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Low-Cycle Fatigue Calculation of Gas Turbine Engine Disks under Flight Cycle Conditions

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We address the effects of the actual flight cycle for gas turbine engine disks, which is influenced by low-cycle fatigue. An approach is proposed which improves reliability of life cycle prediction owing to schematization of flight cycle with a criterion for reaching the maximum intensity of total strain range. Contribution of subcycles to the cumulative damage is demonstrated.

Keywords: low-cycle fatigue, finite element method, flight cycle, transient regime, temperature difference, total strain range.

Introduction. A study of low-cycle fatigue (LCF) in gas turbine engine disks under real flight cycle conditions represents quite a challenge. Operation modes, such as alternation of steady-state and transient regimes, long endurances at constant loadings and temperatures, etc., in many respects determine characteristic features of thermal and mechanical loading of these parts [1]. The maximum values of intensity of total strain range, which govern the LCF life, can be achieved both for steady-state and transient regimes.

Problem Statement. The subjects of this investigation are the disks of gas turbine engines, which experience thermal and mechanical loading during a flight cycle. At present, selections of the most loaded regimes for the cyclic life assessment are made based on technical requirements for typical flight cycle (TFC). Usually these can be regimes with the maximum rotor rotation speed, temperatures, duration, or combinations thereof. In many cases, TFC is replaced by subcycles: the major cycle [2] with the maximum rotation speeds and temperatures, the part throttle cycle corresponding to a transient regime, and other subcycles describing the TFC effects (Fig. 1a).

The main feature of disk loading is the high temperature difference between the rim and the hub (Fig. 1b). In the take-off cycle, hot gas starts heating up the disk rim quickly while the hub is not warmed yet. Then the thermal condition of the disk is characterized by the temperature difference decreasing as the hub is warmed through. Taking into account the cycling of all the regimes and features of uniform thermomechanical loading will permit a more accurate LCF life assessment of disks.

The LCF calculation of discs under flight cycle conditions includes the following:

(i) variation of stresses and strains during TFC for a stabilized hysteresis loop;

(ii) analysis of variations of the total strain range intensity $\Delta\varepsilon_i$ in each subcycle of TFC;

(iii) assessment of total LCF damage during TFC for critical areas.

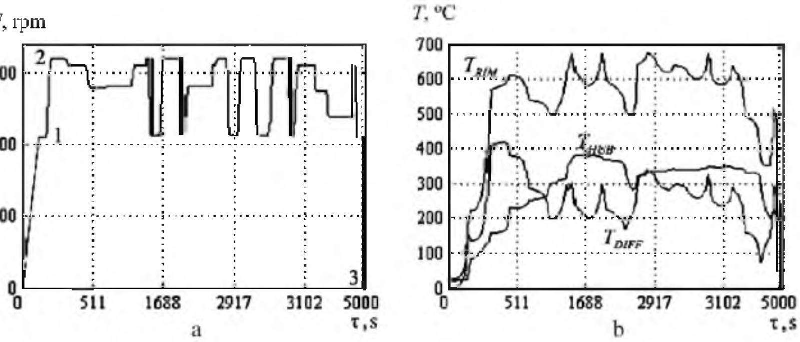

Fig. 1. Rotation speed variation during TFC (a) and characteristic temperature differences in aircraft engine disks (b).

Results and Discussion. The stress analysis was carried out using the MSC software package. The turbine engine disk was modeled for a 3D FEM analysis. The loads considered were the disk inertia load, loads from blades, and thermal load. Temperature variation is assumed to be 3D fields during all the loading cycles (about 500 fields). No creep was considered in the present analysis.

Plastic strains in the disc hub arise after the first loading cycle of the engine, which causes stress redistribution. After the second loading cycle the curve $\sigma - \varepsilon$ in the disk critical areas is stabilized (Fig. 2a) and the total strain range between any two points of loading and unloading can be determined. It can be seen that the difference in strains between the second and third cycles is less than 1%, while that between the first and the second cycle is approximately 20%.

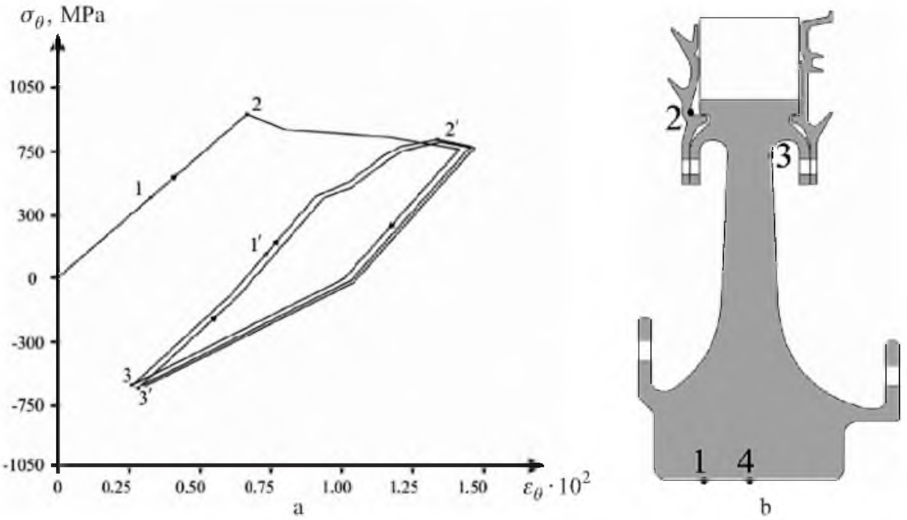

Fig. 2. Hoop stresses vs. hoop strains during three initial major cycles (a) and the disk critical areas (b).

The LCF life assessment in terms of the number of cycles prior to cracking N_f was carried out for the disk critical areas during the major cycle (Fig. 2b). For the $\Delta\varepsilon_i$ definition the moment of engine shutdown was used as a reference point of unloading (point *3* in Fig. 1a), while for loading we used all reference points every second of flight (50 reference points). The $\Delta\varepsilon_i$ variation during the major cycle in the critical areas is shown in Fig. 3, where the instants of reaching maximum values are marked bold.

The maximum value $\Delta\varepsilon_i = 0.79\%$ in the disk hub (Fig. 3b) is reached in the 506th second of flight at the end of take-off, where the rotation speed is 97% of the maximum value and the temperature difference between the rim and the hub is maximum (Fig. 3a). At the beginning of the loading cycle with the maximum rotation speed and small temperature difference the $\Delta\varepsilon_i$ value is 25% below the maximum and increases with a gradual growth of the temperature difference. A similar situation can be observed in the disk web where the difference in $\Delta\varepsilon_i$ could be 20% (Fig. 3d).

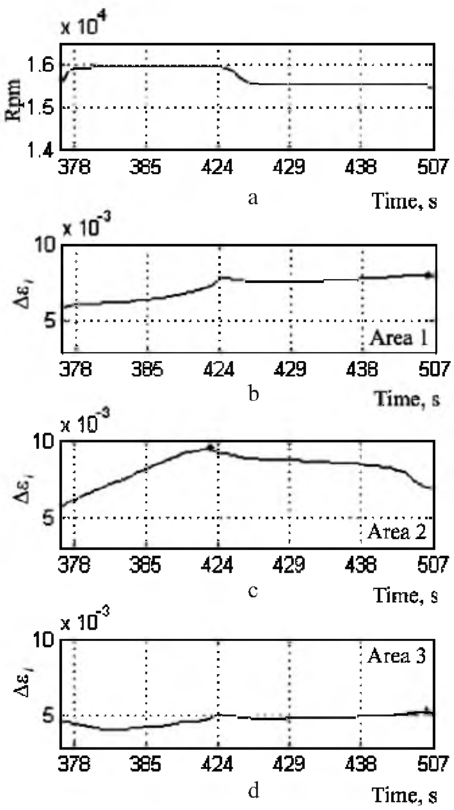

Fig. 3. Rotation speed variation (a) and $\Delta\varepsilon_i$ in critical areas (b, c, d) during the major cycle.

The maximum value $\Delta\varepsilon_i = 0.95\%$ in the left covering disk is reached in the middle of take-off in the 407th second of flight at the maximum rotation speed and high values of the temperature difference. At other instants of operation in the take-off regime the difference between $\Delta\varepsilon_i$ values could be 30% (Fig. 3c).

Thus, each critical area of the disk under flight cycle conditions exhibits variations of stresses and strains and the maximum damages occur at different instants of time. This depends on a combination of thermal and mechanical loading during the flight cycle. A conventional selection of two reference points in the major cycle for the LCF life assessment can lead to incorrect determination of $\Delta\varepsilon_i$ and N_f.

Damages accumulate during each subcycle with corresponding values of $\Delta\varepsilon_i$. A study of characteristic features of a flight cycle can enable one to determine the minimum N_f value in the critical areas by the procedure described above.

The results of calculation of cyclic durability by means of the $\varepsilon - N$ curve [3, 4] and the linear damage accumulation hypothesis [5] show that the main portion of damages (approximately 40%) in the disk hub are caused by the major cycle (Table 1); other subcycles (3rd through 10th) are characterized by identical low level of $\Delta\varepsilon_i$. In the covering disks a fraction of damages due to the major cycle is approximately 80%. Others subcycles have low $\Delta\varepsilon_i$ values. The contribution to damages in a loading cycle occurs differently for each critical area.

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Comparison of $\Delta\varepsilon_i$ and N_f Values and Fraction of Damages (Ω) in Each Subcycle with the Proposed Approach that Uses All the Reference Points for LCF Life Assessment

Subcycle	Conventional approach using two reference points for LCF life assessment			Proposed approach using all reference points for LCF life assessment		
	$\Delta\varepsilon_i$, %	N_f, cycles	Ω, %	$\Delta\varepsilon_i$, %	N_f, cycles	Ω, %
1	0.7769	11,770	47.8	0.7978	10,093	40.0
2	0.0976	999,999	0.5	0.1136	640,248	0.5
3	0.3657	80,670	7.0	0.3394	60,681	6.7
4	0.3620	96,020	5.4	0.3582	48,321	8.3
5	0.3566	102,910	5.5	0.3378	57,971	6.9
6	0.4063	49,630	11.3	0.3744	36,805	10.9
7	0.3370	93,900	5.5	0.3211	58,994	6.8
8	0.3606	70,240	7.5	0.3400	48,761	8.3
9	0.3510	83,670	6.2	0.3345	54,156	7.4
10	0.3258	197,980	2.8	0.3105	108,044	3.7
11	0.1956	999,999	0.5	0.1765	999,999	0.5
Total		5622	100		4025	100

Selection of the most loaded regimes for the cyclic life assessment, where equivalent stresses reach maximum values, can lead to inaccurate definition of $\Delta\varepsilon_i$ and N_f. That approach disregards the history of thermomechanical loading. The difference in cyclic durability assessment could be 30% (see Table 1). On the one hand, it depends on incomplete $\Delta\varepsilon_i$ determination at the instants of transient operation. On the other hand, the most critical area with the maximum damages in the case under study is displaced into the left side of the disk hub (point *4* moves to point *1* in Fig. 2b). This statement can have an influence on numerical estimation of residual life of a disk with an initial defect present in the most critical area, and also in the case of cyclic spin tests with initial defect.

Conclusions. A new approach is proposed for the LCF life assessment of turbine engine disks taking into account the characteristic features of the actual flight cycle. By the example of numerical FEM simulation of turbine engine disk during a loading cycle, the following results are shown:

1. Each critical area in a disk under flight cycle conditions has the features of stresses and strains variation, and the maximum damages in these areas occur at different instants of time. A conventional selection of two reference points in the major cycle for the LCF life assessment can lead to incorrect determination of $\Delta\varepsilon_i$ and N_f. The new approach improves reliability of the cycle life prediction owing to schematization of flight cycle with a criterion for reaching the maximum intensity of total strain range, which provides more accurate results.

2. The contribution of subcycles to cumulative damage during a loading cycle for each critical area occurs differently.

3. This can also have an influence on numerical estimation of residual life of a disk with an initial defect introduced in the most critical area and also makes it possible to carry out cyclic spin tests with an initial defect.

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