Life Assessment of a Jet Engine Component
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Summary

Thermo-mechanical fatigue life of pins connecting the first stage low pressure turbine (LPT) nozzle to the LPT nozzle support in an F110-GE-100 engine has been assessed. A commercial finite element code is used for thermal and stress analysis. The analysis is performed over a hypothetical flight profile and temperature and stress histories are computed. Geometry factor is calculated for a crack at the critical pin location. Crack growth and creep life are then computed.

Introduction

Usage monitoring and life assessment are crucial issues in ensuring integrity of jet engines. An engine is simulated thermodynamically under a typical flight/mission profile and various temperature and pressure histories inside the engine are computed. Heat transfer between gases/cooling air flows and engine parts is analyzed to compute the variation of temperature distribution in an engine part throughout a flight. Thermal stress histories are computed at critical locations. One can then, in principle, carry out a failure analysis or a life assessment study using whatever type of failure mechanism is in effect. The processes at work in an engine are highly complex and what is described is not an easy task.

In this paper, low cycle fatigue (LCF) life of a structural part in the first stage low pressure turbine nozzle of an F110-GE-100 engine is assessed under a hypothetical mission profile (Fig. 1). A commercial finite element program is used for heat transfer and stress analysis and for modeling a crack.

Heat Transfer Analysis

The gas temperature and pressure distributions inside the engine were obtained from a thermodynamic simulation\cite{1}. Figure 2 shows the variation of the first stage low-pressure turbine (LPT) nozzle inlet gas temperature during a single flight where a normalized flight time of 1.0 denotes the end of a flight. A heat transfer analysis is performed to obtain the history of temperature distribution in the components throughout the assumed flight profile. For this purpose, a two-dimensional (2-D) axisymmetric finite element model of the high pressure turbine (HPT) rotor and the LPT nozzle and rotor are generated with MARC\textsuperscript{®}. The

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surrounding gas (core gas and cooling air) flowing through the components are included in the model. Convective heat transfer between the surrounding fluid and the components, and heat conduction within the components are taken into account. After a stress analysis is performed, the critical region is determined and a second set of models is generated for heat transfer analysis with a crack of varying lengths at the critical location. Temperature distributions calculated from thermal analysis are used both in stress analysis and creep damage assessment.

![Diagram of a pin connecting the First Stage LPT nozzle to its Support](image)

Figure 1. Detail of a Pin Connecting the First Stage LPT nozzle to its Support

![Graph of LPT Nozzle Inlet Gas Temperature Profile in a Flight](image)

Figure 2. LPT Nozzle Inlet Gas Temperature Profile in a Flight

**Stress Analysis**

The same set of finite element meshes (with and without crack) used in heat transfer analysis is also used in stress analyses. Hence LPT rotor, LPT stator and
HPT rotor are modelled as axisymmetric components whereas, in reality, they are not axisymmetric; there are passageways through them. This implies that these components are modelled stiffer than they really are. To account for this effect, a correction factor for the modulus of elasticity is used. Gas stream and cooling air pressures and the thermal analysis results are input as mechanical and thermal loads in stress analysis.

A limited number of stages of the engine are modeled to keep the model size at a reasonable level. In order to account for the structural effect of engine stages fore and aft of the model, linear springs are attached to the relevant boundary nodes where the model would interface with the rest of the engine. The pins which connect the outer band of the LPT nozzle to the nozzle support are among the critical parts and of interest here. There is a fine mesh around the pin.

A stress analysis is performed for the whole flight with the associated temperature and pressure profiles as inputs. Fracture critical location in the pin is identified as the point of maximum principal stress the time history of which is given in Figure 3.

![Max. Principal Stress Profile](image)

Figure 3. Maximum Principal Stress Profile in a Flight at the Critical Location

**Fracture Mechanics**

The quarter point element proposed by Barsoum [2,3] is used to model a crack because of its simplicity and ease of implementation. Quarter point displacement technique (QPDT) is used to compute stress intensity factors (SIF) from quarter point element displacements[4].
A crack of varying lengths, the propagation direction of which is determined by using the Maximum Tangential Stress Criterion (MTS) [4], is modelled by MARC. The aim is to calculate geometry factors (or $\beta$ factors) for various lengths of a crack. Maximum tangential stress value, which was the maximum principal stress, is taken as the reference (remote) stress. The maximum stress variation throughout the mission profile under investigation is given in Figure 3. For a set of crack lengths at the peak of the EPLA history during the mission, the mode I and mode II SIFs were calculated using QPDT, from which an effective SIF was obtained:

$$K_{eff} = \sqrt{K_I^2 + K_{II}^2}$$

(1)

where $K_I$ and $K_{II}$ are the mode I and II stress intensity factors, respectively. Then,

$$\beta = \frac{K_{eff}}{\sigma \sqrt{\pi a}}$$

(2)

where $\sigma$ is the remote stress, $a$ is the crack length, and $\beta$ is the geometry factor. Variation of $\beta$ with the length of a crack at the pin is shown in Fig. 4.

![Figure 4. $\beta$ Factor Variation with Crack Length](image)

**Life Assessment**

Thermo-Mechanical Fatigue (TMF) life of a pin is predicted with the model proposed by Chen et al.[6], which is a linear damage summation method to predict the fatigue and creep-fatigue behaviour of nickel-based super alloys at high temperature. This model is used in conjunction with AFGROW, a crack growth calculation program. The model predicts the thermo-mechanical life as

$$N = \left[ N_f^{-1} + t_h/t_r \right]^{-1}$$

(3)
where $N_f$ is the number of cycles to failure in pure fatigue conditions, $N$ is the number of cycles to failure in fatigue-creep tests, $t_h$ is the hold time and $t_r$ is the rupture time for pure creep conditions. Fatigue life is calculated without creep too. The initial crack size is taken as 0.015 inches (0.381 mm). Life ($N$) predictions are performed with three models: i) no-retardation, ii) closure model with OLR of 0.3 (a common value for most metals), iii) Willenborg model with SOLR of 2.5 (AFGROW’s default value). Crack growth histories are given in Fig. 5.

Creep rupture time ($t_r$) of the component was calculated by invoking the time dependence option of AFGROW. Before starting calculations, hold periods of the maximum principal stress profile of the critical location were determined. After determining hold periods and calculating creep rupture times corresponding to these stress and temperature values, thermo-mechanical fatigue (TMF) life of the component was assessed by using Eq. (3). TMF life prediction results for the three cases are given on Table 1. Critical engine parts are usually designed to twice the life requirement. The most conservative TMF life of the pin is calculated as 4820 hours (Table 1), and therefore, under the hypothetical profile, the pins should be replaced at 2410 hours.

![Crack Growth Histories with Three Models](image)

Figure 5. Crack Growth Histories with Three Models
Table 1. Fatigue and TMF Fatigue Life Values

<table>
<thead>
<tr>
<th>Case</th>
<th>Fatigue Life ($N_f$)</th>
<th>TMF Life (N)</th>
<th>% change</th>
</tr>
</thead>
<tbody>
<tr>
<td>No retardation</td>
<td>4837 hours</td>
<td>4820 hours</td>
<td>-0.35</td>
</tr>
<tr>
<td>Closure Model</td>
<td>4919 hours</td>
<td>4902 hours</td>
<td>-0.35</td>
</tr>
<tr>
<td>Willenborg Model</td>
<td>5136 hours</td>
<td>5116 hours</td>
<td>-0.39</td>
</tr>
</tbody>
</table>

Conclusions

Thermo-mechanical fatigue life of pins connecting the first stage low pressure turbine nozzle to its support in an F110-GE-100 engine has been assessed. It is found that creep is not a significant factor in the life of pins since temperatures and temperature gradients are not as severe for the LPT stage as they are for the HPT. Of the three crack growth models used, closure and Willenborg models predict a fatigue life longer than the no-retardation model by 1.7 % and 6.2 %, respectively. The accuracy of the results can be improved by better flow modelling.

References


