Nationaal Lucht- en Ruimtevaartlaboratorium
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Integrated lifing analysis for gas turbine components

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INTEGRATED LIFING ANALYSIS FOR GAS TURBINE COMPONENTS

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ABSTRACT

A method to predict gas turbine component life based on engine performance analysis has been developed [1]. Engine performance history is obtained from in-flight monitored engine parameters and flight conditions and downloaded for processing by a tool integrating a number of software tools and models. Data acquisition is performed by the FACE system, installed in a large number of RNLAF F-16 fighter aircraft. Data then is processed by a thermodynamical engine system model, calculating gas properties like pressure and temperature at the required station in the engine. With a combination of a heat transfer and thermal finite element model the temperature distribution in the component is calculated. The stress distribution is obtained with a structural finite element analysis and finally a life consumption model is used to determine the damage accumulation in the component. The applicability of the tool is demonstrated with a number of analyses on real engine components. Examples are a creep life analysis of the F100-PW-220 engine 3rd stage turbine rotor blade during a recorded RNLAF F-16 mission and a crack growth analysis for the 2nd stage fandisc hub for a representative mission mix. Furthermore, using the engine system model with a detailed control system, the effect of engine deterioration on blade life consumption rate was determined. The tool has significant potential to enhance on-condition maintenance and optimize aircraft operational use.

1 INTRODUCTION

Maintenance costs form a major part of total aircraft engine operating costs. A significant reduction in these costs would be obtained if inspection intervals could be extended and component service life increased. Inspection intervals and service life are commonly based on statistical analysis, requiring a limited probability of failure (a certain level of safety) during operation. However in many cases this approach leads to conservative inspection intervals and life limits for the majority of parts or components. The analysis tool presented offers a way to attempt to reduce maintenance costs and improve safety by applying usage monitoring to predict operational component condition and thereby facilitating “on-condition maintenance”.

The algorithms and system models incorporated in this tool represent the relation between operational usage of the engine and component condition. Optimally, the system is able to accurately determine component condition and predict life consumption based on operational data obtained from a number of sensors.

The developed analysis tool predicts engine component (or part) life based on analysis of engine performance. Engine performance history is obtained from in-flight monitored engine control parameters and flight conditions and downloaded for processing by a number of software tools and models.

Most of the models and tools used to determine engine performance, component usage and condition (health) and to predict life consumption were already commonly applied at the National Aerospace Laboratory (NLR) as stand-alone. The benefit of the integrated tool is the direct relation between engine performance and component life.

The following section will describe the several constituents of the analysis tool and show some sample results, where the tool is demonstrated and evaluated on a hot section part (third stage turbine rotor blade) of the F100-PW-220 engine of a Royal Netherlands Airforce (RNLAF) F-16 fighter aircraft. Furthermore a case study is reported, analyzing the effect of component deterioration on life consumption, finally followed by the conclusions and recommendations for further research.

2 DESCRIPTION OF THE INTEGRATED ANALYSIS TOOL

The integrated analysis tool presented consists of a sequence of software tools and models. An overview of this sequence is given in Fig. 1. The sequence ranges from the measurement of operational engine data to ultimately predicting the life consumption during the analyzed mission. The following tools must subsequently be applied to process the data:

FACE	Fatigue and Air Combat Evaluation (FACE) system for monitoring flight / engine data
GSP	Gas turbine Simulation Program (GSP) for calculating engine system performance data
CFD model	Computational Fluid Dynamics (CFD) model for calculating the heat transfer to hot section components
MARC	Finite Element (FE) model for calculating thermal and mechanical stress in hot section components
Lifing model	for deriving life consumption data from the stress history data

FACE

The FACE system used to measure flight data is based on the Autonomous Combat Evaluation (ACE) system of RADA Electronic Industries, which is used for pilot debriefing purposes. The NLR has developed a fatigue analysis system that has been combined with ACE to form the FACE system [2]. The FACE system consists of both on-board and ground-based hardware. In the aircraft two electronic boxes are installed: the Flight Monitoring Unit (FMU) and the Data Recording Unit (DRU). The ground-based hardware relevant for maintenance purposes is the Logistic Debriefing Station (LDS).

The FMU is a programmable unit that determines which signals are stored and how they are stored. By generating a Set-up Configuration File (SCF) and uploading it into the FMU, the data collection process can be adapted to all requirements. In this way several data reduction algorithms (e.g. peak and through, time at level) can be selected and the sampling frequency can be adapted. The relevant signals stored by the DRU are engine parameters from the engine's Digital Electronic Engine Control (DEEC) and avionics data. The DEEC signals can be sampled at a maximum frequency of 4 Hz. The following signals, which together fully describe engine usage, are stored:

- Fuel flow to the gas generator
- Fuel flow to the afterburner
- Exhaust nozzle position
- Flight conditions: Mach, altitude and air temperature

These parameters, as functions of time, are used as input for the GSP model, which is the next tool in the sequence. The first three parameters could also be substituted by the Power Lever Angle (PLA) signal, provided that the GSP model contains a control unit, which translates the PLA to the appropriate fuel flows and nozzle area. A data reduction algorithm is applied to reduce the amount of operational data before it is used as input for GSP.

GSP

The Gas Turbine Simulation Program (GSP) is a tool for gas turbine engine performance analysis, which has been developed at the NLR [3],[4]. This program enables both steady state and transient simulations for any kind of gas turbine configuration. A specific gas turbine configuration is created by arranging different predefined components (like fans, compressors, and combustors) in a configuration similar to the gas turbine type to be simulated. An example of a model for a twin spool turbofan engine like the Pratt & Whitney F100-PW-220 is given in Fig. 2. The simulation is based on one-dimensional modeling of the processes in the different gas turbine components with thermodynamic relations and steady-state characteristics ("component maps"). A comprehensive gas model based on a NASA code is included [5], fully describing effects of gas composition and dissociation on hot section engine performance.

For the current purpose, GSP can be used to calculate gas temperatures, pressures, velocities and composition at relevant engine stations from measured engine data. This particularly applies to stations for which no measured data is available such as the critical high-pressure turbine entry temperature. Also, GSP is able to accurately calculate dynamic responses of these parameters (critical to engine life) where measured data is not available or has unacceptable high time lags or low update frequencies.

The GSP model input obtained from FACE includes all measured flight conditions and engine power setting data. With GSP, the entire engine transient (usually an entire mission) is calculated with an integration step size of 0.05 seconds. With a smallest input step size of 0.2 seconds, this is sufficient to accurately calculate the critical effects such as typical severe acceleration / deceleration temperature transients in the hot section. A GSP report is used to output data for further processing by the CFD and MARC finite element (FE) models.

CFD model

The Computational Fluid Dynamics (CFD) model is used to accurately calculate the heat transfer from the hot gas stream to the component. For this calculation it is important to have detailed information on the geometry of both the flow channel and the different components that disturb the flow (blades, vanes). From CFD analysis of the gas flow through the gas turbine, values for the heat transfer coefficient h are obtained at specific locations in the component. The h value varies significantly along the flow path, due to variations in the flow conditions (gas velocity, type of flow (laminar, turbulent), etc). The CFD model also allows incorporating the effects of film cooling of the blade on heat transfer. For some components, the results for the heat transfer coefficient, obtained by the CFD model, are not suitable for use in the thermal model. For these components an engineering approach was followed [6], which resulted in a number of functions that describe the approximate distribution of the heat transfer coefficient across the blade surface. These functions are specific for the component under consideration.

Finite Element model

The Finite Element (FE) model consists of two interrelated models. The thermal model calculates the temperature distribution in the component, based on the heat input from the hot gas stream. The mechanical model calculates the stresses and strains in the component, caused by the varying temperature distribution and the externally applied loads. The finite element code used is MARC, which is a commercially available, multipurpose finite element package. Definition of the geometry and mesh generation is performed with the pre-processor MSC/PATRAN. MSC/PATRAN is also used as postprocessor to view and analyze the results.

The thermal model calculates the temperature distribution in the component. For each finite element on the surface of the component, the heat transfer coefficient follows from the CFD model. With the thermal conductivity α of the material, the temperature distribution in the component can be calculated. A transient thermal analysis is performed for the complete flight under consideration with the time-varying ambient gas temperature obtained from GSP as input. An example of the temperature distribution in an internally cooled turbine blade at some point during a flight is shown in Fig. 3. A limited number of CFD packages, having the ability to incorporate fluid-structure interaction, can perform both the heat transfer coefficient and temperature distribution calculation. This would make the MARC thermal model calculation redundant.

The mechanical model calculates the stress and strain distribution in a component. There are two sources for the stress in a rotating component: centrifugal forces due to rotation of the component and temperature gradients in the material. Again a transient analysis is performed for the complete mission. In this case the rotational frequency and the temperature distribution, both as function of time, are the input for the model and the stress and strain distributions in time appear as output. The temperature distribution is obtained from the results of the thermal analysis and the values of the rotational frequency are read from the GSP report file. An example of the stress variation at 3 different locations on a turbine blade is shown in Fig. 4.

Lifing model

A lifing model generally calculates either total time to failure or number of cycles to failure for a certain component subjected to a specific load sequence. A large number of specific life prediction models have been developed over the last twenty years, where each model is appropriate for a specific application. The major division in lifing models is between total life models and crack growth models. Total life models, like the Palmgren-Miner model [6],[8], only calculate the time to failure, not considering the way failure is reached. These models are representative for the Safe Life philosophy, aiming to retire a component before a crack originates. On the other hand, crack growth models represent the Damage Tolerance philosophy, which accepts the presence of material defects and aims to monitor crack growth and remove the component before the crack becomes unstable. Note that crack growth models perform a local analysis, using stress histories at very specific locations on the component, being the location of crack initiation. The results are only valid for that location. In addition, several different mechanisms can cause the failure of a component, for example fatigue, creep or oxidation. Every failure mechanism requires a specific lifing model. In the end, the actual choice of the lifing model(s) depends on the expected failure mechanism of the component under consideration.

3 CASE STUDY I: EFFECT OF HPT DETERIORATION ON 3RD BLADE CREEP LIFE CONSUMPTION RATE

The analysis tool that has been presented in the previous section is demonstrated by applying it to the F100-PW-220 engine of the RNLAF F-16 fighter aircraft. The component selected for analysis is the 3rd stage turbine blade, which is the first stage rotor of the low-pressure turbine (LPT) module. As input an arbitrary mission has been selected. Figure 5 shows the variation in altitude and fuel flow as measured by FACE during the mission. The purpose of this case study is to show the effect of high-pressure turbine (HPT) deterioration on the life consumption of the 3rd stage blade.

Common deterioration types include compressor fouling, increased tip clearance, and corrosion and erosion of especially the HP turbine blades. All these types result in lower component efficiencies and usually require higher fuel flows and turbine inlet temperature to maintain minimum thrust. The consequence is an increasing rate of deterioration. Also, transient performance changes and both lower acceleration rates and higher temperature rates in the HP turbine may be expected with a deteriorated engine in many cases.

HPT deterioration is incorporated in GSP by applying a +1% change in HPT flow capacity and –2% change in HPT isentropic efficiency. This is a typical combination of the two deterioration modes. Simulating component deterioration is a standard option in GSP.

The engine control system usually tries to compensate loss of performance due to deterioration by maintaining compressor or fan rotor speed or another thrust related parameter. With the F100-PW-220 engine, fan rotor speed is maintained, which means thrust is virtually unaffected by HPC (High Pressure Compressor), HPT or LPT deterioration. However, to maintain fan rotor speed with a deteriorated HPT, TIT (Turbine Inlet Temperature) and FTIT (Fan Turbine Inlet Temperature) levels increase, and compressor speed may drop. This implies that in order to analyze deterioration effects on thermal loads during operation, integration of the control system in the gas turbine performance model is required.

The effect of HPT deterioration is calculated with GSP. The FTIT appears to increase by 25 to 35 degrees in the deteriorated engine. The calculated temperatures (FTIT) can also be compared to actually measured values obtained from FACE, which is done in Fig. 6. The fluctuation in measured signal appears to be much less than in the calculated value, which is due to the finite response time of the thermocouple used to measure the temperature in the engine. The differences in steady state values are due to the fact that the actual engine already has sustained some deterioration, while the GSP calculation is based on a new engine. Although it is possible to include deterioration effects in the GSP analysis, the non-deteriorated engine model results are shown here because the actual amount of deterioration in the real engine is hard to quantify.

From the GSP-outputted FTIT the FE models firstly determine the temperature distribution and its variation in time and secondly the stress and strain distribution and its variation in time. In the mechanical model the creep phenomenon is incorporated, because creep is assumed to be the life-limiting factor for the 3rd stage turbine blade. For a new component the amount of creep strain is nil and after sustaining a certain amount of creep failure occurs. Therefore the creep strain is a damage parameter and the evolution of creep strain is representing damage accumulation. Note that in this way the lifing analysis is integrated into the mechanical FE model. The results of this combined analysis are given in Fig. 7, which shows the accumulation of creep strain in the blade during the mission for both a new engine and a deteriorated engine. The creep strain accumulation appears to be faster in the deteriorated engine, which implies that the rate of life consumption is higher, in this case, a factor of 1.9. This shows the very high sensitivity of creep strain accumulation for temperature changes: a 3% temperature increase causes a 90% increase in creep strain.

4 CASE STUDY II: CRACK GROWTH ANALYSIS ON 2ND STAGE FANDISC HUB

The lifing analysis tool has also been applied to the hub of the 2nd stage fandisc [9]. During inspections, cracks were found in this component at one of the 21 thrust balance holes (Fig. 8). To investigate the failure, a crack growth analysis was performed for this location. A database with FACE measured RNLAF F-16 missions was used to construct a representative loading history of 1000 flights. In this sequence the distribution of the different mission types represents the actual mission mix. Because the fan disc is a cold section component, thermal loads can be omitted in this analysis and the CFD and thermal FE model can be skipped. The dominant loading parameter in the hub is the varying torque in the shaft coming from the fan drive turbine (LPT). The engine performance program GSP is used to calculate the variation in torque for all different mission types. The torque values are then easily transformed to shear stresses in the hub, which can be used as input for the crack growth analysis. Therefore a FE analysis is not needed to calculate the stresses in this case.

However, a crack growth analysis requires a stress intensity factor (SIF) solution for the geometry under consideration, which relates the local stress at the crack tip to the remotely applied stress for every crack length. A FE analysis is used to obtain this SIF solution. The model is shown in Fig. 9. For symmetry reasons, only one-seventh part of the hub has been modeled. The rigid bore of the disc is modeled by a fixed boundary condition and the torsional load is applied at the opposite edge of the model. Finally, the material crack growth properties (crack growth rate da/dN vs. stress intensity ΔK) are obtained from material handbooks.

When all these preparations have been completed, the actual crack growth analysis is performed with the CRAGRO program. The initial crack size is taken to be 0.254 mm (1/100 inch). The loading sequence is applied until either the critical crack length is reached or net section yielding occurs. The resulting crack propagation life is very well comparable to the value provided by the OEM.

5 DISCUSSION

An important point of discussion for this tool is the accuracy of the calculated results. The accuracy of the integrated tool is obviously dependent on the accuracy of the separate tools and models. The measurements of the FACE system combined with the data reduction algorithm introduce a maximum error of about 1%. The GSP model inaccuracy is considered to be less than 2%, provided that a suitable integration time step has been chosen. The accuracy of the temperatures calculated with the thermal FE model is mainly determined by the accuracy of the heat transfer coefficient value h. Using the approximation functions for the heat transfer, the uncertainty in heat transfer coefficient is about a factor 2, which is caused by uncertainty about the degree of turbulence. This could be less when a CFD model is used to calculate the heat transfer. The uncertainty in heat transfer coefficient will cause uncertainty in the temperatures during transients. However, the steady state temperatures are unaffected by the heat transfer rates. This means that for creep life calculations the value of the heat transfer coefficient is not very important, but for fatigue life calculations it is of crucial importance. The mechanical FE model has an inaccuracy of less than 2%, due to variances in material data. Obviously the inaccuracy of the FE calculations will be larger when an inaccurate geometry or a course mesh is used, but this can be improved rather easily and is therefore not considered to be a limitation of the tool. Note however that refining the FE mesh rapidly increases the computation time and the required memory.

All together this means that the loading of a component can be calculated with an inaccuracy of about 10%, provided that sufficient (aerodynamic) information about the specific component is available.

However, performing the actual life prediction will introduce an additional inaccuracy of 20 to even 50%. This large inaccuracy is due to the large scatter in experimentally determined material data used for the life prediction. The actual inaccuracy depends on the type of material data used by the model. For example, S,N-curves, representing the relation between number of cycles to failure and applied stress level, show a higher scatter than crack growth curves. It is therefore a fundamental material property phenomenon, which has its effect on the lifing model inaccuracy. Development of lifing models must be focused on model types, which are based on material data with little scatter (like crack growth data). Another problem is the unavailability of material data for the component under consideration. Using material data for a slightly different material (regarding to composition or heat treatment) leads to less accurate results.

6 CONCLUSIONS AND POTENTIAL

An integrated analysis tool for life prediction of gas turbine components has been demonstrated. The tool consists of a sequence of software tools and models, which were already commonly applied at the NLR as stand-alone. It has been demonstrated that the mechanical and thermal loads of gas turbine components can be calculated from operational flight data, and that subsequently a life prediction can be performed. As the overall life prediction inaccuracy of the tool is dominated by the relatively high inaccuracy of lifing models and the large scatter in the associated material behavior, future work must be focussed on improving those models. A more accurate FE model geometry, a more detailed GSP engine control model and an accurate CFD model can improve the accuracy further.

The potential of the analysis tool presented here is twofold. Firstly the tool can be used to apply *on-condition maintenance*. The load history of every individual component could be tracked and could be used to determine the inspection interval or actual life limit of that specific component. The general and mostly very conservative life limits supplied by the manufacturer are based on a certain assumed usage, on top of which a safety factor has been applied to account for heavier usage. This safety factor can now be quantified and probably decreased, which leads to a huge saving in spare parts and inspection costs.

Secondly, the tool can be used to compare different missions with respect to life consumption. The results can be used to optimize the use of the aircraft.

7 ACKNOWLEDGEMENTS

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Figure 1: Overview of the integrated analysis tool.

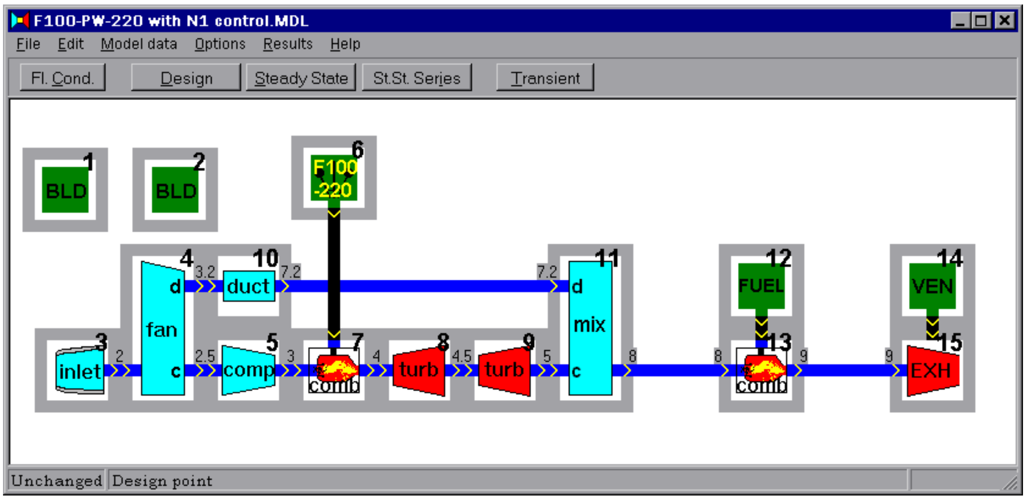


Figure 2: GSP model of the Pratt & Whitney F100-PW-220 turbofan engine.

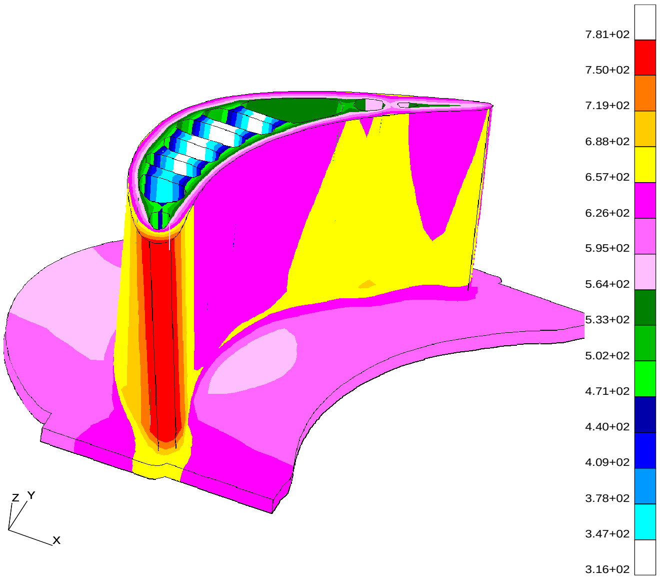


Figure 3: Temperature distribution (^{o}C) in the lower half of an internally cooled turbine blade.

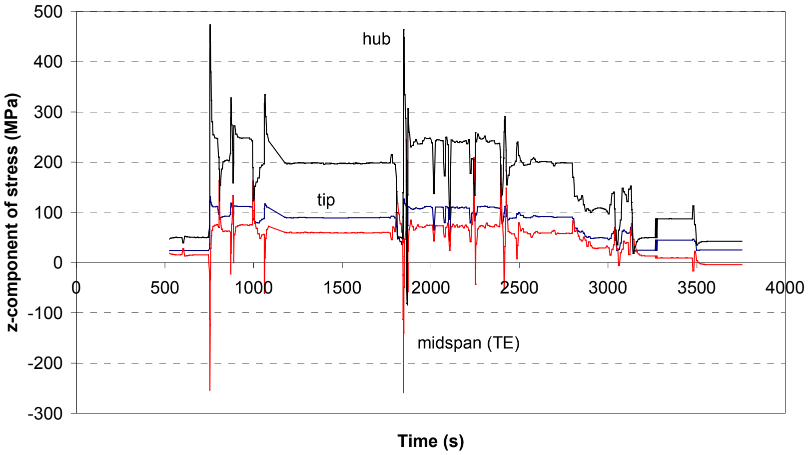


Figure 4: Variation of stress in time for three different locations on the blade.

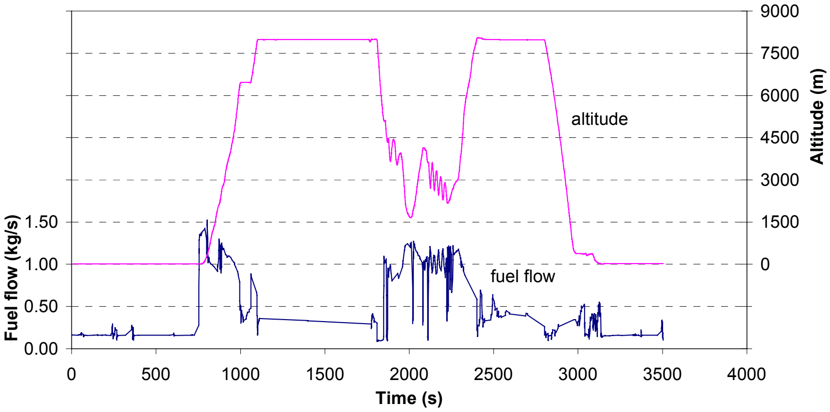


Figure 5: Measured variation of fuel flow and altitude during the selected mission.

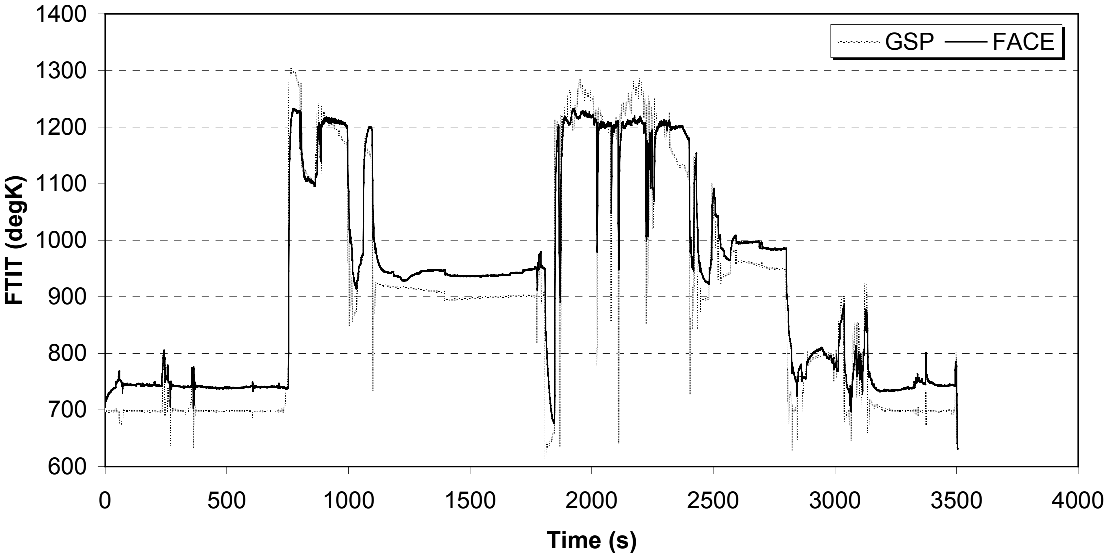


Figure 6: Comparison of FTIT as measured by FACE and calculated by GSP.

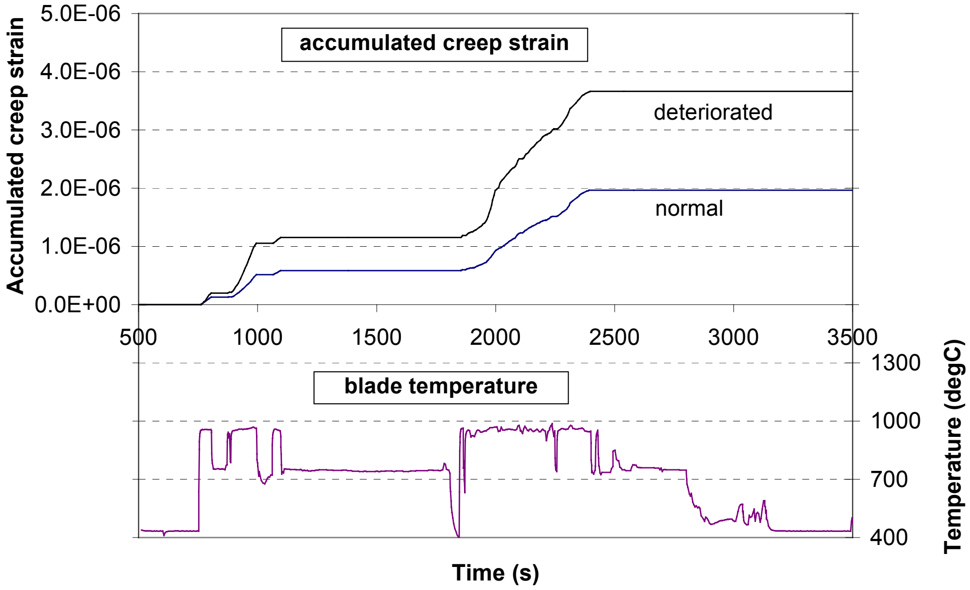
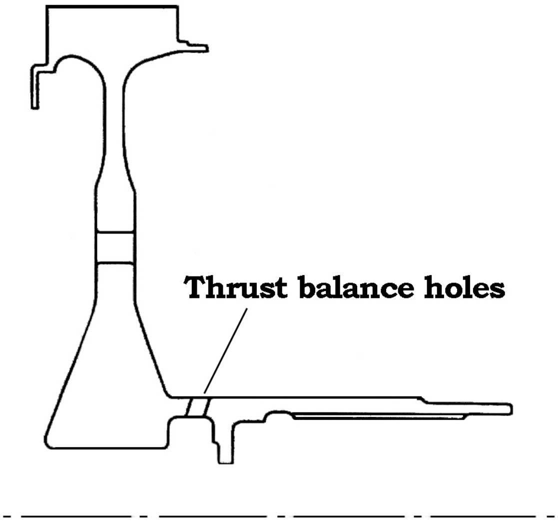


Figure 7: Effect of HPT deterioration on creep strain accumulation.



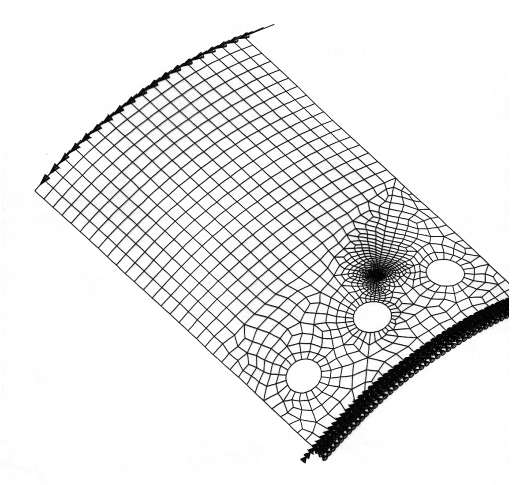


Figure 8: Schematic cross section of 2^{nd} stage fan disc

Figure 9: Finite Element model to determine stress intensity factor solution for 2^{nd} stage fan disc hub