | **120** |
| **Acceleration to the maximum range** | **6** |
| **Maximum range** | **150** |
| **Deceleration to the idling range** | **6** |
| **Idling** | **180** |
| **Acceleration to the maximum continuous range** | **6** |
| **Maximum continuous range** | **150** |
| **Deceleration to the idling range** | **6** |
| **Idling range** | **120** |
| **Cool-down and engine shut-down** | **126** |

For a high-pressure turbine's disk in such engine, the probability of fault-free operation is assumed to be at the level of 99.9%. Utilizing the probability distribution function and relevant multipliers, it has been determined that one may assume the fatigue life of such disk to be equal to e.g. 4000 cycles, provided that for three disks tested performed fatigue tests allowed to achieve at least 36630 fault-free operating cycles for each disk, i.e. by an order of magnitude more than the manufacturer-specified life[1].

This indicates that current methods for determining the safe number of fatigue cycles require further test work and specifications.




zakres = range

Fig. 2. A method of incorporating fatigue-related loads, based on the analysis of a combat aircraft engine's operating ranges in a typical mission (a) shortened engine test (b) example test corresponding to air combat (c) and combat support missions (d). Engine operating ranges are identified as: *bj* – idling, *prz* – cruising, *max* – maximum without afterburning, *dop* – maximum with afterburning

[1]This indicates that current methods for determining the safe number of fatigue cycles require further test work and specifications.

Tab. 2 presents numbers of operating cycles which are being currently assumed during preliminary engine design stages, for various aircraft types in USAF.

Tab.2. Number of operating cycles currently assumed during engine preliminary design stages for various aircraft types in USAF

| Aircraft type | Engine modules | Type I cycles | Type III cycles | Type IV cycles | Afterburner or thrust reverser deployment |
|---|---|---|---|---|---|
| fighter | I…C<br>CC…ES | 3200<br>1600 | 20000<br>10000 | 24000<br>12000 | 17000<br>8500 |
| bomber | I…C<br>CC…ES | 2700<br>1350 | 30000<br>15000 | 30000<br>15000 | 16000<br>8000 |
| transport | I…C<br>CC…ES | 10000<br>5000 | 14000<br>7000 | to be determined | not applicable |
| trainer | I…C<br>CC…ES | 15000<br>7500 | 150000<br>75000 | 150000<br>75000 | |
| helicopter | I…C<br>CC…ES | 15000<br>15000 | not applicable | not applicable | not applicable |

The type I cycle referred to in the table involves engine start, reaching its maximum range without afterburning or with afterburning followed by the engine shut-downType III cycle involves transition from idling to maximum rev range without afterburning or with afterburning and return to the idling range. Whereas the type IV cycle involves a transition to the cruising rev range and to the maximum range, without afterburning and then return to the cruising range.

## 2. METHODS OF ENGINE CYCLES COUNTING

From the perspective of aircraft engine exploiters, it is necessary to precisely determine a method for counting operating cycles occurring during engine operation. A single, complete engine operating cycle shall be understood as its starting-up, transition to the maximum range (takeoff range) and shut-down. In case of commercial aircraft engines, during a single flight the engine, with all its parts in ambient temperature, is first started up and then for a brief moment it warms up until temperature distribution of its parts and components stabilize and until all clearances and fits between matching parts are brought up to standards. While taxing and while waiting for takeoff, the engine continues to run in its idle range or in a similar revs range. Afterwards, during takeoff and climb phase of the flight it reaches its maximum or near-maximum range. On the longest leg of the flight the engine runs within the cruising range, which is then reduced during the descent and landing phases, finally reaching the idle range. In the final phase of the engine operation, thrust reverser is enabled and then the aircraft taxis to the parking area, where the engine is left to cool down, shut down and brought down to the ambient temperature. For an engine operated in this regime, one may assume, by approximation, that during each flight one full operating cycle is performed.

In case of engines of multi-purpose combat aircraft, due to their different in-flight use regime, it is also necessary to take into consideration partial changes of engine parts' and assemblies' loads, which are important values of the complete cycle. In aviation industries of various countries, various methods for operating cycles counting are used.

In case of older engines, cycles are often counted „manually", by the technical staff, using simplified formulas or even using predefined cycle „utilization" values in relation to flight hour, depending on the aircraft mission (see Tab. 3).

Tab. 3. Conventional operating cycle utilization figures expressed in flight hour, according to the aircraft mission type. Source: Rolls-Royce

| Mission type |
|---|
| team aerobatics |
| training |
| bombardment or firing at ground targets using machine guns |
| supporting land forces |

In latest engine designs, cycles are counted by dedicated ground computer systems fed with data from FDR’s or directly by engine monitoring systems installed onboard the aircraft.

One of the first developed operating cycle counting methods, based on FDR data, is used primarily by US Air Force. In this method the number of so-called cumulated operating cycles is determined using the following formula:

$$c_{TAC} = c_{LCF} + \frac{c_{FTC}}{4} + \frac{c_{CIC}}{40}$$

where:
$c_{LCF}$–is the number of type I cycles, $c_{FTC}$–is the number of type III cycles, a $c_{CIC}$–is the number of type IV cycles.The cumulated operating cycles counting method is used, for example for F100-PW-229 engines of F-16. In German Air Forces, for Panavia Tornado's RB199 engine, another cycle counting method is used. This is the so-called Rain-Flow method. In this method (its name depicts similarity of the calculation procedure to the effect of a raindrop flowing down a pagoda roof), one selects such amplitudes of stress changes from recorded data, above which (an imaginary) rain drops would flow (see Fig. 3).

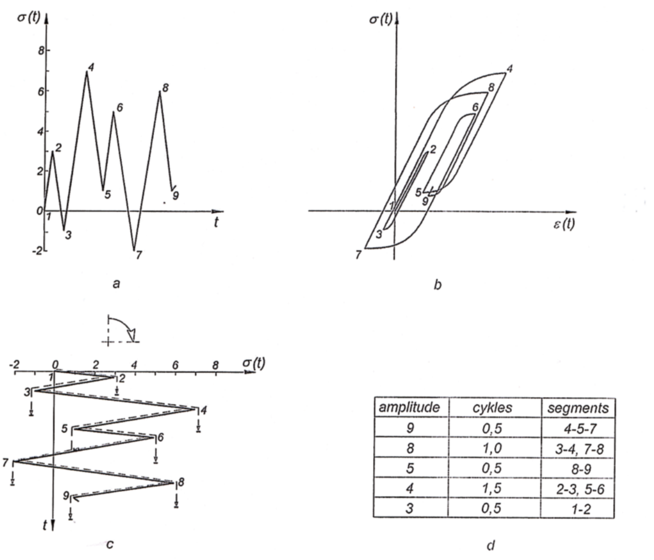



Fig. 3. Rain-Flow fatigue cycle counting method: *a* – change of stress in time, *b* – changes of fatigue cycles in time, *c* – diagram illustrating how water would flow from a pagoda roof formed by the "*a*" diagram rotated 90˚, *d* – determined cycle counts

Water is poured on each fragment of an imaginary roof at its topmost point, whereas the part which extends the furthest is being considered first. From it water flows down to lower parts of the roof, until a point where it can freely reach the imaginary ground. The amplitude of the cycle stress is depicted by the horizontal distance between the initial point of a water drop and the point where it reaches the earth. If a drop of water flowing from the next starting point does not flow off a piece of roof but it rather contributes to the water stream flowing from higher parts of the roof, then the stress amplitude is equal to the distance between the drop's start point and the point when it meets the water stream incoming from above.

Another and somewhat simpler method of counting fatigue cycles is the so-called Reservoir method, in which the graph of stress changes in time „is flooded with water" (see fig. 4) and then water is drained at its lowermost points (indicated on fig.4 with scissor symbols).

The height of the column of the water flowing out describes the cycle stress. By successively emptying the reservoir by releasing water at its lowermost points, the number of cycles with stress amplitudes equal to heights of water columns in individual parts of the reservoir is counted.

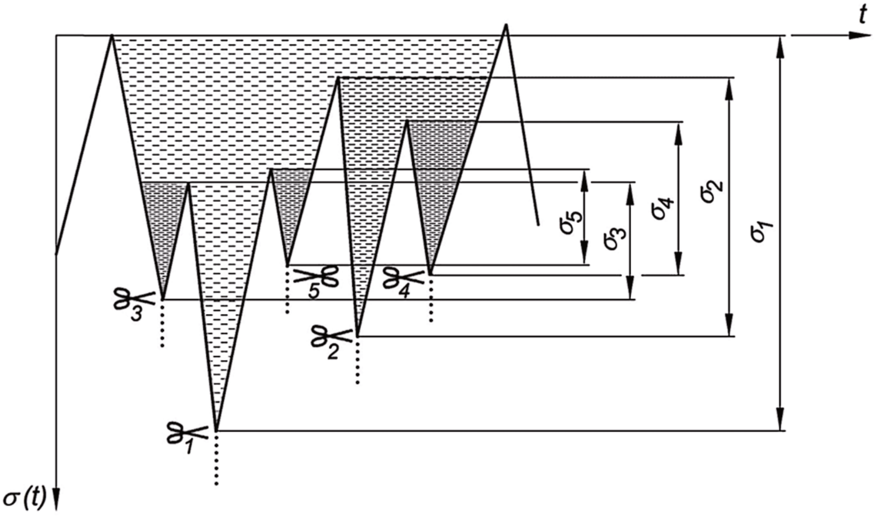



Fig. 4. Diagram illustrating the method of fatigue cycle counting in the so-called Reservoir method: $\sigma_i$ – stress amplitude, $t$ – time (scissors symbols indicate successive water draining” points)

Both methods produce the same results.

For the RB199 engine an algorithm of low-cycle fatigue life calculation has been developed, which utilizes in-flight recorded rotor speed.

First, the relative speed of the rotor is calculated as a fraction of the maximum speed without afterburning

$$\bar{n} = \frac{n}{n_{100\%}}$$

next, using the Rain-Flow method, minimum (nmin ) and maximum (nmax ) speed values are isolated for each cycle from the FDR. Next, for each cycle, its maximum and minimum stress values are calculated, which are proportional to respective rotational speeds:

$$\sigma_{\min} \sim n_{\min}^{2}, \sigma_{\max} \sim n_{\max}^{2}$$

and then, threshold stress values are determined $\bar{n} = \frac{n}{\ }$ which correspond to the maximum permitted speed ngr (e.g. such, at which the rotor would break apart) and maximum allowable stress values for an unlimited fatigue life (above 106 cycles) are calculated $\sigma_{nieogr} = p \cdot \sigma_{gr}$ where *p* is the value expressing the specified stress ratio of

$$\frac{\sigma_{\text{nieogr}}}{\sigma_{\text{gr}}}$$

Next, using the Goodman's formula, equivalent stress of a cycle is calculated:

$$\sigma_r = \frac{\sigma_{gr} \cdot \left(\sigma_{\max} - \sigma_{\min}\right)}{\left(\sigma_{\text{gr}} - \sigma_{\min}\right)}$$

Then, damage value corresponding to a specific rotational speed of the rotor is determined:

$$D = \left( \frac{\frac{\sigma_r}{\sigma_{\text{nieogr}}} - p}{\frac{1}{\sigma_{\text{nieogr}}} - p} \right)^m$$

where m is determined using Wöhler's curve gradient in lg $\sigma$ (lg C) coordinates.

In case of the RB199 engine, calculations for the LP and HP rotors are performed independently, assuming accordingly *ngr*=120%, *p*=0.55 and *m*=3.5 for the HPR and $n_{gr}$=130%, p=0.4 and *m*=2 for the LPR (fig. 5).

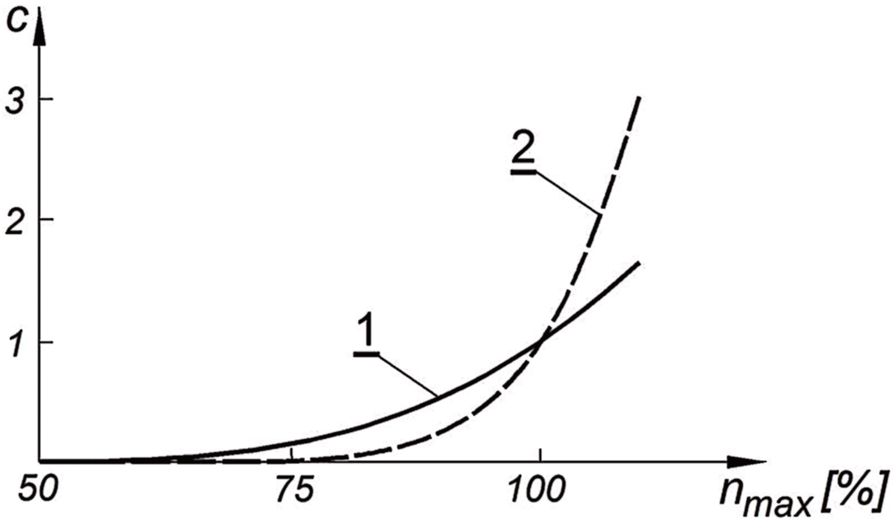



Fig. 5. Dependencies of fatigue cycles utilization c and the maximum speed *nmax* of the LPR (1) and the HPR (2) of the RB199 engine in a certain operating cycle

The graphs shown on fig. 5 indicates, that for speeds of rotors lower than max., utilization of fatigue cycles is higher for LPR's than in case of HPR's.

## CONCLUSION

Awareness of fatigue life–related issues of aircraft turbine engine parts and methods of counting operational cycles utilized by such engines certainly has a significant impact on flight safety. The choice of the correct engine operational cycle counting method becomes even more difficult, as turbines in particular are subject to time-variable mechanical loads (resulting primarily from the rotational motion of rotor elements as well as from changes of their speeds), but also thermal ones due to uneven heating of their parts. Another problem is that depending on changes of the engine operating range, mechanical and thermal loads may be phase shifted with respect to each other.

In case of multi-rotor engines, utilization of fatigue cycles of each rotor is different and must be calculated independently. In operating ranges lower than max., HPR's utilize less cycles than LPR's. It shall be expected that a specific methodology will be developed for determining the number of fatigue cycles safe for engine's structure, which would take into consideration flight conditions impacting temperature distribution in the most vulnerable engine parts (such as: turbine disks), and that means not just speed of rotors, but also their variable cooling performance, which depends on the altitude H and the speed V of an aircraft.

Of course data on utilized cycles as well as forecasts regarding engine's continued safe operation would depend on the design of each engine type–as the same airframe may be equipped with many engine types. Many aircraft are designed with the option permitting installation of various engines with similar specifications, e.g. on aircraft such as Airbus or Boeing, engines from Pratt&Whitney, Rolls-Royce or General Electric (SNECMA, CFMI, IAE) can be alternatively used. The same applies in case of F-16, which may be equipped with various types of Pratt&Whitney F100 engines or General Electric F110 engines.

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# METODY ZLICZANIA CYKLI PRACY LOTNICZYCH SILNIKÓW TURBINOWYCH

*Streszczenie*

*Zagadnienie zmęczenia niskocyklowego jest bardzo istotne z punktu widzenia bezpieczeństwa eksploatacji lotniczych silników turbinowych. W artykule przedstawiono sposoby wyznaczania granicznej liczby cykli stosowane w lotnictwie USA, a także metody zliczania cykli pracy silnika turbinowego w celu określenia pozostałości czasu jego bezpiecznej eksploatacji (resursu) wyrażonego w cyklach. Opisano metody wykorzystywane podczas użytkowania zarówno silników starszych typów, jak i współczesnych.*