

GT2013-96033

NEW SIMULATION PROCESS FOR THE LIFE MANAGEMENT OF THE GAS TURBINE ROTORS

Paolo Di Sisto
paolo.disisto@ge.com
GE Oil & Gas
Florence, Italy

Mauro Parodi
mauro.parodi@exemplar.com
Exemplar Srl
Turin, Italy

ABSTRACT

The Gas Turbine manufacturers are continuously engaged in providing to their customers machines with higher performances, longer lives, better reliability and availability. Since the late 70's, the gas turbines are designed by using computational tools able to simulate through **physic based models** the thermal and mechanical behavior of the engines by predicting with high accuracy gas turbine internal pressures, temperatures, stresses etc., across the full flange to flange architecture; but it is only in the last one or two decades that computational predictions have done a huge step forward thanks to the great progress of the information technology. What was before designed with a worst case deterministic approach, it is now designed through optimization, by assessing many different configurations and it is made robust through sensitiveness and statistical assessments.

One further step forward has been made possible by new software tools able to manage **simulation process** flows made of a variety of applications, including commercial CAD/CAE software, in house software and Excel spreadsheets. The simulation process described in this paper has been developed for rotor life assessments and the proprietary company is currently using the process to manage part of its heavy duty gas turbine fleet engaged in the oil and gas application for the estimation of risk to extend rotor life beyond inspection interval [1].

1. INTRODUCTION

The gas turbine rotors have a limited life and for this reason are subjected to a maintenance program involving removal, disassembly and thorough inspection (i.e. **rotor life management** [2-3]). Reliable maintenance programs should even include the estimation of the risk to extend rotor life beyond inspection interval. The risk assessment should include not only a thorough investigation of all the inspection findings, but shall even be based on the estimation of the rotor residual life. Automated life predictions may help to quickly address the investigation, allowing customers to restart machine in few weeks, without the need of replacing meantime the rotor under investigation. The simulation process described in this paper has been developed with the use of a commercial code and it is able to manage a complete rotor life assessment by using as input the rotor operating data (e.g. ambient temperature, compressor and exhaust discharge temperatures, rotor speed) and all the relevant inspection findings, in particular it is able to estimate with the support of physic based models: 1) all secondary flows internal to the gas turbine main flow path in terms of mass flow, temperatures and pressures, 2) all rotor metal temperatures and stresses, 3) hours and cycles to crack initiation and propagation for all rotor parts (without and with inspection findings), 4) rotor defects per million of opportunities (DPMO) before next inspection.

2. ROTOR LIFE MANAGEMENT BACKGROUND

Gas Turbine rotors are highly energetic parts that are most susceptible to burst and therefore their life assessments should be based on crack initiation; in general, rotor cracks should be considered cause of scraping, while indications as scratches and pitting should be removed and addressed by estimating the rotor residual life by including in the simulation even the modified rotor geometry. Even rotor crack propagation assessments should be carried out, because rotors shall be able to operate with defects that may have not been detected by inspections, and assessment shall be performed using the probability of detection of the applicable non-destructive test. Customer rotor historical data (e.g. accumulated operating hours and cycles, compressor and exhaust discharge temperature etc.) may be used to better define the real status of the rotor and it may be leveraged to forecast future rotor operating conditions. The life estimations are typically done with tools able to simulate the gas turbine thermal and mechanical behavior, and the accuracy of the predictions are validated through extensive test campaign, but they are rarely tuned with defects generated during operation, because cracks or crack-like defects are not common in gas turbine rotors. In the Oil and Gas application, gas turbine are mainly operated in continuous duty, for this reason the rotor life management (RLM) described by this paper mainly focuses on turbine wheels and compressor aft shafts and in general with all rotor parts operated at high temperature for which, material strength may degrade with time (e.g. aging embrittlement) and creep failure mode is of most concern, but however for the sake of safety, it even assesses less critical components as the compressor wheels, for which heavy pitting or deep handling scratches are always of main concern.

3. PYSHIC BASED MODELS

The simulation process described in this paper manages the following computational physic based models: 1) secondary flow model, 2) rotor thermal models and 3) rotor structural models. These models, specific for the rotors, are supported by the gas turbine performance model output data and by mono or bi-dimensional computational fluid dynamic model output data for both compressor and turbine flow path sections (CFD). The secondary flow model is a net formed by mono-dimensional elements; the net includes all the flows that actively take part to the thermal behavior of the rotor, with the exception of the main flow paths (i.e. compressor and turbine) that are included as boundary conditions (inputs from CFD); each net element simulates a portion of the air flow, dedicated elements are available for labyrinth seals, rotating cavities, impellers etc. and for each element the execution of the net model estimates mass flow, air temperature, air pressure and heat fluxes between flow and metal. The secondary flow model doesn't include the rotor physic structure (e.g. rotor thermal inertia), the metal

temperatures are supplied as boundary conditions and therefore the net calculations shall be performed iteratively (by replacing the metal temperatures) till heat fluxes (btw air and metal) don't reach convergence. The main thermal model is an axial-symmetric model that includes the rotor structure and the secondary flow net (Figure 1); the air temperatures and air pressures estimated by the secondary flow model are included as initial conditions, while the mass flows as boundary conditions. During the execution of the thermal model, the metal temperatures, air temperatures and air pressures are estimated iteratively till heat fluxes don't reach convergence; iteration is performed automatically by the code.

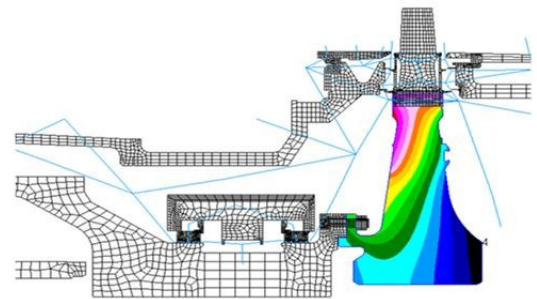


Figure 1: thermal model of a portion of the HP rotor

3D features as turbine dovetails are even sub-modeled so to correctly estimate the 3D thermal effects; in particular, the models are executed (Figure 2) using as boundary conditions the convection coefficients and bulk temperature estimated by the secondary flow model.

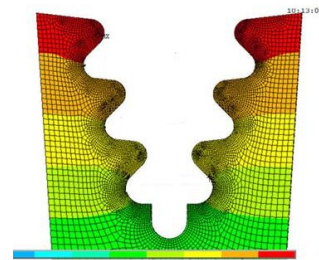


Figure 2: Midsection of Dovetail thermal model

The main structural model is an axial-symmetric model (Figure 3), buckets/blades/bolts are simulated with orthotropic materials, the metal temperatures (applied as body loads) and the pressure (applied as surface loads) are imported from the thermal model, while rotor speed is included as an inertial load. The thermal and structural axisymmetric models include even a portion of the casings, though the stator components are not scope of the RLM their presence allows to estimate the mutual thermal expansion and therefore correctly quantify the High Pressure Package Seal (HPPS) clearances between stator and rotor parts; it should be noted that this clearance estimation is

fundamental since it directly affects the mass flow rate of the secondary flows and consequently the temperature in the forward wheel space and the high pressure turbine rotor metal temperatures. This calculation is usually a manual iterative process that provides new clearance to the secondary flow model and extracts updates mass flow rates until convergence is reached.

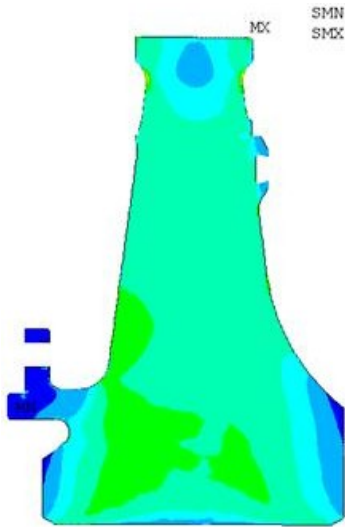


Figure 3: Turbine wheel Von Mises stresses

Dovetails are even simulated with 3D sub-models so to correctly predict local stresses (Figure 4). Both thermal and structural sub-models are fundamental to RLM because the circumferential averaged predictions of the axisymmetric models are not directly applicable for not axisymmetric features as dovetails and even the technique to estimate the correct stresses by using stress concentration factors (K_t) is too conservative for LCF and creep damage assessment.

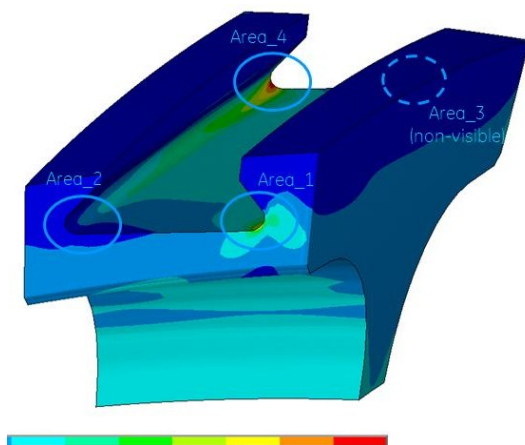


Figure 4: compressor wheel Von Mises stresses

4. PROCESS DESCRIPTION

All the models/operations previously described are usually managed in a manual way since they involve many different disciplines and simulation tools. This often leads to a deterministic approach, because the manual process is very time consuming.

An analytical approach to RLM requires the capability to drive all the operations previously described in an automated way, so a dedicated software tool is needed to manage input and output of each single task and to exchange data and files between different applications. The development of such process enables the automatic execution of many different analyses under different conditions.

The process described by this paper is formed by the two following main components:

1. Transient component (Figure 5)
2. Design of experiment (DOE) component (Figure 7)

The transient component performs different tasks that are preliminary to the DOE:

- K_t calculation for holes
- Startup profile sensitivity
- Detection of the locations with shorter life
- Transient scaling factors calculation
- Re-machining

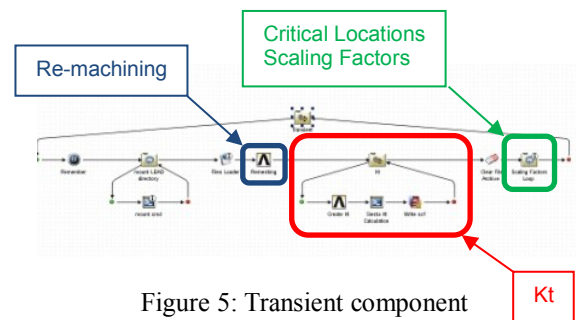


Figure 5: Transient component

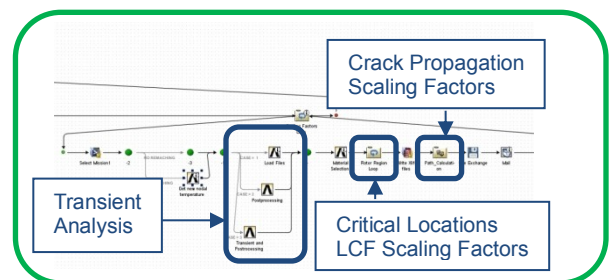


Figure 6: Scaling factor sub component

The tool for the estimation of stress concentration factors (K_t) around holes (e.g. bolt holes) is based on geometrical data only

and therefore is performed before any stress calculation, values are saved in a text file and are used by the next components to linearly correct the stress calculated by the axial symmetric model. The simulation of one or more gas turbine missions is implemented in order to account for the different transient conditions that can occur; three different profiles are modeled in the current revision of the process: normal startup, hot restart and trip. The individuation of the locations with shorter life is also a preliminary task that may be selected to speed up the later DOE component execution. Before starting the process, user should divide rotor in regions, than process performs screening by identifying per each region the locations with shorter LCF life. Process has even provision to screen through shorter crack propagation life, however this option has not been used yet because much more time consuming and because in heavy duty rotors, stresses are essentially driven by centrifugal load, furthermore stress concentrations are typically supported by high net section stresses therefore locations with shorter LCF life tend to coincide with locations with shorter crack propagation life. In any case, it is best practice to divide each rotor part in small regions so that in each region, all its locations are as much as possible loaded at the same way (e.g. wheel bore, fillet, rabbet, grove for balancing weights). The fourth step performed by the process is to estimate the transient scaling factors for each location individuated by the previous screening; the factors are estimated for each stress component (e.g. σ_x , σ_y) as ratios between the values estimated at the transient time steps individuated by the LCF assessment and the values estimated at steady state condition. The scaling factors are used later by the DOE component in order to include the transient effects into the LCF analyses and into the crack propagation analyses. It should be noted that the scaling factor approach is reliable only if mechanical simulations are performed with elastic material proprieties and if parts are linearly impacted by the selected vital X's. The remodeling of the mechanical physic based model has been also implemented in order to include the effects of re-machining operations that can be executed after inspection. Those re-machining activities have the purpose of eliminating scratches or defects but shall be investigated to properly estimate their impact on the total life of the components.

The DOE component has the capability to manage DOEs, by changing the numerical values of input parameters according to the chosen plan. The process manager automatically repeats the calculation sequence replacing the numerical values of input parameters and managing the models updates as well as data mapping between the different applications.

User may select the DOE variables between the following parameters:

- Ambient temperature
- Compressor efficiency
- Firing temperature
- Dovetail wear

- HPPS clearance
- Re-machining
- Type of mission;

Other parameters may be added to the list by performing minor process modifications; in the early RLM development phase, screening was performed on many different parameters related to geometric details as bucket twist-locks and cover plate clearances, bearing labyrinth seal clearance etc. in order to measure their influence on the metal temperatures.

The DOE component is composed by three main sub-components. The first one is the thermal mechanical component (Figure 7 square 1 and Figure 8) that manages the secondary flow simulation, the thermal simulation and finally the mechanical axisymmetric simulation. For each DOE combination the component iterates by updating each time the metal temperatures and the HPPS clearance inside the secondary flow model using the thermal and mechanical predictions of previous iteration. The loop stops when thermal and mechanical model predictions match results of previous iteration within a given tolerance. This subprocess takes at maximum three iterations to converge.

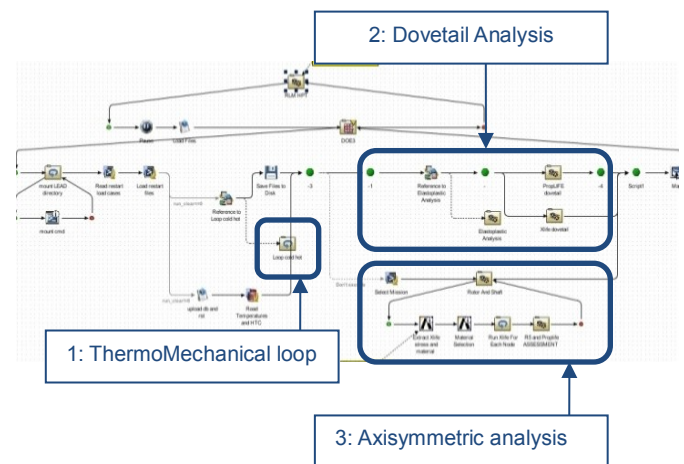


Figure 7: DOE component

Figure 8 shows an expanded view of the thermo-mechanical loop. The casing and the rotor are analyzed separately; displacements are then extracted and post-processed to calculate the clearance. In figure 9 is shown a detail of the secondary flows model that provides mass flow rates, pressures, boundary temperatures and swirls factors to the thermal model.

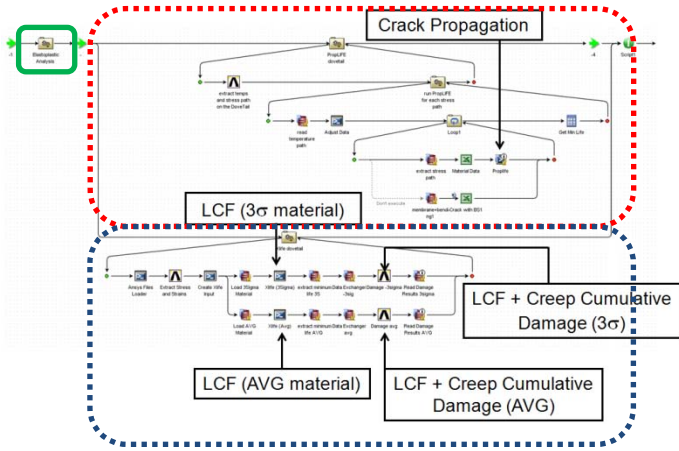


Figure 10: dovetail sub component

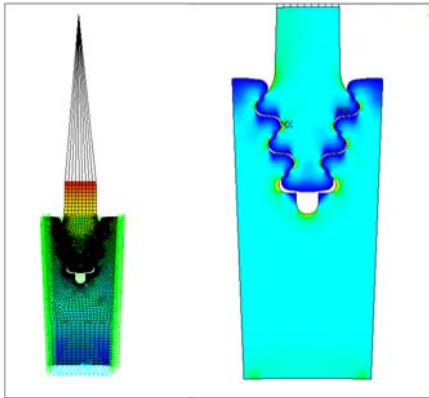


Figure 11: dovetail plane strain sub model

Other parameters that are accounted in the dovetail analysis are the rotational speed of the disc and the wear (due to the cleaning of the dovetail after inspection) that can lead to a different contact pressure on the three tangs so that higher than expected stress concentrations can arise. The uniform wear is simulated by using three different sub-models, one representative of the dovetail design size, one of a medium wear and one of a heavy wear, while the not uniform wear is simulated by modifying the properties of the contact elements that are positioned in between bucket and rotor dovetails. The last subcomponent is the rotor and shaft component that evaluates all axisymmetric rotor features versus LCF plus creep damage and crack growth propagation. Basically the same operations that have been described in the transient component are executed, but a steady state analysis is used instead of a full transient analysis due to execution time restrictions while analyzing hundreds of configurations; transient effects are obtained scaling the steady state results by the scaling factors previously calculated.

5. PROCESS MANAGER

The process is formed by a flow of data and files that are exchanged between the different applications and disciplines. It is split in simple components that execute simple operations, and in complex components that execute complex sequences of operations and/or using calculation codes; they can be further collected in tasks (single execution), loops (run as many times as the control condition is satisfied) or design drivers (DOE, Montecarlo, Optimization) as shown in Figure 12.

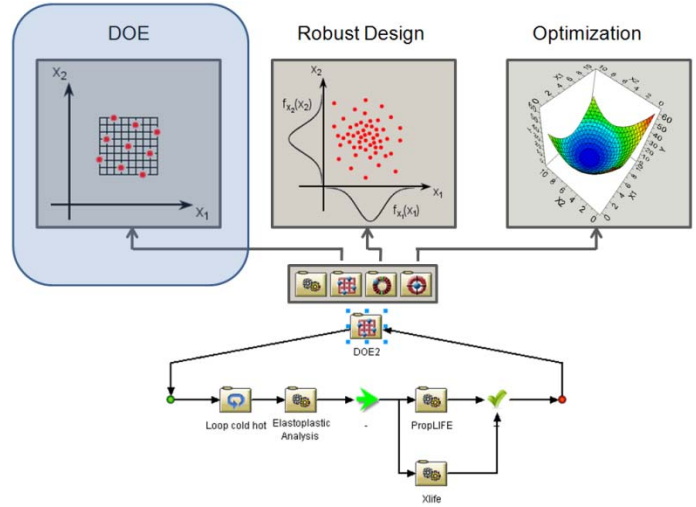


Figure 12: Design Drivers

Components execute the basic steps of the more general process, reading data from file, modifying input files for any analysis code (in house or commercial, e.g. FEA, CFD), executing Excel spreadsheets etc. They are connected each other sequentially or in parallel following the logics of the process (Figure 13).

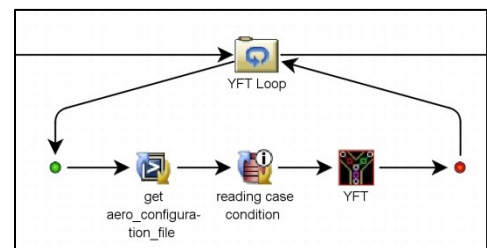


Figure 13: connection between components

When two components are connected, special links are activated enabling data and file exchange between upstream and downstream objects.

Figure 14 shows an example of connection between components usually referred as data mapping., where yellow line indicate input data coming from the upstream component and the blue line indicate output data provided to the next components.

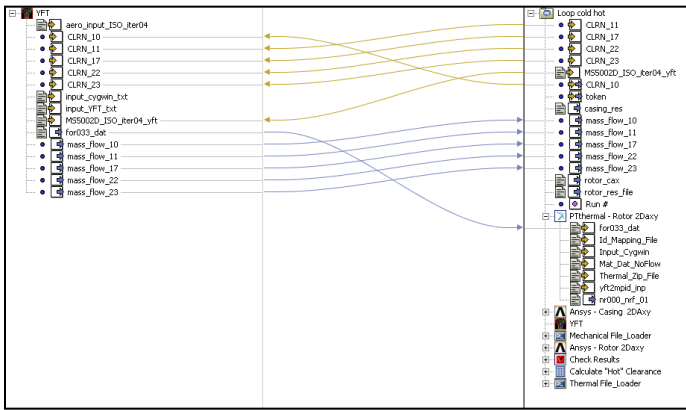


Figure 14: example of data-mapping

Branches can be enabled defining whether execute or not each component or task basing on a control condition, so all the main tasks (e.g. transient calculations, hot-cold loop, creep calculations, etc) have been created as independent modules that can be skipped wherever results are already available from a previous run.

Most of the operations executed in the main components are common to different turbines and can be easily implemented in other processes (e.g. casing life management as well as wheel design optimization).

The main purpose of the proposed methodology is process automation, that compresses the overall execution time of orders of magnitude enabling the analysis of many different configurations of the turbine; a positive side effect that makes this approach even more interesting is standardization, since it uses certified methodologies and tools, references the same resources (in terms of data, spreadsheets, revision of executables and solvers) every time it is executed, making each execution of such a complex sequence of events fully replicable.

6. PROCESS DEVELOPMENT/PERFORMANCES

The whole process is formed by 160 process steps; its development was carried out for a specific heavy duty gas turbine rotor (pilot rotor) by a process expert with the support of two gas turbine experts (i.e. heat transfer and mechanical senior engineers) for a total of 100 working days. The execution of all the process steps, using only one workstation (CPU: 8Gb, 64bit, 3.2GHz), requires just 2.5 hours, making possible to execute a full DOE of 143 runs in less than one week, or even one night if more hardware and software resources are available. The process has even successfully been tested on a different type of heavy duty rotor, replacing the physic based models with the appropriate models applicable to the new rotor and adding new vital X's (e.g. nozzle diaphragm clearance, clearance between nozzle sectors); in general, a

replacing activity is rather quick and most of all makes the new rotor life assessment totally consistent with previous ones.

7. PROCESS INPUTS

The process has been structured to have all the inputs at the top level. The requirements for the execution are:

- Definition of DOE plan (selection of parameters, variation range definition, combination of parameters)
- Definition of analysis models (structural, thermal and secondary flows) and boundary data (GT performance and CAFD outputs)

The parameters driving the life of the rotor are hereafter referred as vital X.

The user may select vital X's from the list of available parameters designed for variation during analysis (refer to process description). Even X's ranges (Figure 15) may be selected between a list of already tested ranges; whenever using new vital X's and/or ranges or using the process on a new rotor architecture, user should carefully validate the selection with some preliminary tests in order to check if the physic based models are able to manage selected ranges (e.g. convergence of the secondary flows model).

	X	Min	Max
Ambient temperature	Tamb_eff [°C]	-32	50
Compressor efficiency	Eff [%]	90	100
Firing Temperature	Tfire [°C]	746	968
High Pressure Package Seal Clearance	HPPS [mm]	0.972	1.600
Wear on first tang	wear1 [mm]	-0.10	0
Wear on second tang	wear2 [mm]	-0.10	0
Uniform wear on dovetail	Dovetail_wear	0	2

Figure 15: example DOE input setup

DOE Design should be selected between Factorial and Face Centered Composite (FCCD). Factorial may be used during the vital X's screening, while FCCD is the best suited to generate the final results; it should be noted that FCCD has been successfully tested even whit 7 different vital X's. Gas turbine performance and CAFD outputs should be consistent with DOE plan. The thermal transient (missions) simulations have intentionally been left outside the process, because they are part of physic based model development phase.

8. PROCESS OUTPUTS - TFs GENERATION

Most of the physic based model outputs are connected to the process and can be quickly viewed by the user, but with the generation of the transfer functions (TF's), the full process is synthetized into a bunch of equations. TF's are created using the DOE component outputs for the prediction of:

- Rotor low cycle fatigue life
- Rotor creep life
- Rotor crack growth crack life,

plus for some fundamental variables as:

- WSTs (wheel space temperature)
- Metal temperatures.

They are able to cover in detail all the surfaces of the rotor components; as example in Figure 16 the TF's locations for the turbine rim are highlighted.

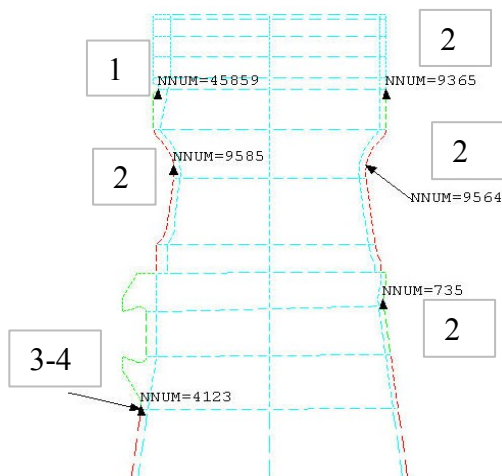


Figure 16: locations with TF's

9. TFs (AND PROCESS) VALIDATION

Pilot rotor metal temperature and WST TF's have been validated through an extensive prototype test campaign. WST TF's validation has even been performed on eight different engines.

Figure 17 summarizes the good match of the forward WSTs between predicted and actual for the eight different engines (x axis), the error is in percent (dotted line), while the values of the actual temperatures (red and blue curves) as well as the predicted temperatures (green curve) have been omitted for IP reasons.

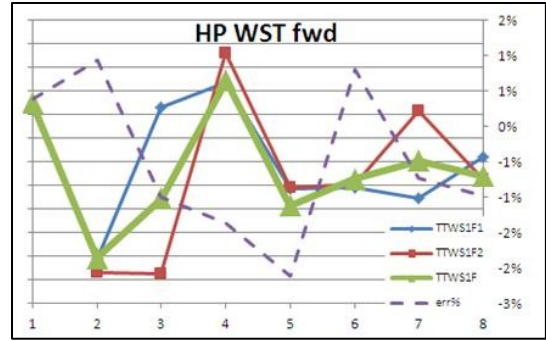


Figure 17: WST TF validation

The goodness of the TFs validation is even confirmed by how have been set seven of the eight HPPS clearances so to match predicted with actual, Figure 18 shows the clearance trend for each engine (values are omitted for IP reason):

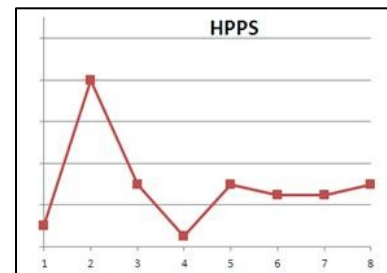


Figure 18: HPPS cold clearance

It should be noted that the HPPS clearance is the most challenging vital X of the pilot rotor because due its position inside the engine, it is very difficult to measure; the other two vital X's that affect forward WST are: 1) the compressor efficiency that can indirectly be estimated by using the compressor discharge temperature and pressure engine control panel readings, and 2) the ambient temperature. It should finally be noted that the wheel space temperatures (WST) TF's are the fundamental bricks of the process, because they are used in the first phase of the RLM when it is verified if the gas turbine under RLM is consistent with the physic based models of the process.

10. RESIDUAL LIFE PREDICTIONS

The TF's may be used for both deterministic and statistical life assessments. The deterministic assessments is performed using Miner equation; in doing so the historical data are grouped per year (Figure 19) and for each year, data are subdivided inside vital X sub-ranges (e.g. ambient temperature between 10°C and 30°C = 50% of the time). Partial damages are then estimated, by using the TF's and associating the proper amount of time to

each combination of sub-range vital X's and finally, they are summed together using the Miner assumption (Figure 20).

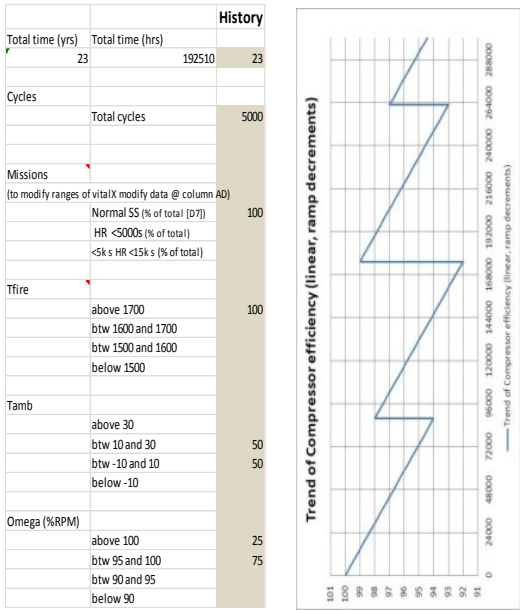


Figure 19: LCF inputs

The statistical assessment is used to determine the defect per million of opportunities (DPMO) for one or more specific operating conditions; DPMO are estimated by assigning to each vital X the proper variation (e.g. process capability).

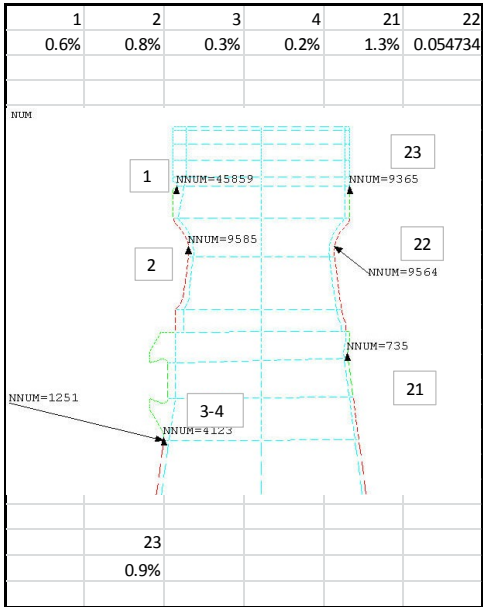


Figure 20: LCF damage per location

The assessment becomes mandatory when few degrees difference in metal temperature or some mils of not uniform

wear (e.g. turbine dovetails) may sensible reduce (x10) the residual life of the component. As example it is shown the comparison between the turbine wheel LCF+creep damage predicted with both 2nd and 3rd order TF's, the damage is acceptable if less than 1 and the DPMO can be estimated by dividing the amount of cases with damage above 1 per total.

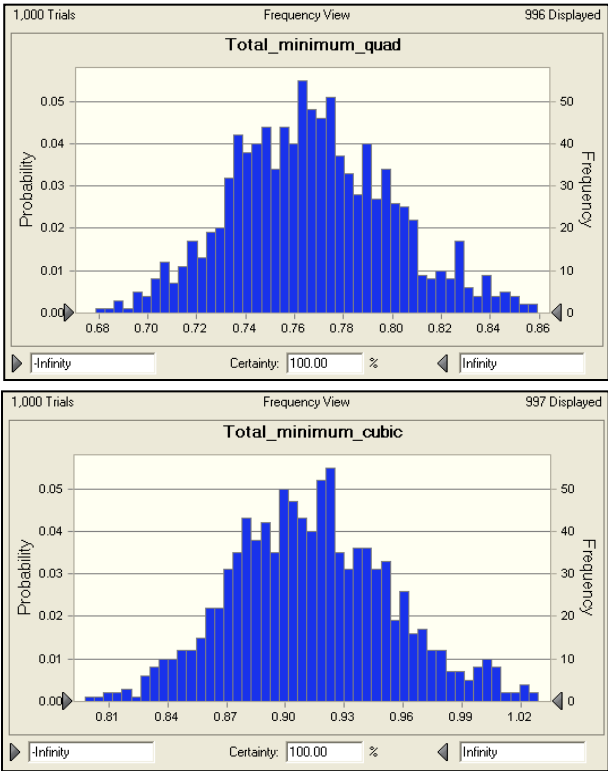


Figure 21: dovetail damage

One other example of statistical assessment is the crack growth graph of Figure 22. The crack growth (green curve) predicted through TF is plotted together with the worst (pink curve) and best (orange curve) DOE combinations, this means with the curves inside which the TF prediction (DOE envelope) should always fall. It is plotted the upper limit (i.e. red curve) as well; it is estimated from the outputs of all the DOE cases and it represents the envelope of the end of life cycles for the different combinations. The amount of residual life cycles, this means the X axis delta between green dot (defect size) and the intersection of the green curve with the red curve can finally be estimated including even the contribution of the variation that for simplicity is calculated only for the final crack size through a Montecarlo simulation.

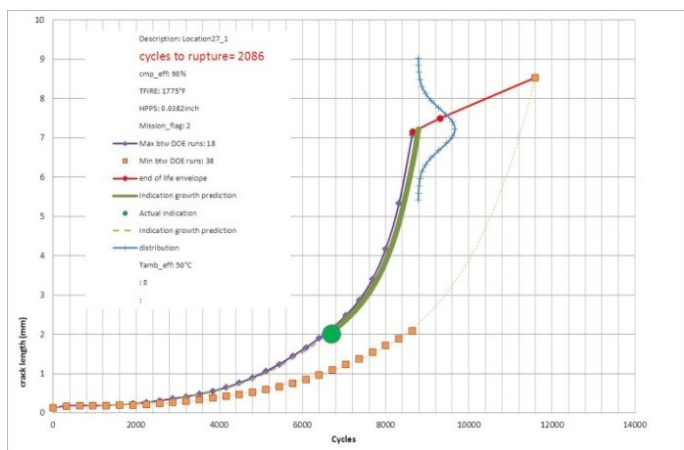


Figure 22: crack growth

11. CONCLUSIONS

The process described by this paper has been developed with the only goal to estimate failure modes that are specific of heavy duty rotor usage. Future developments will target the implementation of all the verification steps (e.g. rabbet crush stress, burst margin, flange scrubbing) that are typical of the rotor design requirements and the implementation of new features as rotor optimization (e.g. wheel shaping to minimize weight) and 3D sub-modeling assessments (e.g. compressor dovetails). It should be noted that the new features will not make the process heavier, because thanks to its modularized architecture, portions of process not applicable to RLM or vice-versa to new design, may be skipped keeping the process always lean.

The pilot RLM process is already used by the proprietary company to extend life of rotors with same architecture of the pilot rotor; it has already been duplicated once to support the life assessment of the low pressure turbine wheels of another type of rotor and two more duplications will be done before the end of 2014. The duplication of the RLM process is easy to be accomplished because requires the only replacement of the physic based models and eventually the creation of some more links between components so to allow the control of new variables. Much more time (approximately a full year) it is instead required for the characterization (i.e. lab tests as LCF, creep, fracture), if not already available, of the rotor materials exposed for a long time to usage at high temperature and for the development of probes (e.g. eddy current probe) that are used during rotor inspection to verify the integrity of the rotor.

It is opinion of the authors that processes like the RLM, should be developed in the early design phase and support the machine from the cradle to the grave; the time spent in creating a process is always well paid back, because the possibility to re-

run assessments by changing one or more system variables, makes possible all sort of sensitiveness analyses driving the design to a much more robust design; the facility to quickly re-run one or more assessments at any time comes useful even when the physic based models shall be tuned and validated through lab and field test campaigns and even later when engineering will be supporting: the manufacturing by handling non conformities, the customers by supporting field issues and the business by supporting life extensions.

12. AKNOWLEDGMENTS

The authors gratefully thank Guido Peano for managing but most of all believing and supporting the RLM team across the several difficulties, Riccardo Valorosi in trusting and subsequently sponsoring the idea of the process and finally Roberto De Prosperis and Meciej Borkowsky as contributors to the development of the process.

NOMENCLATURE

CAD: Computer-Aided Drafting
CAFD: computational aero fluid dynamics
CAE: Computer-aided engineering
CFD: Computational fluid dynamics
DOE: design of experiment
FCCD: faced composite centered DOE
DPMO: defect per million of opportunities
FC: faced centered DOE
FE: finite element
FEA: finite element analysis
GT: gas turbine
GTP: gas turbine performance
HPPS: high pressure package seal
IP: intellectual property
LCF: low cycle fatigue
PCD: pressure compressor discharge
POD: probability of detection
RLM: rotor life management
TCD: temperature compressor discharge
TF: transfer function
YFT: 1D flow network solver
WST: wheel space temperature

REFERENCES

- [1] Gas turbine life prediction and optimization device and method (patent application number: CO2011A000032) – Paolo Di Sisto, Roberto De Prosperis, Meciej Borkowsky
- [2] GER3620: Heavy-Duty Gas Turbine Operating and Maintenance Considerations
- [3] TIL-1576-R1: Gas turbine rotor inspection

BIBLIOGRAPHY

- [1] Collaborative engineering process for multidisciplinary optimization of a gas turbine component, Mauro Maccio' and D. Pinna (Ansaldo Energia) – 2011 Simulia Customer Conference
- [2] Machining Part Program Optimization through an Advanced Multidisciplinary Procedure, A. Del Prete, A.A. DeVitis, M.Parodi - NAFEMS Wor