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Tracking Initial Cracks in Turbojet Engine Disks and Possibilities of Postponing their Occurrence

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The first stage disk of the low pressure compressor rotor of one turbojet engine was observed in this paper as a critical component. The maintenance costs of the engine were increased due to premature initial cracks in this disk and subsequent interventions. The probabilities of occurrence of initial cracks on two types of the observed disk were described in the paper by Weibull expressions used for determining time intervals of ultrasonic control. The damage computation results for one start-stop engine cycle were used as a basis to show how and for how long occurrence of initial cracks in disks could be postponed and how replacing disks in an engine service life can be eliminated.

Key words: **aircraft engine, turbojet engine, disk, damage, crack, initial crack, computation method, Weibull distribution**.

Introduction

AN initial crack on turbojet engine disks is considered to be a crack of an approximate length of 0.8 mm that appears on a specific disk with probability $P(t)$ = 0.001 (on one disk out of 1000) [1]. Thus defined initial crack is mainly a result of Low Cycle Fatigue (LCF) caused by centrifugal forces of blades and own centrifugal forces with or without influence of temperature. In practice, on the basis of computation and experimental testing, service life (SL), or rather, Low Cycle Fatigue Life (LCFL) of turbojet engine disks is prescribed. If an initial crack on a disk is timely discovered, the simplest solution is to replace the damaged disk with an undamaged one, increasing engine maintenance costs in the long-term. However, on the basis of a positive analysis, we can start with a project of new disk organizing with which occurrence of initial cracks could be postponed. As a representative of turbojet engine disks, the first stage Low Pressure Compressor Rotor (LPCR) disk of the R25-300 engine was selected and observed here.

Tracking of cracks on a selected and observed disk

The existing first stage LPCR disk of the R25-300 turbojet engine was obtained by reconstruction of the disk predecessor, withdrawn from exploitation because of the premature initial cracks in the area of joints with blades. The reconstruction consisted of increasing the back rim part and consequently the shape of pins and the method of fixing blades were changed. It was expected that, with the existing disk, the prescribed service life would be 1200 flight hours. However, this did not happen. Premature cracks in the area of joints with blades occurred as well as on the existing disk. Aware of the problem, the manufacturer of the R25-300 engine proposed that all existing disks and the remaining disks predecessors should be subject to ultrasonic control after every 25±5 flight hours. On the basis of the accepted proposal, enough data about ultrasonically discovered cracks were collected. The data contained in [2] were statistically processed. As a final result of processing, Weibull expressions were obtained.

$$P_1(t) = 1 - e^{-\left(\frac{t}{356}\right)^{3.6172}}$$
$$P_2(t) = 1 - e^{-\left(\frac{t}{336}\right)^{2.764}} \quad (1)$$

where: $P_1(t)$ - Probability of occurrence of initial cracks on the disk predecessor (the sample of 83 disks was processed), $P_2(t)$ - Probability of occurrence of initial cracks on the existing disk (the sample of 79 disks was processed) and t - Time expressed in flight hours.

The typical probabilities of occurrence of initial cracks on the disk predecessor and the existing disk are probabilities $P_1(t)$ = 0.001 and $P_2(t)$ = 0.001. With these probabilities, the occurrence of an initial crack on the disk predecessor can be expected after 52.7 flight hours, and on the existing disk after 27.6 flight hours.

The existing disks and all disks predecessors are still subject to ultrasonic control after every 25 flight hours for safety reasons. This time interval, used during the data gathering about occurrence of initial cracks on the basis of probability $P_2(t)$ = 0.001, is practically confirmed. In remaining disks predecessors it is not necessary to use this interval. Based on the probability $P_1(t)$ = 0.001, the interval of 50 flight hours can be taken for the time interval of their control. The difference in construction between the existing disk and the disk predecessor, with an example of a crack discovered on one disk predecessor, is shown in Fig.1.

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Fig.2 illustrates probabilities of crack occurrence on the existing disk and the disk predecessor.

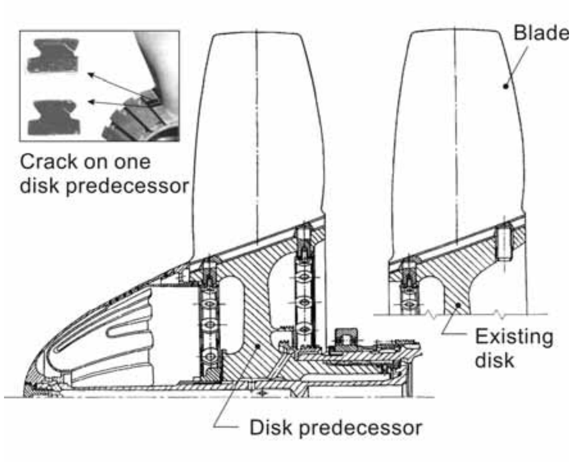

Figure 1. Difference in construction between the existing disk and the disk predecessor with an example of a crack discovered on one disc predecessor

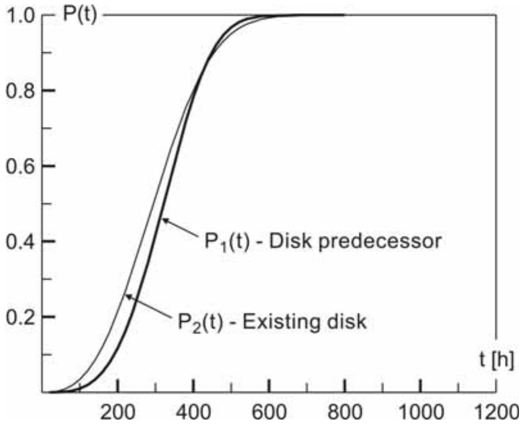

Figure 2. Illustration of probabilities of crack occurrence on the existing disk and the disk predecessor

Possibility of postponing initial crack occurrence

The only method to postpone initial cracks occurrence on the first stage LPCR disk of the R25-300 engine is to launch the third disk (disk successor) organizing. This was even done once but the project was terminated at the moment when the nickel alloy Inconel 718 was selected for the test sample of disk successor forgings, instead of the original material, steel 13H11N2V2MF. Here the question can be asked whether and for how long the initial crack occurrence could be postponed with a disk successor made of the mentioned alloy. In search for an answer the knowledge and methodology from [2,3] were useful. It started with an assumption that centrifugal forces of blades and own centrifugal forces are the main loads (influence of all other loads, including temperature, was ignored). It was still assumed that premature initial cracks on a selected disk are a consequence of low cycle fatigue the analysis of which is based on the cyclic properties of the material used for turbojet engine disks. The damage D of the existing disk and the disk successor, caused by the start-stop cycle of engine control after mounting it on aircraft, was taken as a parameter used for predicting initial cracks occurrence on a selected disk. The mentioned start-stop cycle, defined as a block of rotation frequency /n/ of the LPCR (Fig.3), is divided by the method of "reservoir" into simple *X-Y-X* cycles of rotation frequency for the purpose of damage computation (Fig.4).

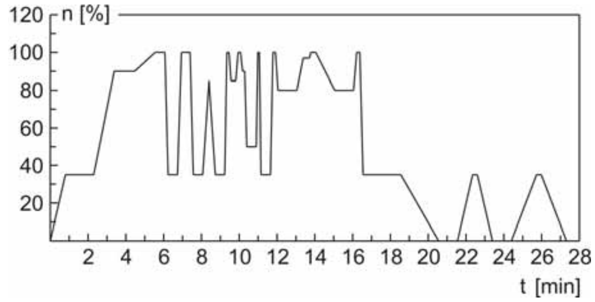

Figure 3. Start-stop cycle of the R25-300 engine control after mounting it on aircraft, defined as a block of rotation frequency

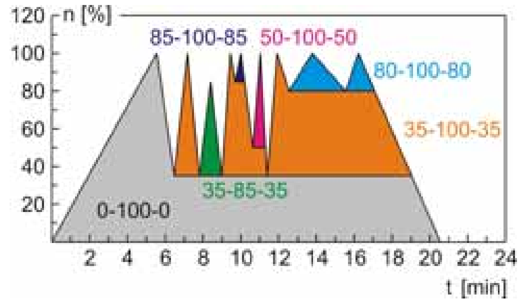

Figure 4. Start-stop cycle of the R25-300 engine divided into simple cycles of rotation frequency

Simple *X-Y-X* cycles of rotation frequency, sorted according to the level /*i*/ and a number of appearing of N_i within a given start-stop cycle that is defined as a block of rotation frequency, are given in Table 1.

Table 1. Simple *X-Y-X* cycles of rotation frequency

Level, *i*	X_i-Y_i-X_i [%]	Cycles in block N_i
1	0-100-0	1
2	35-100-35	3
3	50-100-50	1
4	80-100-80	2
5	85-100-85	1
6	35-85-85	1

The cyclic properties of steel 13H11N2V2MF in the delivered state used for the production of the existing disks of the R25-300 engine LPCR are given in Table 2.as well as the assumed cyclic properties of the nickel alloy Inconel 718 used for the disc successor forgings.

Table 2. Cyclic properties of steel 13H11N2V2MF in the delivered state [2] and the assumed cyclic properties of Inconel 718 [4]

Property	13H11N2V2MF	In. 718
Modulus of elasticity, E [MPa]	206682	208500
Cyclic strength coefficient, K' [MPa]	1103	1530
Cyclic strain hardening exponent, n'	0.118	0.07
Fatigue strength coefficient, σ'_f [MPa]	1818.8	1640
Fatigue strength exponent, b	-0.144	-0.06
Fatigue ductility coefficient, ε'_f	0.5351	2.67
Fatigue ductility exponent, c	-0.6619	-0.82

In order to compute damage of the existing disk of the first stage LPCR of the R25-300 engine, caused by the start-stop cycle shown in Fig.3, it was necessary to determine its stress-strain response at a point of expected crack initiation (at a critical point). Therefore, the blade and the critical part of the disk, at the beginning, were observed as separate ideally elastic bodies. The linear stress response of the blade and the nodal reactions at contact surfaces of its root were obtained using the Finite Element Method (FEM) for a maximum rotation frequency of $n = 186\,s^{-1}$ (100%). In order to obtain a stress response of the disk critical part, using FEM with the same rotation frequency, the mentioned reactions are used in transformed form as active nodal forces. The axially symmetric stress response of the existing disk, observed as a blisk (bladed disk), was obtained using the FEM as well (Fig.5).

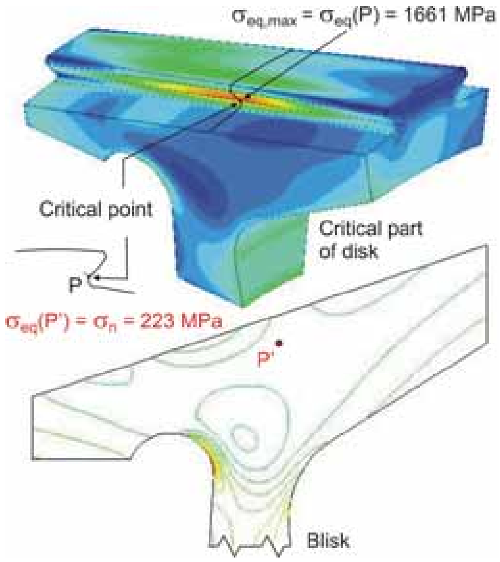

Figure 5. Linear stress response of the critical part of the existing disk with an axially symmetric linear stress response, observed as a blisk

The maximum Mises's equivalent stress $\sigma_{eq,\max} = 1661$ MPa at a critical point P of the existing disk and relevant strain is unreal.

The equivalent stress at a point P' of a blisk corresponding to a critical point P, taken as a nominal stress value, has served for the computation of a so-called equivalent stress concentration factor $K_{eq} = 7.45$, using a simple expression

$$K_{eq} = \frac{\sigma_{eq}(P)}{\sigma_n} \qquad (2)$$

A real stress-strain response at a critical point P of the existing disk (metal memory was taken in account) is defined by stabilized hysteresis loops, associated to all simple X_i-Y_i-X_i cycles of the rotation frequency, within the engine start-stop cycle. The first point of the stress-strain response for $i = 1$ and for a maximum rotation frequency of $n = 100\%$ was obtained by solving the system of equations

$$\begin{aligned} &\varepsilon = \frac{1}{2}\frac{K_{eq}\cdot\sigma_{ni}}{E}\left(\frac{K_{eq}\cdot\sigma_{ni}}{\sigma}+1\right) \\ &i = 1 \\ &\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'}\right)^{\frac{1}{n'}} \end{aligned} \qquad (3)$$

where the first equation represents the equation of Sonsino-Birger's curve, derived on the basis of references [5, 6]. The second equation in this system is the equation of the cyclic stress-strain curve.

The dimensions of the stabilized hysteresis loops $(\Delta\varepsilon \times \Delta\sigma)$, for $i = 1, 2, ..., 6$, were obtained by solving the following system

$$\begin{aligned} &\varepsilon = \frac{1}{2}\frac{K_{eq}\cdot\Delta\sigma_{ni}}{E}\left(\frac{K_{eq}\cdot\Delta\sigma_{ni}}{\Delta\sigma}+1\right) \\ &i = 1, 2, ..., 6 \\ &\Delta\varepsilon = \frac{\Delta\varepsilon}{E} + 2\left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}} \end{aligned} \qquad (4)$$

where the first equation is the equation of Sonsino-Birger's curve, expressed using stress ranges, and the second equation is the equation of Masing's curve, used also for modeling the stabilized hysteresis loops. The values of the nominal stresses σ_{ni}, and the nominal stress ranges $\Delta\sigma_{ni}$, for i-th X_i-Y_i-X_i cycles of rotation frequency, used for solving systems (3) and (4), were computed by the expressions

$$\begin{aligned} &\sigma_{ni} = 223\cdot\left(\frac{Y_i}{100}\right)^2 \\ &i = 1, 2, ..., 6 \\ &\Delta\sigma_{ni} = 223\cdot\left[\left(\frac{Y_i}{100}\right)^2 - \left(\frac{X_i}{100}\right)^2\right] \end{aligned} \qquad (5)$$

The needed cyclic properties in systems (3) and (4), with the known equivalent stress concentration factor $K_{eq} = 7.45$, were taken from Table 2. The graphical solution of these systems, described in [3], is given in Fig.6.

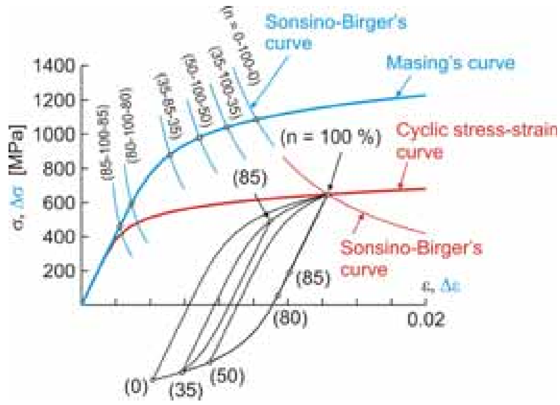

Figure 6. Graphical solution of system equations (3) and (4)

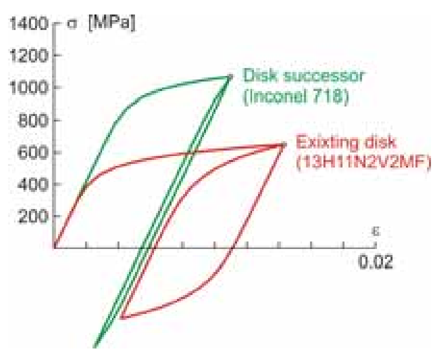

Figure 7. Stress-strain response at a critical point of the existing disk and the disk successor for the 0-100-0 cycle of rotation frequency

A real stress-strain response at a critical point of the disk successor was determined similarly as a stress-strain response at a critical point of the existing disk. It was accepted that

Poason's coefficients of nickel alloy Inconel 718 and steel 13H11N2V2MF are approximately the same $(\nu = 0.29)$. The equivalent stress concentration factor $K_{eq} = 7.45$ stayed the same because of its unchanged geometry. The nominal stress in the amount of $\sigma_n = 223$ MPa here was multiplied by the relation of Inconel 718 mass density (8200 kg/m^3 and steel 13H11N2V2MF mass density (7820 kg/m^3). The nominal stress value of the disk successor, in the amount of 233.8 MPa, was thus obtained. The needed cyclic properties of Inconel 718 in systems (3) and (4) were taken from Table 2. In expressions (5) factor 223 was replaced by factor 233.8. The stress-strain response at a critical point of the existing disk and the disk successor, for the 0-100-0 cycle of rotation frequency, is shown in Fig.7.

All numerical data of the stress-strain response at a critical point of both discussed disks for all *i*-th X_i-Y_i-X_i cycles of rotation frequency are given in Table 3 and Table 4.

Table 3. Numerical results of the stress-strain response at a critical point of the existing disk

i	X_i-Y_i-X_i [kN]	σ_{mi} [MPa]	$\Delta\sigma_i$ [MPa]	$\Delta\varepsilon_i$
1	0-100-0	106.149	542.84	0.00508466
2	35-100-35	128.664	520.32	0.00423427
3	50-100-50	158.157	490.83	0.00342179
4	80-100-80	351.909	297.08	0.00145221
5	85-100-85	418.642	230.34	0.00111619
6	35-85-35	50.092	454.84	0.00274980

Table 4. Numerical results of the stress-strain response at a critical point of the disk successor

i	X_i-Y_i-X_i [kN]	σ_{mi} [MPa]	$\Delta\sigma_i$ [MPa]	$\Delta\varepsilon_i$
1	0-100-0	224.571	843.234	0.00424552
2	35-100-35	309.555	758.250	0.00368083
3	50-100-50	415.161	652.644	0.00313538
4	80-100-80	754.161	313.645	0.00150430
5	85-100-85	826.056	241.749	0.00115948
6	35-85-35	73.892	522.587	0.00250661

The damage D at a critical point of the existing disk of the first LPCR of the R25-300 engine, caused by the start-stop cycle of that engine control after mounting on aircraft, is computed here by Palmgren-Miner's rule of linear damage accumulation [7,8]

$$D = \sum_{i=1}^{6} D_i = \sum_{i=1}^{6} \frac{N_i}{N_{fi}} \tag{6}$$

In the above expression, the damage caused by simple X_i-Y_i-X_i cycles of rotation frequency is marked with D_i. This damage represents the relation between the occurrence number N_i of *i*-th X_i-Y_i-X_i cycles in the start-stop engine cycle and the number N_{fi} of the same simple cycles which disk material can endure until the occurrence of the initial crack. Numbers N_i are given in Table 1 and numbers N_{fi} were determined by solving the system of equations

$$\begin{aligned} &\frac{\Delta\varepsilon}{2} = \frac{\sigma_f^{'} - \sigma_{mi}}{E} N_f^b + \varepsilon_f^{'} N_f^c \\ &i = 1, 2, \ldots 6 \\ &\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_i}{2} \end{aligned} \tag{7}$$

where the first equation represents Morrow's curve of LCF [7,9] which takes medium stresses σ_{mi} into account. The values $\Delta\varepsilon_i/2$ in the second equation were taken from Table 3 and Table 4.

The graphical solution of system (7) for 0-100-0 cycle of rotation frequency (for $i = 1$) is given in Fig.8. Data set on N_i, N_{fi}, D_i and D is in Table 5 and Table 6.

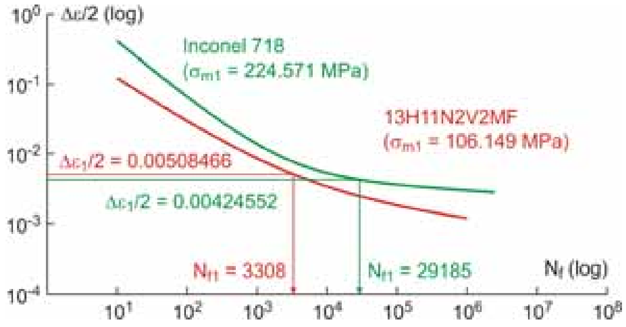

Figure 8. Graphical solution of system (7) for 0-100-0 cycle of rotation frequency

Table 5. Data set on N_i, N_{fi}, D_i and D (existing disk)

i	X_i-Y_i-X_i [%]	N_i	N_{fi}	D_i
1	0-100-0	1	3308	0.00030230
2	35-100-35	3	5226	0.00057405
3	50-100-50	1	9278	0.00010778
4	80-100-80	2	162040	0.00001234
5	85-100-85	1	495345	0.00000202
6	35-85-35	1	28078	0.00003562
			D	0.00103411

Table 6. Data set on N_i, N_{fi}, D_i and D (disk successor)

i	X_i-Y_i-X_i [%]	N_i	N_{fi}	D_i
1	0-100-0	1	29185	0.00003426
2	35-100-35	3	52827	0.00005679
3	50-100-50	1	106241	0.00000941
4	80-100-80	2	33418272	0.00000006
5	85-100-85	1	613896277	0.00000000
6	35-85-35	1	88339512	0.00000001
			D	0.00010054

It is easy to notice that the damage D of the existing disk of the first LPCR of the R25-300 engine, caused by the start-stop cycle of engine control after mounting on aircraft, is 10.3 times bigger than the damage of the disk successor. This indicates that the LCFL of the disk successor would be 10.3 times bigger than the LCFL of the existing disk, under the conditions of testing with start-stop cycles in Fig.3, defined as blocks of rotation frequency. In this way it is proven that the initial crack occurrence on the first LPCR disk of the R25-300 engine could be postponed with a disk successor, made of nickel alloy Inconel 718, with assumed cyclic properties given in Table 2.

Conclusion

It can be concluded that the occurrence of initial cracks on certain turbojet engine disks can be eliminated by replacing them with new disks made of alloy with better cyclic properties. However, it means that only by changing of the heat treatment regime can be obtained a new disk. For different regimes of heat treatment, it is thus necessary to test resistance of a selected alloy to low cycle fatigue and find a regime that gives the best cyclic properties. In some cases, changing the shape in critical areas would be enough to alleviate stress and strain concentrations and in that way the occurrence of the initial crack would be postponed. It is possible that initial crack occurrence can be put off by changing the shape of disks as well as by applying alloys with better cyclical properties. Later occurrence of crack initiation definitely reduces turbojet engine maintenance costs.

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O praćenju inicijalnih naprslina diskova turbomlaznih motora i mogućnostima odlaganja njihove pojave

U ovom radu je, kao kritična komponenta, posmatran disk prvog stepena rotora kompresora niskog pritiska jednog turbomlaznog motora. Zbog prevremenih inicijalnih naprslina ovog diska i posledičnih intervencija, troškovi održavanja motora su uvećani. Verovatnoće pojave inicijalnih naprslina na dva tipa posmatranog diska, u radu su opisane Weibull-ovim izrazima koji su iskorišćeni za određivanje vremenskih intervala ultrazvučne kontrole. U radu je takođe, na osnovu rezultata proračuna oštećenja za jedan motorki start-stop ciklus, pokazano kako i za koliko bi pojava inicijalnih naprslina diskova mogla biti odložena i zamena diskova u radnom veku motora eliminisana.

Ključne reči: **avionski motor, trubomlazni motor, disk, oštećenje, prskotina, inicijalna prskotina, metoda proračuna, Vejbulova raspodela.**

О наблюдении инициальных трещин дисков турбореактивных двигателей и возможности отложения их возникновения

В настоящей работе в роли критической составляющей рассматриван диск первой степени ротора компрессора низкого давления одного турбореактивного двигателя. Из-за преждевременных инициальных трещин этого диска и последственных действий (интервенций), расходы в обслуживании двигателя увеличены. Вероятности появления инициальных трещин на двух типах рассматриваемого диска в настоящей работе описаны выражениями Вейбуля, которые использованы для определения временных интервалов ультразвукового контроля. В работе тоже, на основании результатов расчёта повреждений за один старт-стоп цикл двигателя, показано как и на какое время появление инициальных трещин дисков могло бы быть отсрочено, а в том числе и устранена замена дисков в сроке службы двигателя.

Kly~evwe slova: **авиационный двигатель, турбореактивный двигатель, диск, повреждение, трещина, инициальная трещина, метод расчёта, распределение Вейбуля.**

Sur le suivi des fissures initiales chez les disques des turboréacteurs et les possibilités de prolongation de leur apparition

Dans ce papier on a observé, comme une composante critique, le disque du premier degré du rotor de compresseur à basse pression chez le moteur turboréacteur. A cause des fissures initiales prématurées de ce disque et des interventions ultérieures, les frais de l'entretien du moteurs sont augmentés. Les probabilités de l'apparition des fissures initiales chez les deux types du disque observé ont été décrit dans ce travail par les expressions de Weibull, utilisées pour la détermination des intervalles temporelles du contrôle ultrasonique. A la base des résultats de computation du dommage pour un start stop cycle du moteur on a déterminé comment et combien cette fissure initiale des disques pourrait être prolongée et le remplacement des disques dao cours de la vie de travail du moteur éliminé.

Mots clés: **moteur d'avion, turboréacteur, disque, dommage, fissure, fissure initiale, méthode de computation, distribution de Weibull.**