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Initial Fatigue Life Estimation in Aero Engine Discs

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This paper deals with the holes on aero engine discs. Flat discs with four, six and eight eccentrically arranged holes were observed. The estimation of their low cycle fatigue life was carried out in conditions of variable revolutions per minute. The blocks of variable revolutions per minute of a low pressure compressor rotor of one aero engine were used. Four blocks were observed during landing and one block was observed during a specific training flight. It is shown how the low cycle fatigue of discs depends on the assigned geometry and material characteristics. It is also shown how the solutions of simple problems can be useful in design of fatigue resistant aero engine discs.

Key words: **aero engine, disc, material fatigue, low cycle fatigue, fatigue strength, life cycle estimation, finite element method.**

Introduction

IN aero engines, the life to fracture of critical parts, such as discs, is limited by low cycle fatigue.

Gas turbine aero engine components are classified into 'critical' or 'non-critical' depending on the consequences that a malfunction might have on the integrity of the aircraft.

Turbine and compressor discs and shafts are the major fracture critical components since their failure in service could hazard the safety of the aircraft. These components possess enormous kinetic energies that reach their highest levels during the take-off sequence. Such operations induce severe cyclic stresses which, in the absence of an adequate life prediction policy, would eventually lead to low cycle fatigue (LCF) failures. Since it is not practical to design engine casings capable of containing these events, it is essential to ensure that their occurrence in service is an extremely remote possibility. This is achieved through the application of the Joint European Airworthiness Requirements (JAR-E) [8].

Fatigue resistance of aero engine discs, to a great extent, depends on the assigned geometry and material used[1-3]. Variable centrifugal forces of blades and own centrifugal forces, without or together with variable temperature, provoke their low cycle fatigue (LCF). A very important mission in a design process is to choose which geometry and which material to select in order to make discs with a satisfying LCF life, expressed in start-stop cycles or flight hours.a.

Low Cycle Fatigue Life

The traditional methods of the LCF life estimation of aero engine discs are based on equivalent testing on test benches, flight testing and exploitation testing. In the last twenty years, significant research efforts were made towards experimental and analytical methods [6,7].

The analytical method of the LCF life estimation is used in the design process of fatigue resistant aero engine discs. It includes load, geometry and material data processing.

A design flow chart of fatigue resistant aero engine discs is presented in Fig.1 and in general, it can be applied in the design of all metallic parts subjected to LCF.

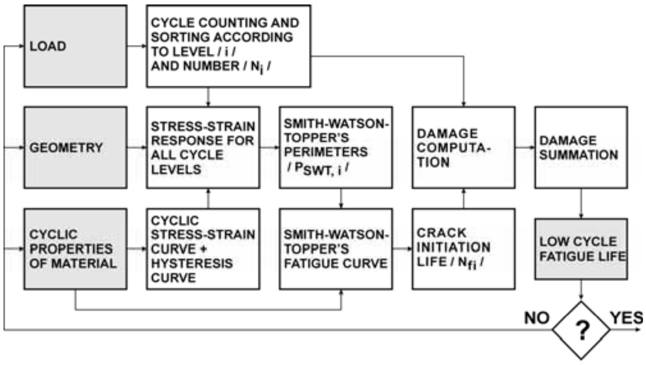

Figure 1. Design flow chart of fatigue resistant aero engine discs [1]

At the beginning of the design process it is necessary to notice and solve simple problems useful for the design of fatigue resistant aero engine discs. This time, the attention is devoted to a problem of holes on discs.

The holes on aero engine discs have an important role. They lighten discs and serve for assembling and air cooling.

Some of aircraft accidents were caused by disk fractures, because the disk fractures were initiated in hole areas. One example is given in [1].

Case of Flat Discs with Eccentrically Arranged Holes

Geometry and loads

A designer can draw useful conclusions needed for making decisions in connection with the size, number and arrangement of holes on aero engine discs by analysing flat discs with eccentrically arranged holes, taking into account

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the results of the LCF life estimation. Flat discs with 4, 6 an 8 eccentrically arranged holes (Fig.2) served here as an example. Their LCF life estimation was carried out under conditions of variable revolutions per minute (R.P.M).

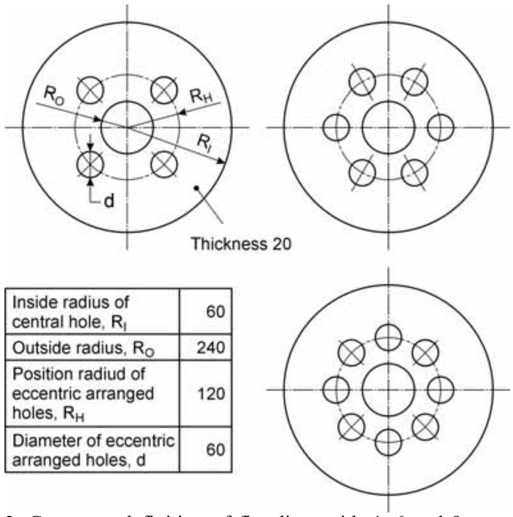


Figure 2. Geometry definition of flat discs with 4, 6 and 8 eccentrically arranged holes

Variable R.P.M were simulated using R.P.M blocks of the low pressure compressor rotor of one aero engine (Fig.3). The blocks A, B, C and D are regulated and serve for ground engine testing. The block E was registered during a specific training flight.

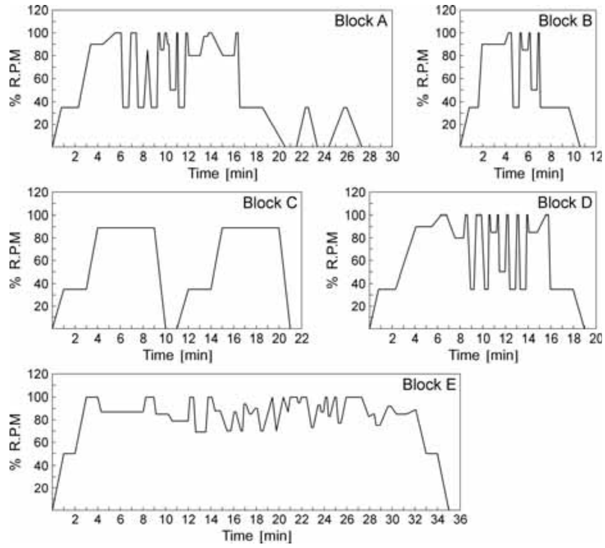


Figure 3. Blocks of variable R.P.M of the low pressure compressor rotor of one aero engine [1]

In order to estimate the LCF life, the listed blocks were decomposed in simple X-Y-X R.P.M cycles. For example, the decomposition of the block D, in accordance with the recommendations from [2] is shown in Fig.4.

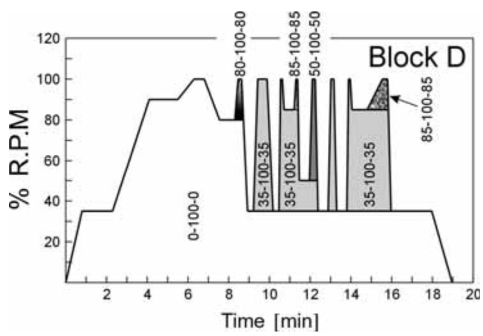


Figure 4. Block D decomposed on simple R.P.M cycles

Simple X-Y-X R.P.M cycles per blocks, sorted according to the level / i / and the number / N_i /, are given in Tables 1-5.

Table 1. X-Y-X R.P.M Cycles in the block A

i	X-Y-X R.P.M Cycle	N_i
1	0-100-0	1
2	35-100-35	3
3	35-85-35	1
4	50-100-50	1
5	80-100-80	2
k = 6	85-100-85	1

Table 2. X-Y-X R.P.M Cycles in the block B

i	X-Y-X R.P.M Cycle	Ni
1	0-100-0	1
2	35-100-35	1
3	50-100-50	1
k = 4	85-100-85	1

Table 3. X-Y-X R.P.M Cycles in the block C

i	X-Y-X R.P.M Cycle	Ni
k = 1	0-89-0	2

Table 4. X-Y-X R.P.M Cycles in the block D

i	X-Y-X R.P.M Cycle	N_i
1	0-100-0	1
2	35-100-35	4
3	50-100-50	1
4	80-100-80	1
k = 5	85-100-85	2

Table 5. X-Y-X R.P.M Cycles in the block E

i	X-Y-X R.P.M Cycle	N_i
1	0-100-0	1
2	70-100-70	3
3	70-87-70	1
4	70-94-70	1
5	73-100-73	1
6	75-92-75	1
7	77-100-77	1
8	79-100-79	1
19	83-100-83	1
10	83-85-83	1
11	85-89-85	1
12	85-90-85	1
13	87-100-87	3
k = 14	95-100-95	1

Cyclic Properties of the Material

Let us assume that the material determined for manufacturing the discs in Fig.2 is steel 13H11N2V2MF in state S1 (State of delivery) and in state S2 (Quenched and tempered state: Heating at 1000°C, Quenching in oil, Tempering at 640°C, Air cooling). The cyclic properties of this steel are given in Table 6.

Depending on the named steel states, the flat discs with 4, 6 an 8 eccentrically arranged holes, are marked as: D4S1, D6S1, D8S1 and D4S2, D6S2 and D8S2.

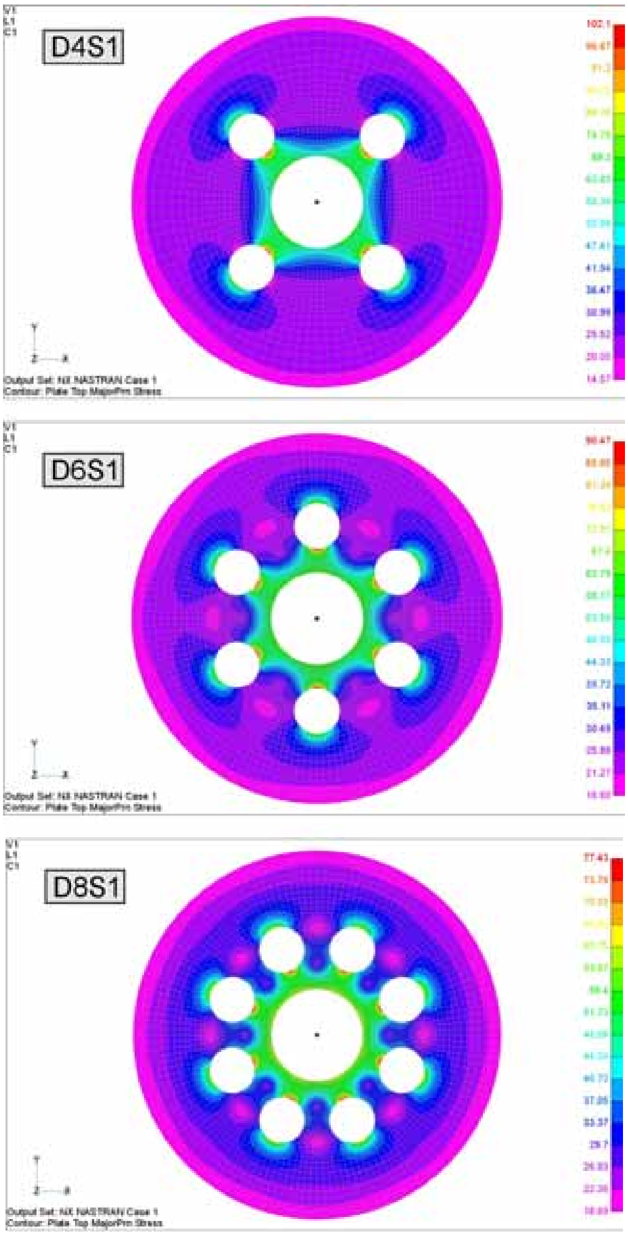
Table 6. Cyclic properties of steel 13H11N2V2MF

PROPERTY	STATE	
	S1	S2
Modulus of elasticity, E [MPa]	206682	229184.6
Cyclic strength coefficient, K' [MPa]	1103	1140
Cyclic strain hardening exponent, n'	0.118	0.0579
Fatigue strength coefficient, σ_f' [MPa]	1818.8	1557.3
Fatigue strength exponent, b	-0.144	-0.0851
Fatigue ductility coefficient, ε_f'	0.5351	0.3175
Fatigue ductility exponent, c	-0.6619	-0.7214

The cyclic properties of steel 13H11N2V2MF in state S1 were taken from [3] while the cyclic properties of the same steel in state S2 are the result of a project which is in progress.

Stress-Strain Response

The stress response of the discs D4S1, D6S1, D8S1 and DS1, for a maximum number of R.P.M = 11860, was obtained using the finite element method (FEM) implemented in the NASTRAN software. The distribution of the principal stresses σ_1 of the listed discs is presented in Fig.5. All discs were observed as ideal elastic circular plates.



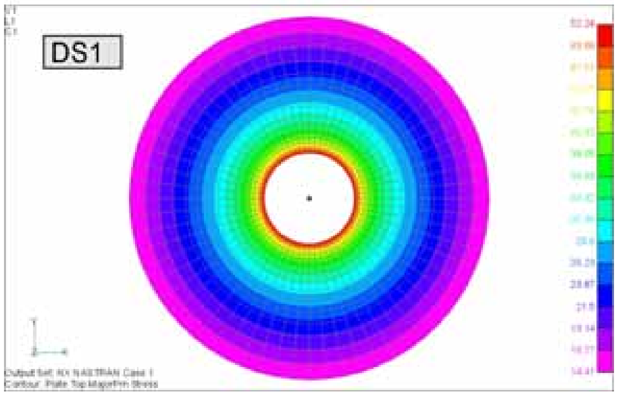


Figure 5. Distribution of the principal stresses σ_1 on the discs D4S1, D6S1, D8S1 and DS1

The principal stresses σ_1 have the maximum values at the critical points *P* (Fig.6):

$$\sigma_{1,P}\,(\text{D4S1}) = 1021.0 \text{ MPa},$$

$$\sigma_{1,P}\,(\text{D6S1}) = 904.7 \text{ MPa}$$

$$\sigma_{1,P}\,(\text{D8S1}) = 774.3 \text{ MPa}.$$

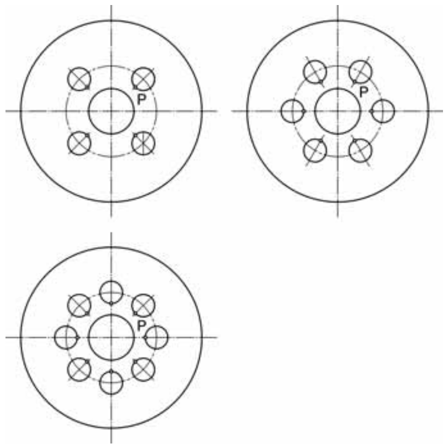


Figure 6. Position of the critical points *P* on the flat discs with the eccentrically arranged holes

The position radius of the critical points *P* is *R* = 90 mm. For that radius, the value of the principal stress σ_1 on the disk DS1 yields:

$$\sigma_{1,R90}\,(\text{DS1}) = 358.3 \text{ MPa}.$$

If it is supposed that the upper stress is the nominal stress (σ_n), hen the stress concentration factor K_{TP} for the critical points P of the discs with 4, 6 and 8 eccentrically arranged holes (discs D4, D6 and D8) can be determined by the expression

$$K_{TP} = \frac{\sigma_{1,P}}{\sigma_n} \tag{1}$$

The stress concentration factors for the critical points P of the discs D4, D6 and D8 according to (1) have the following values:

$$K_{TP}\,(\text{D4}) = 2.849,$$

$$K_{TP}\,(\text{D6}) = 2.525,$$

$$K_{TP}\,(\text{D8}) = 2.161.$$

The real stress-strain response of the discs in Fig.2, in comparison with the stress-strain response of discs as ideal elastic circular plates, is completely different. Namely, their stress-strain response can be described by the hysteresis loops associated to all simple X-Y-X R.P.M cycles in Tables 1-5.

The upper point of the hysteresis loops was obtained by the solution of the system equations

$$\sigma\varepsilon = \frac{K_f^2 \sigma_n^2}{E} \qquad \varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'}\right)^{\frac{1}{n'}} \tag{2}$$

The widths and heights of the hysteresis loops were obtained by the solution of the system equations

$$\Delta\sigma\Delta\varepsilon = \frac{K_f^2 (\Delta\sigma_n)^2}{E} \qquad \Delta\varepsilon = \frac{\Delta\sigma}{E} + 2\left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}} \tag{3}$$

The first equations in (2,3) are two forms of Neuber's hyperbola. The second equation in (2) is the equation of the cyclic stress-strain curve. The second equation in (3) is the equation of the hysteresis curve [4,5].

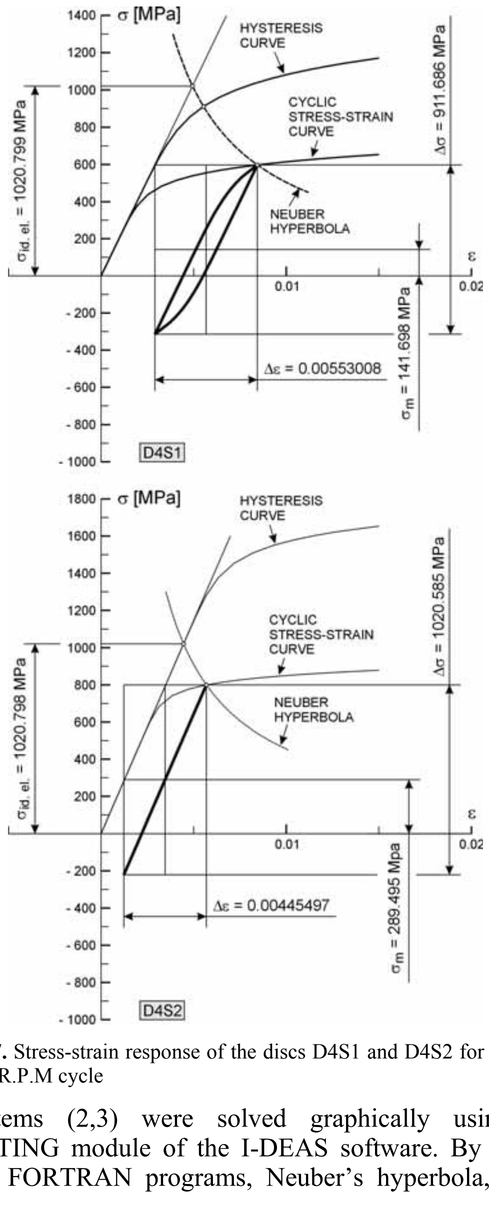


Figure 7. Stress-strain response of the discs D4S1 and D4S2 for the basic 0-100-0 R.P.M cycle

Systems (2,3) were solved graphically using the DRAFTING module of the I-DEAS software. By special Visual FORTRAN programs, Neuber's hyperbola, cyclic stress-strain curves and hysteresis curves, were copied into the corresponding spline curves.

An example of a graphical stress-strain response of the discs D4S1 and D4S2, for the basic 0-100-0 R.P.M cycle, obtained by the solution of systems (2,3), is given in Fig.7.

The notch factor K_f in systems (2,3) is conditionally equalized with the stress concentration factors K_{TP}, connected with the critical points P of the discs in Fig.2.

The values of the nominal stresses σ_n and the ranges $\Delta\sigma_n$ of these stresses, needed for the solution of systems (2,3), for all levels of X-Y-X R.P.M cycles in Tables 1-5, were calculated using the expressions

$$\sigma_{ni} = 358.3 \left(\frac{Y_i}{100}\right)^2 \qquad \Delta\sigma_{ni} = 358.3 \left[\left(\frac{Y_i}{100}\right)^2 - \left(\frac{X_i}{100}\right)^2\right] \tag{4}$$

Estimation of Damage

The estimation of the damage D per blocks of variable R.P.M, was carried out using Kurath's expression [6] in the form

$$D = \sum_{i=1}^{k} \frac{N_i}{N_{fi}} \left(\frac{\Delta\sigma_i}{\Delta\sigma_h}\right)^{\frac{1}{d}} \tag{5}$$

where d is the interactive exponent, and $\Delta\sigma_h$ is the highest range of the stress response in a corresponding block of variable R.P.M.

The expression for determining the interactive exponent d has the following form

$$d = \frac{b}{b+c+1} \tag{6}$$

where b and c are the exponents in Table 6.

The numbers N_i of X-Y-X R.P.M cycles were taken from Table 6, while the numbers N_{fi} were determined using Smith-Watson-Topper's fatigue curves given in the general form

$$P_{SWT} = \sqrt{\sigma_{max} \frac{\Delta\varepsilon}{2} E} = \sqrt{(\sigma'_f)^2 (N_f)^{2b} + E\sigma'_f \varepsilon'_f (N_f)^{b+c}} \tag{7}$$

and Smith-Watson-Topper's perimeters

$$P_{SWT,i} = \sqrt{\sigma_{max} \frac{\Delta\varepsilon_i}{2} E} \tag{8}$$

A graphic illustration of Smith-Watson-Topper's fatigue curves of steel 13H11N2V2MF in the states S1 and S2, copied in spline curves, is shown in Fig.8.

The damage data (D_A, D_B, D_C, D_D and D_E) per blocks A, B, C, D and E in Fig.3 are included in Table 7.

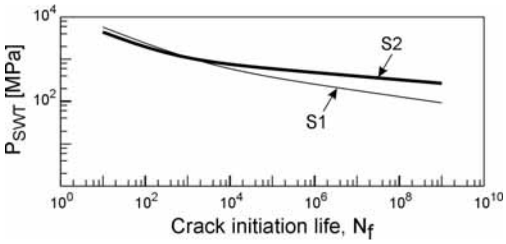


Figure 8. Smith-Watson-Topper's fatigue curves of steel 13H11N2V2MF in the states S1 and S2

Table 7. Damage data per blocks A, B, C, D and E of variable R.P.M

	Disc	
	D4S1	D4S2
D_A	0.000384602475	0.000036175045
D_B	0.000210378736	0.000022279033
D_C	0.000077417357	0.000004722104
D_D	0.000424398907	0.000042328491
D_E	0.000236594366	0.000014360307
	D6S1	D6S2
D_A	0.000249392718	0.000015534507
D_B	0.000136199615	0.000009653356
D_C	0.000049074937	0.000001632455
D_D	0.000275307120	0.000018229776
D_E	0.000149963608	0.000006255282
	D8S1	D8S2
D_A	0.000141191893	0.000004523370
D_B	0.000084259362	0.000002833001
D_C	0.000026695854	0.000000321670
D_D	0.000170887421	0.000005322148
D_E	0.000084673578	0.000001843693

Low Cycle Fatigue Life Estimation

Four hundred flight hours of overhaul intermediate time for the given aero engine consisted of: 2 blocks A, 400 blocks B, 15 blocks C, 14 blocks D, and approximately 685 blocks E of variable R.P.M [1].

The total damage for 400 flight hours of overhaul intermediate time, was determined by the expression

$$D_T = 2D_A + 400D_B + 15D_C + \\ +14D_D + 685D_E \tag{9}$$

The damage D_{1h} per one flight hour was determined using the expression

$$D_{1h} = \frac{D_T}{400} \tag{10}$$

The low cycle fatigue life expressed in flight hours is a reciprocal value of D_{1h}.

Table 8. Damage and the LCFL data of the discussed flat discs

Disc D4S1	
D_T	0.254090685113
D_{1h}	0.000635226713
LCFL [h]	1574
Disc D4S2	
D_T	0.019484204019
D_{1h}	0.000048710510
LCFL [h]	20529
Disc D6S1	
D_T	0.162294126651
D_{1h}	0.000405735317
LCFL [h]	2464
Disc D6S2	
D_T	0.008456983273
D_{1h}	0.000021142458
LCFL [h]	47298
Disc D8S1	
D_T	0.094780391220
D_{1h}	0.000236950978
LCFL [h]	4220
Disc D8S2	
D_T	0.002484511967
D_{1h}	0.000006211280
LCFL [h]	160997

The total damage, the damage per one flight hour, and the LCF life (LCFL) data, of the discussed flat discs, are contained in Table 8. The histogram of the LCFL data is presented in Fig.9.

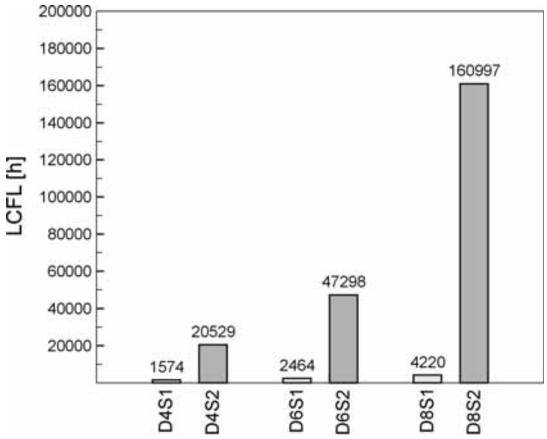


Figure 9. Histogram of the LCFL data

Conclusions

This study combined the finite element structural analysis with strain-life equations to develop a simple and effective procedure for the estimation of the fatigue crack initiation life of aero engine discs. The Neuber method is used to estimate elastic-plastic stresses and strains at the roots of notches on the basis of the elastic stress analysis. It applies where the yielding is limited in extent; under these circumstances it provides a resonable approximation for the redistribution of stress and strain.

By the solution of a simple problem of flat discs with four, six and eight eccentrically arranged holes, it is shown how a number of holes can influence the low cycle fatigue life of aero engine discs. However, the influence of the material selected for manufacturing is essential. The results of the low cycle fatigue life show that it is necessary to avoid aero engine discs with 4 and 6 eccentrically arranged holes in a design process.

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Procena veka diskova avionskog motora

Ovaj rad je usmeren na problem ponašanja diskova avionskog motora u zoni otvora. Razmatrani su ravni diskovi motora sa četiri, šest i osam ekscentrično raspoređenih otvora. Procena veka do pojave inicijalnih oštećenja ovih diskova je izvršena na bazi poznavanja njihovih malociklusnih karakteristika materijala i pri promenjivom spektru opterećenja. Za tu svrhu razmatrani su blokovi opterećenja promenljivih amplituda kod rotora kompresora niskog pritiska avio motora. Razmatrana su četiri bloka opterećenja za vreme sletanja i jedan blok registrovan za vreme specifičnog trenažnog leta. Pokazano je kako zamor diskova motora zavisi od geometrije i karakteristika materijala. Uz to pokazano je kako rešenja jednostavnih elemenata konstrukcija mogu biti uspešno primenjeni i za projektovanje diskova avionskih motora sa aspekta obezbeđenja njihove čvrsoće na zamor.

Ključne reči: **avionski motor, disk, zamor materijala, niskociklični zamor, čvrstoća na zamor, procena veka trajanja, metoda konačnih elemenata.**

Оценка жизненного цикла приводов авиационного двигателя

Настоящая работа ориентирована на проблему поведения отверстия реактивного двигателя в зоне отверстия. Здесь рассматриваются плоские диски двигателей с четырьмя, шестьми и восьми эксцентрично расположеными отверстиями. Оценка жизненного цикла до появления начальных повреждений дисков проводилось на основе знаний их малоцикловых свойств материалов и при переменной нагрузке. С этой целью считались блоки переменных амплитуд у ротора компрессора низкого давления авиационных двигателей. Были обсуждены четыре блока при посадке и один блок выявлен в ходе конкретной лётной подготовки. Тут показано, как усталость дисков двигателя зависит от геометрии и свойств материала. Кроме того, было показано, как решения простых конструкционных решений могут быть с успехом использованы для дизайна дисков авиационных двигателей в плане обеспечения их сопротивляемости усталости.

Kly~evwe slova: **авиационный двигатель, привод (диск), усталость материала, малоцикловая усталость, сопротивляемость усталости, оценка жизненного цикла, метод конечных элементов.**

Estimation de la durée de vie pour les disques du moteur d'avion

Ce papier est centré sur le problème du comportement des disques chez le moteur d'avion. On a considéré les disques plats pour les moteurs à quatre, six ou huit ouvertures disposées excentriquement. On a fait l'estimation de la durée de vie de ces disques jusqu'à l'apparition des endommagements initiaux à la base de connaissance de leurs caractéristiques des matériaux à petits cycles et à la charge variable. Dans ce but on a étudié les blocs des amplitudes variables chez le rotor du compresseur basse pression du moteur d'avion. On a considéré quatre blocs pendant l'atterrissage et un bloc a été enregistré pendant le vol spécifique d'entraînement. Cela a démontré que la fatigue des disques de moteur dépend de la géométrie et des caractéristiques des matériaux . On a démontré aussi que les solutions simples de construction peuvent s'utiliser avec succès pour la conception des disques des moteurs d'avion pour assurer leur résistance à la fatigue.

Mots clés: **moteur d'avion, disque, fatigue des matériaux, fatigue de petits cycles, résistance à la fatigue, estimation de la durée de vie, méthode des éléments finis**