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This report is based on a presentation held at the RTO-AVT Symposium on Monitoring and Management of Gas Turbine Fleets for Extended Life and Reduced Costs, Manchester, UK on 8-12 October 2001.

Division:	Structures and Materials
Issued:	September 2001
Classification of title:	Unclassified

Contents

(15 pages in total)

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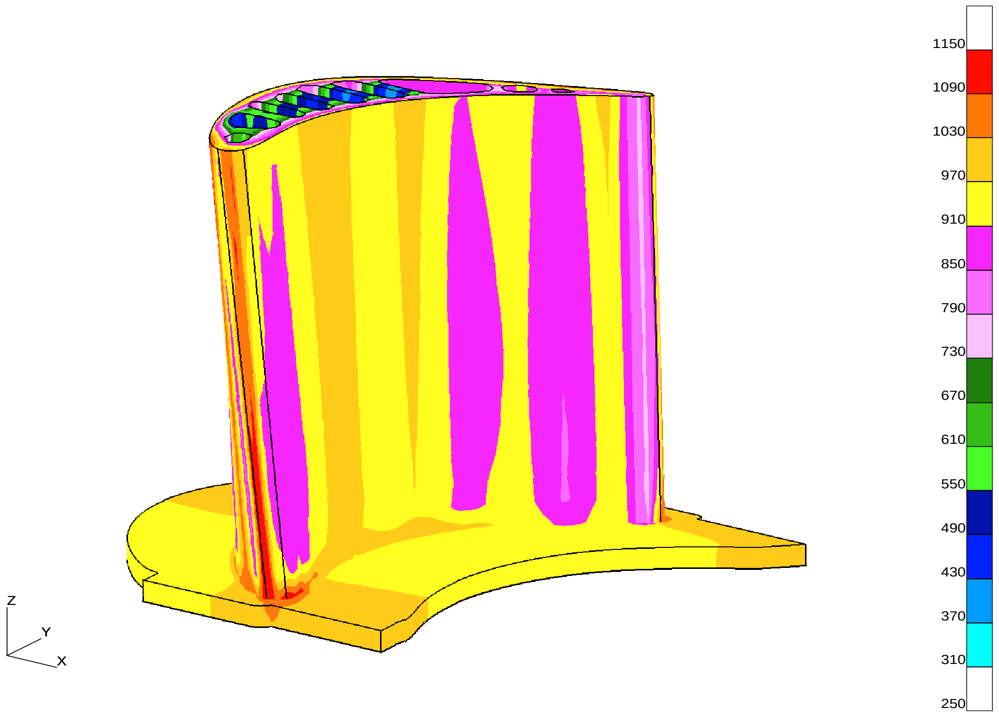

Integrated Lifing Analysis of a Film-Cooled Turbine Blade

Tiedo Tinga, Wim B. de Wolf, Wilfried P.J. Visser and Sandor Woldendorp
National Aerospace Laboratory
P.O.Box 153, 8300 AD Emmeloord, The Netherlands
Tel. +31 527 248727, Fax. +31 527 248210, email: tinga@nlr.nl

Abstract
A method to predict gas turbine component life based on engine performance analysis is demonstrated on a hot section gas turbine component. The mechanical and thermal loading of the first stage high pressure turbine rotor blade of the F100-PW-220 engine, one of the most severely loaded components in the engine, is analyzed and a life assessment is performed. For this analysis, 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. A computational fluid dynamics model, including the blade film cooling, is used to calculate the heat transfer to the blade. A thermal finite element model calculates the temperature distribution in the component and the stress distribution is obtained with a structural finite element analysis. Finally a life consumption model is used to determine the creep and fatigue damage accumulation in the component. The tool has significant potential to enhance on-condition maintenance and optimize aircraft operational use.

Acronyms

NLR	National Aerospace Laboratory
RNLAF	Royal Netherlands Airforce
FACE	Fatigue and Autonomous Combat Evaluation
GSP	Gas Turbine Simulation Program
CFD	Computational Fluid Dynamics
FE	Finite Element
FMU	Flight Monitoring Unit
DRU	Data Recording Unit
LDS	Logistic Debriefing Station
SCF	Set-up Configuration File
DEEC	Digital Electronic Engine Control
PLA	Power Lever Angle
HPT	High Pressure Turbine
TIT	Turbine Inlet Temperature
LCF	Low Cycle Fatigue

Symbols

Q	heat flux [W/m^2]
h	heat transfer coefficient [W/m^{2}K]
T_{aw}	adiabatic wall temperature [K]
T_w	wall temperature [K]
η	film cooling efficiency
ω	rotational frequency [rad/s]
L	characteristic length [m]
C_p	specific heat [J/kgK]
T_t	total temperature [K]
p_t	total pressure [bar]
$\tilde{\omega}$	dim.less rotational frequency
$\tilde{\mu}$	dim.less fluid viscosity
$\tilde{p}$	HPT pressure ratio

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 developed at the NLR [1],[2] offers a way to attempt to reduce

maintenance costs and improve safety by applying usage monitoring to predict operational component condition and lifetime consumption and thereby facilitating “on-condition maintenance”.
The next section will describe the several constituents of the analysis tool. The third section then describes the gas turbine component that is analyzed, a first stage turbine rotor blade of the F100-PW-220 engine of a Royal Netherlands Airforce (RNLAF) F-16 fighter aircraft. In section four the tool is demonstrated and evaluated on this component and in the final section some conclusions are drawn and the potential of the tool to support a gas turbine operator is shown

2. Description of the integrated analysis tool

The integrated analysis tool consists of a sequence of software tools and models. An overview of this sequence is given in Fig. 1. 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 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.
FE model	Finite Element (FE) model for calculating temperature and thermal and mechanical stress in hot section components.
Lifing model	for deriving life consumption data from the stress history data.

Flight data acquisition (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 [3]. 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 combustor
- 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.

Engine system performance (GSP)

The Gas Turbine Simulation Program (GSP) is a tool for gas turbine engine performance analysis, which has been developed at the NLR [4],[5]. 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").
For implementation in the integrated analysis tool, 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 (ASCII format) is used to output data for further processing by the fluid dynamics (CFD) and finite element (FE) models.

Computational Fluid Dynamics analysis (CFD)

The Computational Fluid Dynamics (CFD) model is used to accurately calculate the heat transfer from the hot gas stream to the component. The FINE/Turbo code of Numeca is used to construct the model and perform the calculations, solving the Reynolds-averaged Navier-Stokes equations. For these calculations it is important to have detailed information on the geometry of both the flow channel and the different components (blades, vanes). Real components have been measured with a scanning device and this information is combined with information from drawings and other technical documents to define the model geometry. From CFD analysis of the gas flow through the gas turbine values for the heat transfer coefficient h and adiabatic wall temperature T_{aw} (≈ gas temperature) are obtained along the surface of the component. Values of h and T_{aw} are used to calculate the heat flow Q from the fluid to the structure (with a wall temperature T_w).

$$Q = h\,(T_{aw} - T_w)$$

It is hereby assumed that the heat transfer coefficient is not dependent on the blade temperature. The blade temperature is calculated with the thermal FE model and is still unknown when the CFD analysis is performed. Assuming no dependence of h on blade temperature allows for decoupling of the CFD and FE analysis. For every condition two CFD analyses have to be performed: firstly a calculation with adiabatic conditions (no heat flow from fluid to structure) is performed, yielding the adiabatic wall temperature (T_w) distribution. After that a calculation is done with either a constant heat flux Q or a constant wall temperature T_w. In combination with the known adiabatic wall temperature this yields the heat transfer coefficient (h) distribution. Note that the h value varies significantly along the flow path, due to variations in the flow conditions (gas velocity, type of flow (laminar, turbulent), viscous effects, etc).

Finite element analysis (FE)

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 MSC.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.

In the mechanical model, there are two sources for stress in a rotating component: centrifugal forces due to rotation of the component and temperature gradients in the material. The gas bending forces are in most blade designs counterbalanced by geometric measures like blade leaning. The resulting stresses are therefore much smaller than the stress due to the other two sources, and are thus not considered here.

Lifing analysis

A lifing model defines the relation between loading level and lifetime. It 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 forty 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],[7], 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. 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. Description of the turbine blade

The component under consideration is the first stage high pressure turbine blade of the Pratt & Whitney F100-PW-220 engine (Fig. 3). This blade operates in very severe conditions due to its location just behind the combustion chamber. Because of the severe loading, much effort is put in measures to keep the blade from degrading. The blade is fabricated as a single crystal, having a relatively low elastic modulus in radial direction and having good creep properties due to the absence of grain boundaries. Furthermore several cooling mechanisms are applied to keep the blade temperature acceptably low. Firstly the blade is cooled internally by cooling gas flowing through a number of cooling channels inside the blade (see figure 4). Inside the cooling channels turbulators are positioned to increase the heat transfer. The cooling gas is obtained from one of the last stages of the high-pressure compressor and enters the blade through a number of entries in the root of the blade. Secondly the blade is film-cooled which means that cooling gas is injected into the hot gas stream from orifices in the airfoil. This cooling air forms a relatively cool film between the blade surface and the hot gas, resulting in a decreased blade heating.

4. Integrated analysis of 1st stage turbine blade

This section describes how the integrated tool is applied to the real component described in the previous section.

FACE / GSP

The FACE system is used to measure the flight data for a number of missions flown with F-16 fighter aircraft of the Royal Netherlands Airforce (RNLAF). One arbitrary mission has been selected to be used for the current lifing analysis. The gas turbine simulation program GSP is used to translate the flight data to appropriate gas flow properties, which can be used as input for the fluid dynamics and finite element analyses.

CFD analysis

During the transient analysis of a mission it is impossible to do a separate CFD analysis for every occurring engine operating condition. The following simplification is therefore used. By carefully analyzing the fluid dynamics equations, it is observed that under certain assumptions only three dimensionless groups are needed to characterize any dimensionless flow property in the engine for any operating condition. These dimensionless groups are:

$$\tilde{\omega} \equiv \frac{\omega L}{\sqrt{c_p T_t}}, \qquad \tilde{\mu} \equiv \frac{\mu(T_t)\sqrt{c_p T_t}}{p_t L}, \qquad \tilde{p} \equiv \frac{p}{p_t}$$

where $\tilde{\omega}$ can be seen as a dimensionless rotational frequency, $\tilde{\mu}$ as a dimensionless fluid viscosity and $\tilde{p}$ expresses the pressure ratio over the high pressure turbine (HPT). With GSP the variation of these three groups during a representative mission is analyzed. This results in the definition of seven operating points which cover the complete operating envelope of the engine: one center point and two more points in each dimension are defined. Then for each of the seven points CFD analyses are performed and a tri-linear interpolation function is used to obtain the results for any other condition. In this way only CFD analyses for seven conditions have to be performed to obtain the results for any arbitrary condition. During the transient mission analysis the values of the dimensionless groups for every time step are calculated by GSP, and the corresponding heat transfer and gas temperature values are obtained from the interpolation function.
The CFD model also allows for incorporating the effects of blade film cooling on heat transfer. Cold air is injected through cooling orifices into the outer flow to provide a cooling air layer with effective temperature T_{film} between the blade surface and the outer hot gas flow. The film temperature T_{film} depends on the film cooling efficiency ɖ and the injection temperature T_{inj} in the following way:

$$T_{film} = T_{gas} - ɖ(T_{gas} - T_{inj})$$

Modeling all separate cooling orifices in the airfoil would require a very fine computational grid, resulting in very long calculation times. Therefore a row of orifices is simulated by a cooling slot with the same width as the local grid and covering the blade from root to tip. The cooling efficiency of such a slot is much higher than that of an orifice row (0.8 compared to 0.15 [8]), so a correction is made by increasing the injection temperature, resulting in a more realistic film temperature and heat transfer.

Finite Element analysis

The thermal analysis for the current component is quite complex. The blade is heated from outside by the hot gas and at the same time cooled from inside by the cooling gas. Moreover, the cooling gas is eventually injected into the hot gas stream through cooling orifices to establish film cooling. The blade temperature is therefore dependent on hot gas temperature and cooling gas temperature, but on the other hand the cooling gas temperature is dependent on the blade temperature. Such a coupled fluid-structure problem must be solved in an iterative way. Because it would take too much computation time to solve the complete transient problem in an iterative way, a simple model is used to derive an approximation. This model, which is shown in figure 5, is used to derive a relation between the blade temperature distribution and the turbine inlet temperature (TIT). During the transient analysis this approximated blade temperature distribution is used to calculate the cooling gas temperature distribution, which together with the hot gas temperature distribution is used as input for the thermal analysis. This eliminates the coupling between fluid and structure.

The thermal model is thus used to calculate the temperature distribution in the component. For each finite element on the airfoil of the turbine blade, the heat transfer coefficient and the local gas temperature follow from interpolation in the CFD results. In the cooling channels inside the blade, the heat transfer coefficient is assumed to be constant. The cooling gas is heated while it flows through the hot blade and the local gas temperature is calculated from an approximated blade temperature distribution as explained above. 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 dimensionless groups (used to determine h and T_{aw}), cooling gas inlet temperature and turbine inlet temperature (used to approximate the cooling gas temperature rise) 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. 6. 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 and would allow for a coupled fluid-structure analysis.

The mechanical model calculates the stress and strain distribution in a component. 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. 7.

Lifing model

For the first stage turbine blade both creep and Low Cycle Fatigue (LCF) are important damage mechanisms. Therefore a combined creep / fatigue lifing model is applied. The strain history of the mission, calculated with the mechanical FE model, is used to determine the fatigue damage. The fatigue damage according to Miner's rule is given by

$$D_{fatigue} = \sum_i \frac{n_i}{N_{f,i}}$$

where n_i is the number of cycles at a certain load level and $N_{f,i}$ is the number of cycles to failure at that load level. End of life is reached when the damage becomes 1. This rule is applied to the maximum principal strain sequence for every node in the FE model, yielding the fatigue damage distribution in the blade after one mission. The result is in Figure 8. The creep damage is calculated with Robinson's rule:

$$D_{creep} = \sum_i \frac{t_i}{t_{r,i}}$$

Equivalent to Miner's rule t_i is the time at a certain stress and temperature and $t_{r,i}$ is the corresponding rupture time. This rule is applied to the equivalent stress and temperature sequence for every node. The calculated creep damage is shown in figure 9. Combining these two results yields the total life time distribution (Fig. 10). This number is obtained by adding the creep and fatigue damage contributions and inverting the number. As the damage in Figs 8 and 9 is calculated for one mission, the total life in Fig. 10 is also given in number of missions. As can be seen in these figures, the shortest life is located at the spots with the highest creep damage, indicating that creep is the critical failure mechanism for this component.

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 and adiabatic wall temperature obtained from the CFD analysis. It must be noted that the problem under consideration is at the edge of the capabilities of current CFD codes and a number of assumptions and approximations must be made to even get a solution. Firstly slot cooling is used in stead of orifice cooling and h is assumed to be independent on wall temperature (decoupling of CFD and FE). Furthermore tri-linear interpolation between 7 standard conditions is used to obtain results for any arbitrary condition and finally the thermal interaction between (internal) cooling gas and blade material is removed by approximating the cooling gas heating (no iterative solution of FE problem). Off coarse, these assumptions decrease the accuracy, but still the adiabatic wall temperature can be calculated within about 10% and the heat transfer within a factor 2. 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 much more importance. The mechanical FE model has an inaccuracy of less than 2%, provided that the right and accurate material data is used. For the 1st stage turbine blade analysis, the single crystal material data were not available, and data for an isotropic superalloy were used. 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 and creep rupture curves. It is therefore a fundamental material property phenomenon, which has its effect on the lifing model inaccuracy. Development of lifing models must be focussed on model types, which are based on material data with little scatter (like crack growth data). Another problem is the strong sensitivity of calculated life on deviations in stress and temperature, especially for creep life (see figure 11). A small deviation in stress and especially temperature is therefore amplified in the life prediction.

Due to the assumptions in the CFD analysis and the unavoidable inaccuracy in the life prediction, the tool is not yet suitable to do absolute life predictions. However, the tool is very useful for relative life predictions or sensitivity studies.

6. Conclusions and Potential

An integrated lifing analysis on a complex gas turbine component has been demonstrated. The internally and film-cooled turbine blade has been analyzed with a sequence of software tools and models. Especially the CFD model used is state-of-the-art for current CFD codes, using a slot-cooling model to represent the blade film cooling. It has been demonstrated that the mechanical and thermal loads of the turbine blade can be calculated from operational flight data, and that subsequently a combined creep and fatigue 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 CFD model, having the possibility to model orifice cooling, can improve the accuracy further. The present tool, with its limited accuracy can be used to perform relative life assessments and sensitivity studies.

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 for example be used to optimize the planning of operational deployment of the aircraft.

7. Acknowledgements

This work was supported by the Netherlands Agency for Aerospace Research (NIVR) under contract number 01613N.

8. References

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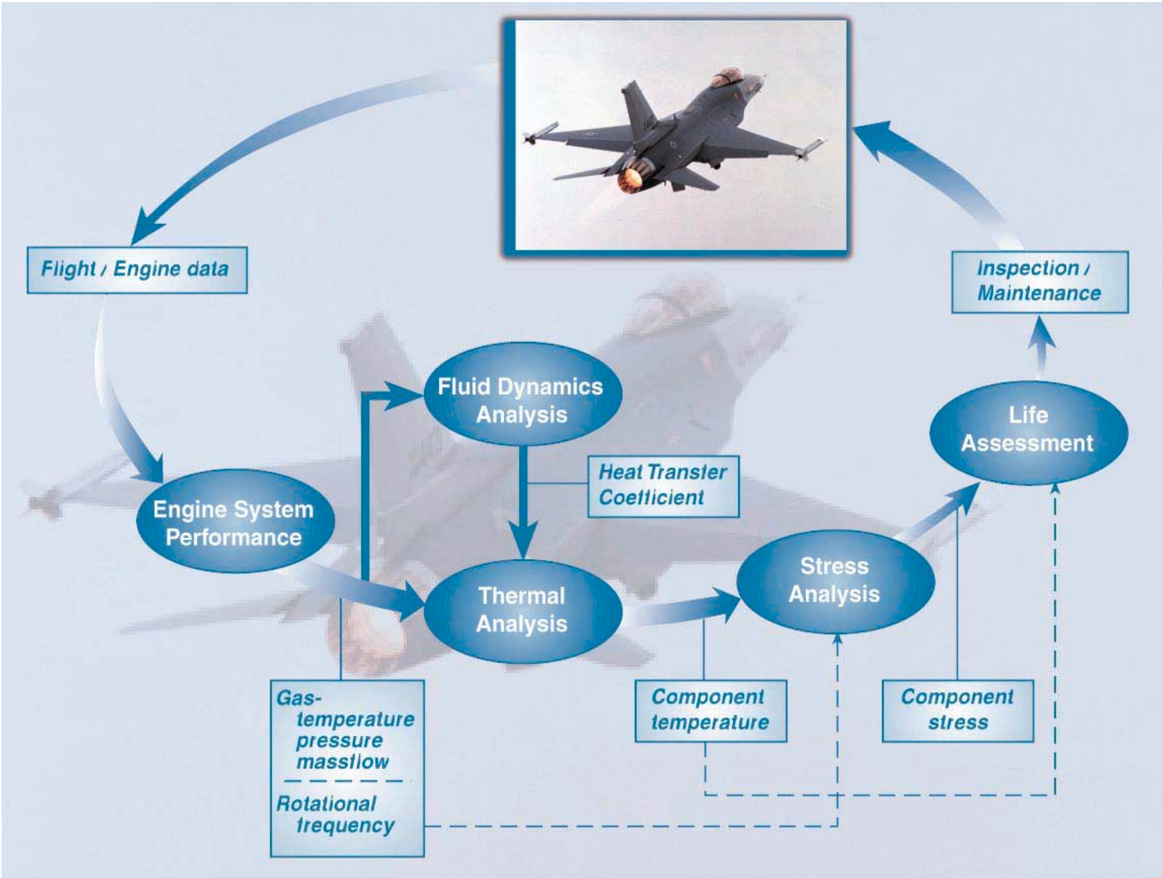


Figure 1: Overview of the integrated analysis tool.

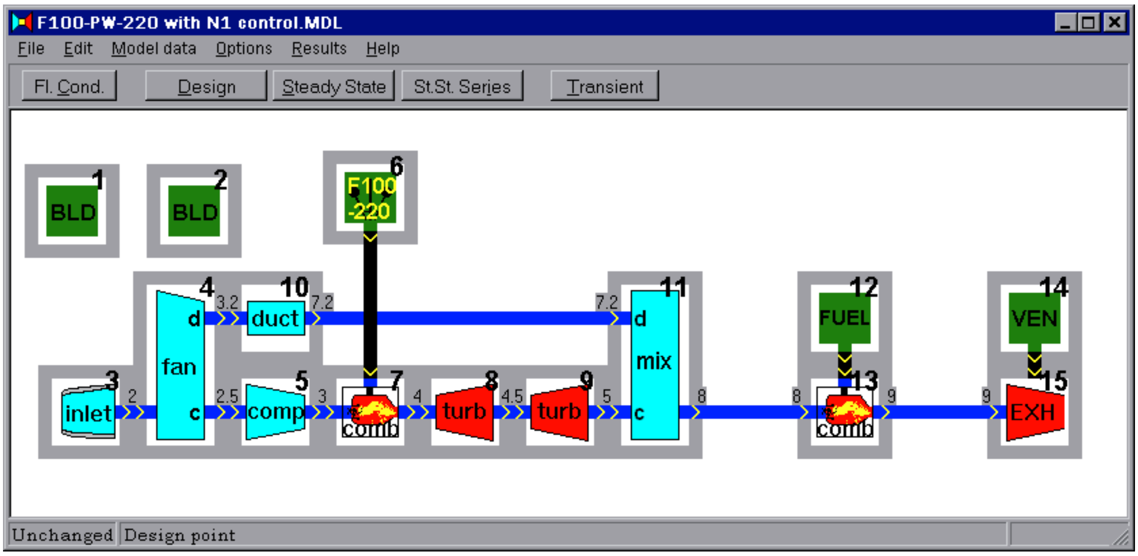


Figure 2: GSP model of the Pratt & Whitney F100-PW-220 turbofan engine.

Figure 3: 1st stage turbine blade

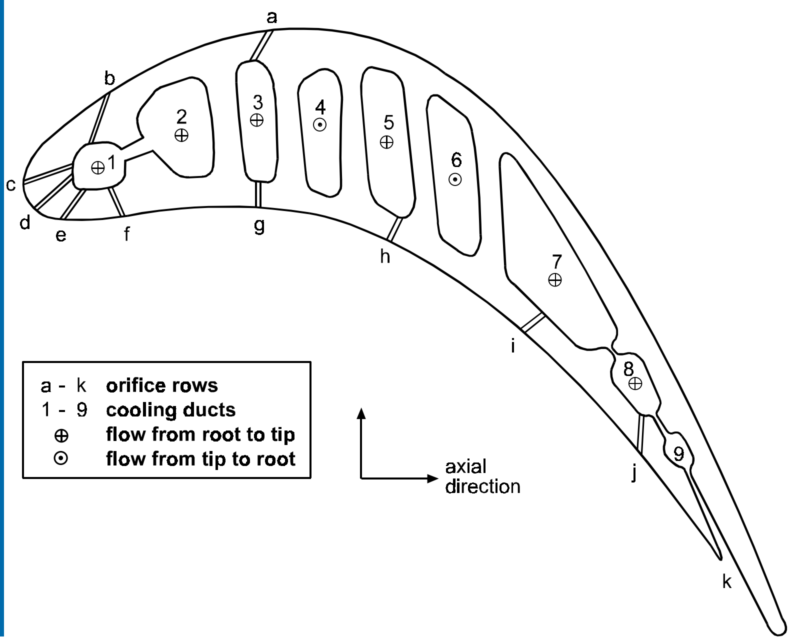
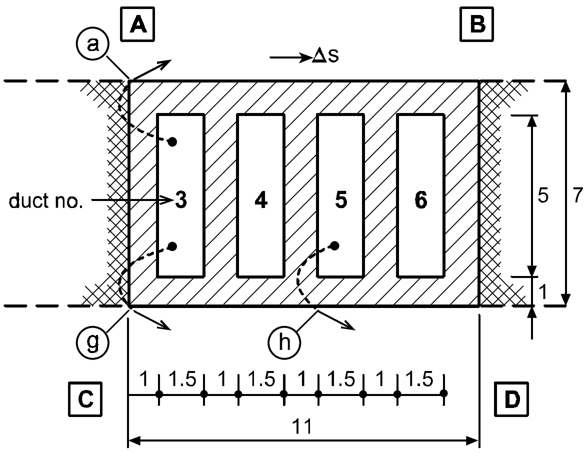
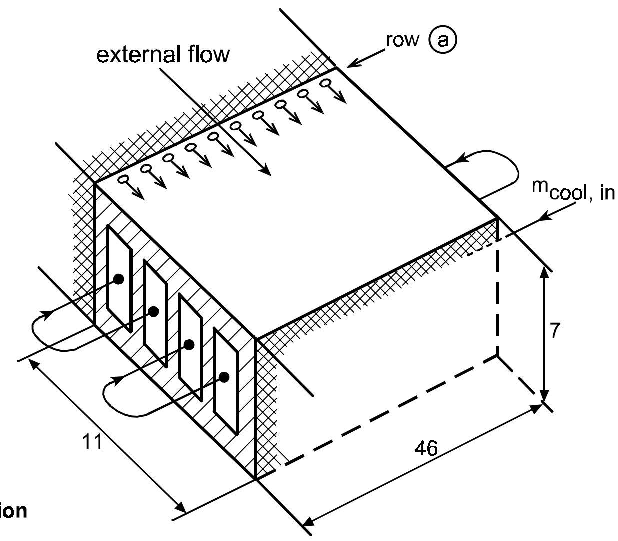


Figure 4: Overview cooling ducts and orifice rows





orifice row	a	g	h
eff. width (mm)	0.053	0.014	0.013

metal
insulation

Figure 5: Model to approximate cooling gas temperature increase

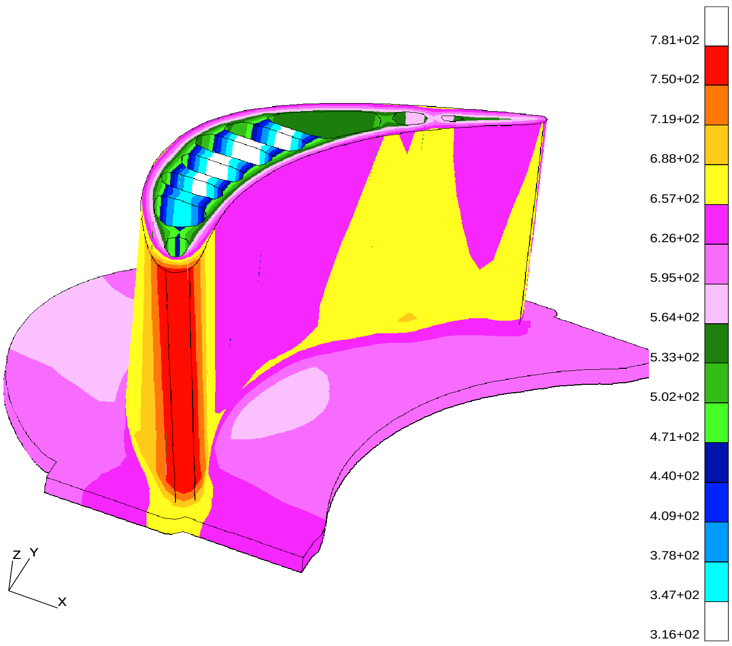


Figure 6: Temperature distribution (^{o}C) in the lower half of an internally cooled turbine blade.

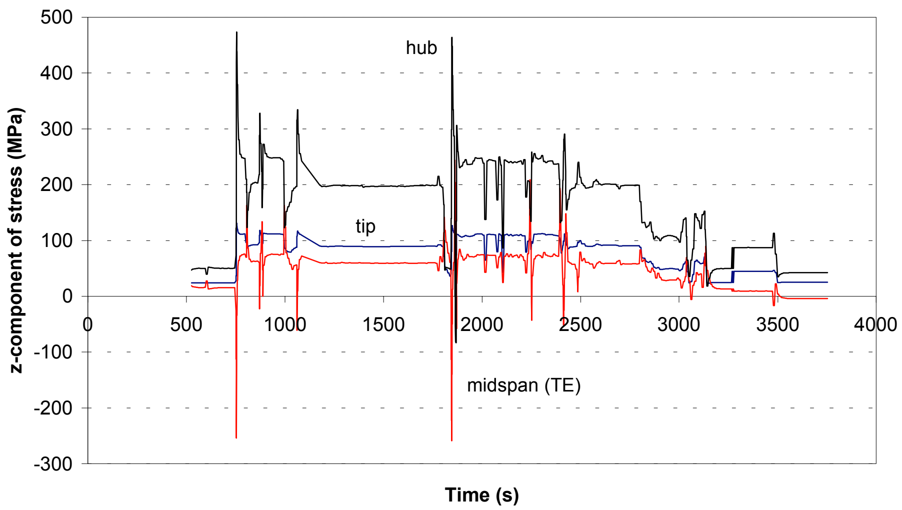


Figure 7: Variation of stress in time for three different locations on the blade.

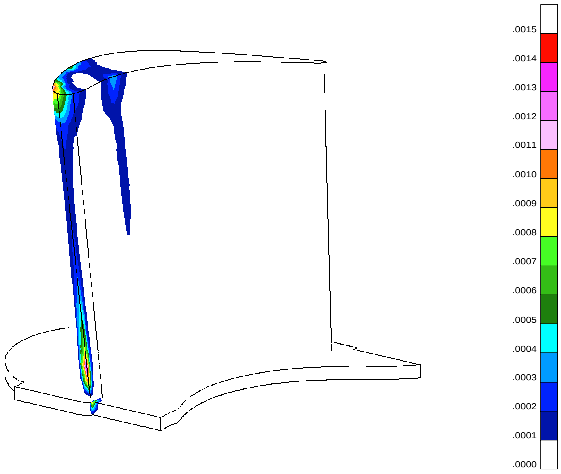


Figure 8: Fatigue damage distribution.

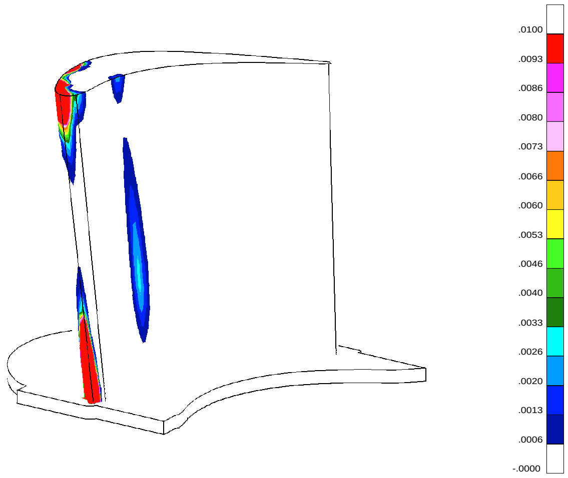


Figure 9: Creep damage distribution.

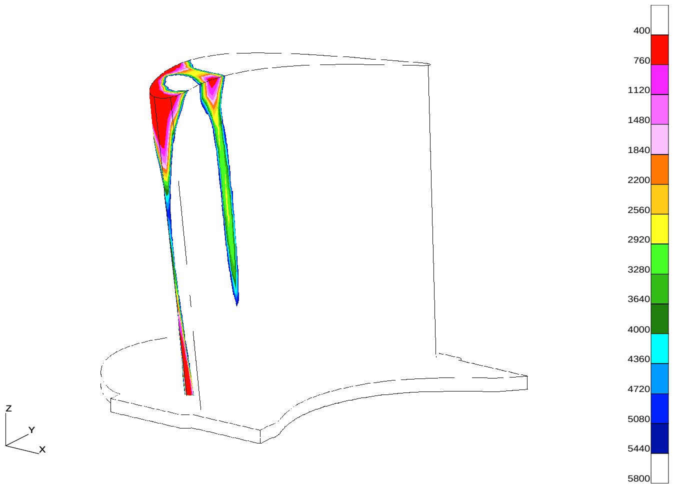


Figure 10: Predicted total life distribution.

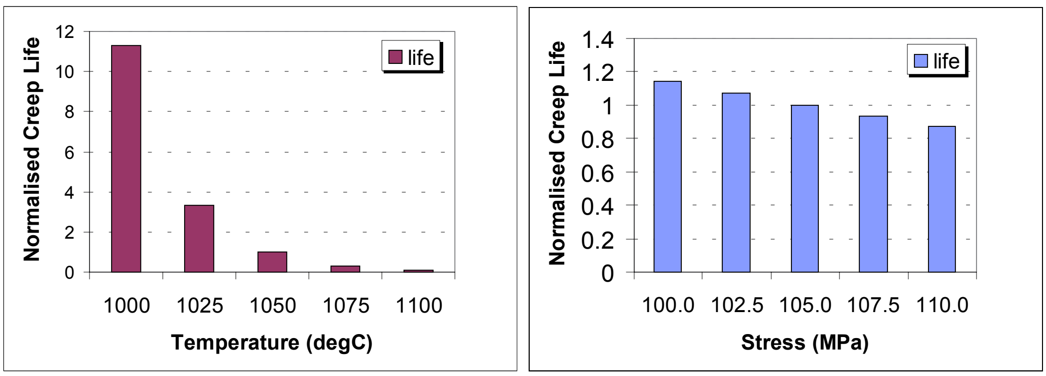


Figure 11: Temperature and stress sensitivity of creep life.