Proceedings of the ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition
GT2019
June 17-21, 2019, Phoenix, USA

GT2019-90882

PHYSICS-BASED SIMULATION IN SUPPORT OF A THROUGH-LIFE GAS TURBINE SERVICE BUSINESS MODEL

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ABSTRACT

The overall aim of the work reported in this paper is to explore whether a physics-based simulation approach has the potential to reduce the uncertainty & variability associated with both predicting & managing maintenance costs and improving engine design to optimise through-life economic performance. The main novelty in the paper is to demonstrate how an innovative Digital Geometry model can represent typical in-service component degradation and then support appropriate simulation meshes to permit degraded performance to be predicted. Two examples are given: blade erosion from particulates; and a simulated cooled blade burn-through event.

NOMENCLATURE

A_{face}	erosion impact face area
AI	Artificial Intelligence
BREP	Boundary Representation
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
c_p	specific heat capacity
d	Level-set signed distance
d_p	eroding particle diameter
DMC	Direct Maintenance Costs
EGT	Exhaust Gas Temperature
ER	Erosion Rate
F	Level-set Speed Function
FC	Flight Cycles
FH	Flight Hours
FL	Flight Leg
h_1	enthalpy at turbine stage entry
h_3	enthalpy at turbine stage exit
HPT	High Pressure Turbine
LLP	Life Limited Parts
m'	mass flow
m_p	eroding particle mass
n	exponent in erosion correlation
NGV	Nozzle Guide Vane
NURBS	Non Uniform Rational B-Spline
OPR	Overall Pressure Ratio
RSVR	Restored Shop Visit Rate
TE	Trailing Edge (of blade)
TET	Turbine Entry Temperature
v_p	eroding particle velocity
v_2	absolute velocity at stator blade exit
w_3	relative velocity at rotor blade exit
W_{net}	gas turbine net cycle work
α	eroding particle impingement angle
η_T	turbine rational efficiency
ξ_N	stator (nozzle) blade loss coefficient
ξ_R	rotor blade loss coefficient
$\Delta\xi$	change in overall blade row loss coefficient
ϕ	Level-set distance field variable

INTRODUCTION

Aircraft engine maintenance represents a significant portion of the operating costs for an aircraft and has a significant impact on the value of the engine (Ackert [2011]). Traditionally, maintenance was based on prescribed, fixed time intervals. Modern on-condition maintenance practices are based on routine monitoring of key parameters like fuel flow, engine rpm, EGT (Exhaust Gas Temperature) margin, etc.. Any degradation beyond specified limits requires the engine to be removed for maintenance. Forecasting and estimating the on-wing life and subsequent shop visit costs play a central role in managing the economic performance of an engine (see, for example, Kennet [1994] & Justin *et al* [2010]).

Engine performance degradation can be caused by a variety of factors: erosion associated with ingested particulates; fouling; deposition of volcanic ash; hot corrosion; excessive local temperature; manufacturing variability compromising local part life; foreign object damage; tip rubs; etc.. Hence the on-wing life of an engine is greatly influenced by operational factors like thrust rating, flight length, the flight environment (dry, hot, dusty, marine, etc.). An excellent review is given by Kurz *et al* [2014]; as illustration, Figure 1 shows the impact of compressor fouling & washing on engine performance.

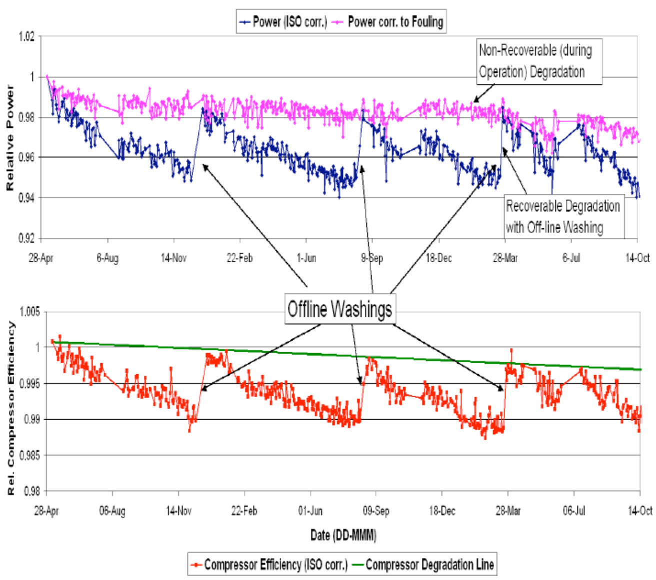


Fig.1: The impact of compressor fouling & washing on engine performance (from Kurz *et al* [2014])

As components degrade and clearances increase (especially in the HPT) the engine has to run hotter to develop the same thrust. EGT sensors provide a surrogate to infer the temperatures seen by the turbine blades and disks (see, for example, von Moll *et al* [2014]). The need for a performance restoration of a degraded engine module is signalled by the EGT margin reducing with flight hours (FH). The various Life Limited Parts (LLP) need replacing after specified flight cycles (FC) and so it is important not to waste any LLP "stub life".

As well as the number of flight hours, the degradation of the EGT margin is very much influenced by environmental factors (sand, temperature, etc.). Figure 2 (from Ebmeyer *et al* [2011]) illustrates this; notable is the wide spread of data and the very severe effect of dust & sand erosive damage (Category A airports) which can double degradation rates.

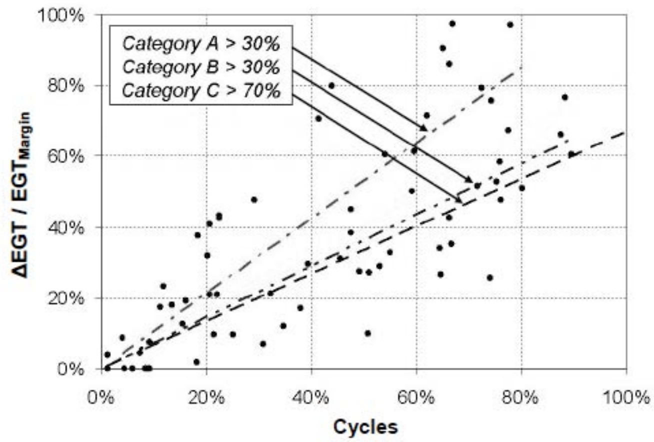


Fig.2: The reduction of EGT margin with engine flight cycles for different airport environments A, B & C; Category A suffers mainly dust & sand erosive damage (from Ebmeyer *et al* [2011])

To illustrate the scale of the challenge, Figure 3 shows typical in-service degradation in aero-engines. In the Figure (top left) is hot corrosion (Wing *at al* [1981]), (top right) deposition & erosion on a HPT NGV (Batalha [2012]) (bottom left) HPT blade deterioration pattern & (bottom right) HPT vane damage – Trailing Edge "bulging" (both from Ebmeyer *et al* [2011].

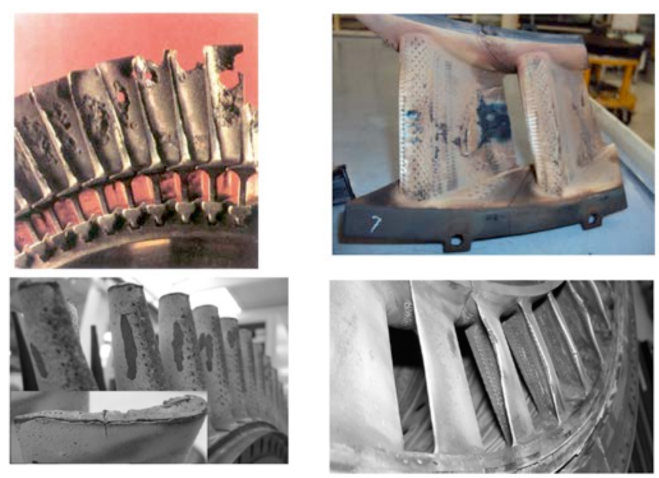


Fig.3: Typical in-service degradation: (top left) hot corrosion (Wing *at al* [1981]), (top right) deposition & erosion on a HPT NGV (Batalha [2012]), (bottom left) HPT blade deterioration pattern & (bottom right) HPT vane damage – Trailing Edge bulging (both from Ebmeyer *et al* [2011]

The particular HPT NGV shown in Figure 3 (top right) had apparently been under observation via borescope and, despite its appearance, at the Shop Visit was declared within limits and sent for repair rather than being scrapped (the replacement cost is around $10-15k per blade (Batalha [2012])). The repair-replace judgement – as well as the judgement that the blade was safe to continue flying – were made using experience and naturally in a conservative way. Aero-engine maintenance is very expensive: the typical cost of "performance recovery" at a Shop Visit is $1.5-2M per engine and the replacement cost of the several Life Limited Parts (HPT module, etc.) is in the range $400-600k each (Ackert [2011]). Given the extremely large costs involved and the current trend to bundle maintenance costs into a long term support package, there is huge scope for a much more physics-based approach.

Work has been carried out to try to simulate the degraded behaviour of engines to better understand and manage their in-service performance. However, this is usually based on a cycle analysis with something like GasTurb™ (see Ebmeyer *et al* [2011] or through-flow simulation (see Campora *et al* [2011]) with empirical data, perhaps fleet averages, used to modify key performance correlations like blade loss coefficients, blade throat (and hence exit angle), tip clearance losses, etc. in some overall averaged way. There have been some attempts within 3D simulation to model degradation by increased roughness levels imposed via modified wall functions (like Aligoodarz *et al* [2013]) but, again, the roughness effects need to be correlated from measured data.

There is clearly a role here for AI, Machine Learning & Data Analytics mining data and finding patterns and trends from all the in-service data currently flowing from a particular engine type. Examples of this are: Yildrin *et al* [2018] & Ntantis *et al* [2015]. However, this cannot follow an individual engine in the spirit of a Digital Twin, nor deal with new engines with no fleet data to mine, nor respond to (perhaps borescope) observed degradation and predict how much life is left in an individual component, nor help design an engine which ages better. What is needed is a more physics-based approach.

The common factor in performance degradation is changes to the *physical geometry* of the engine's primary and secondary flow paths – blades, seals and cooling systems. This paper will describe & demonstrate a physics-based simulation framework consisting of a novel Digital geometry model which can represent a wide range of typical in-service degradation coupled with a meshing system which can deliver the full 3D complexity of the geometry to conjugate aero-thermal-mechanical simulation. Then, predicted (or observed) degradation modifies the geometry, the performance, and so on, with the potential to enable through-life simulation of the economic performance of the engine.

THE STRUCTURE OF THIS PAPER

In this paper there are three core sections describing the three different strands of modelling which need to be brought together to support through-life modelling.

The first strand is a financial perspective on engine maintenance. A brief overview of the financial implications of engine maintenance is presented - in particular the basic uncertainties are described in terms of the wide variability & predictability of maintenance costs.

The next strand is the engine cycle itself. A simple model (purely for illustration) is developed connecting cycle thermodynamics and component efficiency to one of the key in-service condition monitoring measurements, Exhaust Gas Temperature (EGT).

The final strand is the physics-based modelling of the in-service degradation itself. We introduce a novel Digital Geometry model and discuss its potential to support through-life geometry change; we describe particular application to support particulate erosion.

Then, two example simulations are presented to demonstrate the combined capability. The paper ends with some concluding remarks and discussion of possible future directions.

BRIEF OVERVIEW OF THE FINANCIAL IMPLICATIONS OF VARIABILITY & UNCERTAINTY IN ENGINE MAINTENANCE SCHEDULING

An excellent introduction to the financial implications of engine maintenance is given by Ackert [2011]. In simple terms there are two rhythms:

- LLP (Life Limited Parts) are certified for a fixed number of Flight Cycles (FC); these are typically declared as 15,000 to 30,000 FC – after which the parts must be replaced
- Engine wear & deterioration measured by EGT (Exhaust Gas Temperature); for fixed thrust, the efficiency of the engine degrades so the cycle exit temperature rises.

For optimum economic performance these two maintenance rhythms need to be balanced carefully against the flight profiles so no LLP "stub life" is wasted. The key is for wear & deterioration to be as predictable as possible.

Direct Maintenance Costs (DMC) in $/Flight Hour ($/FH) depend on the duty required of the airplane & the environment the aircraft flies through. DMC is expressed relative to a Base

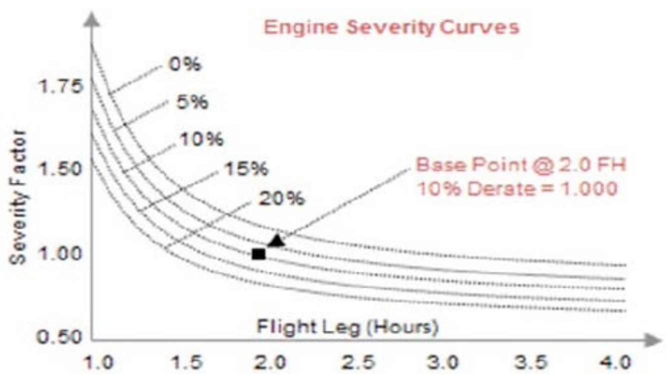
Point (see, for example, Table 1) with variations from the Base Point taken into account via "correction factors":

- "*Severity Factors*" for de-rate (ie. running at reduced thrust) & flight hours (see Figure 4)
- "*Environment Factors*" for temperate, hot/dry & erosive operating conditions (see also Figure 4).

Data	Notes
Fleet average "First-run" RSVR (Restored Shop Visit Rate)=0.050	0.050 per 1000FH = 20,000 FH
"First-run" engine restoration **cost=$1.6M**	Base First-run DMC= $1.6M/20,000=$80/FH
Base Point	de-rate 10%; annual FH=3,000; average FL=2.0 hours; environment="temperate"

Table 1: Example Base Point data (Ackert [2011])

These factors are derived from correlation, in-flight data, manufacturer, fleet averages, etc. and are *key* to managing maintenance costs. Clearly the reliability & predictability of the degradation rate have a significant bearing on the maintenance costs.



"Environment Factors":	temperate=1.00; hot/dry=1.10; erosive=1.20

Fig.4: Correlated engine Severity Curves & Environment Factors which "correct" for engine duty away from the Base Point (from Ackert [2011])

Hence using Table 1 and Figure 4 the DMC in $/Flight Hour ($/FH) can be estimated from the "Severity Factors" & "Environment Factors" used relative to the Base Point – this is shown in Table 2 (with the associated FH). What is immediately noteworthy is the very wide variability - around factor two. This represents a huge financial uncertainty and illustrates the business risk of in-service maintenance packages and leasing contracts.

Flight leg/h	1.0	2.0	3.0
Temperate $/FH (FH)	132 (12k)	80 (20k)	64 (25k)
hot/dry $/FH (FH)	145 (11k)	88 (18k)	70 (23k)
Erosive $/FH (FH)	158 (10k)	96 (17k)	76 (21k)

Table 2: Potential range of DMC (equivalently FH) relative to the engine Base Point

One of the objectives of the work reported in this paper is to explore whether a more physics-based approach has the potential to reduce the uncertainty & variability associated with both predicting & managing maintenance costs and improving engine design to optimise through-life economic performance. This is especially so for new engine variants or even new engine architectures for which there will be a lack of accumulated in-service condition monitoring data to mine.

CONNECTING ENGINE COMPONENT DEGRADATION VIA THE THERMODYNAMIC CYCLE TO THE EGT

Accordingly, the second core strand of this paper is to create a simple way to connect the degradation of individual engine components (like the blading) via the engine cycle to the EGT monitoring measurements. We deliberately adopt a very simple approach to clearly illustrate the physics at play. Figure 5 shows the classic thermodynamic cycle for the core of a by-pass turbofan. Degradation reduces component efficiency and this then needs increased TET (T_{04}) to maintain constant thrust. EGT is a surrogate for the temperature of the HPT blades and disks (the key life limiting components).

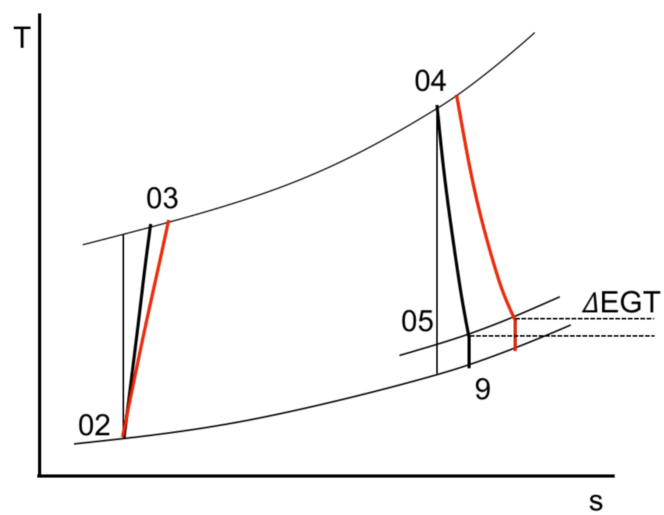


Fig.5: Classic thermodynamic cycle for the core of a by-pass turbofan engine showing the effect of component degradation on efficiency (black to red)

Using simple analysis we can relate the change in component performance to EGT. First, the effect of changing efficiency on EGT can be derived by considering the net work produced by the engine core; this produces thrust both from the core jet and by powering the fan/by-pass flow (Cumpsty [2003]):

$$W_{net} = \dot{m} c_p T_{02} \left[\frac{T_{04}}{T_{02}} \left(1 - \frac{1}{OPR^{(\gamma-1)/\gamma}} \right) \eta_T - \frac{1}{\eta_C} \left(OPR^{(\gamma-1)/\gamma} - 1 \right) \right]$$

If thrust is to be held constant then W_{net} is fixed; assume also that the cycle pressure ratio, OPR, the compressor efficiency, η_c, and T_{02} are constant. The equation can be differentiated to give:

$$\frac{\Delta T_{04}}{T_{02}} = -\frac{T_{04}}{T_{02}} \frac{\Delta \eta_T}{\eta_T}$$

To first order, the change in EGT is the same as the change in TET, ΔT_{04}. Hence, in a typical, modern high by-pass ratio engine at cruise (31,000ft, M=0.85), T_{02}=259K, η_T ~0.90 and T_{04}/T_{02}~6 and so a reduction in turbine efficiency of 0.01 (1% point) leads to an approximate increase in EGT of 16°C. This is very significant.

Component performance can be related to efficiency (again, in a very simple illustrative way) using basic analysis - for example Dixon [1971] gives the following for a stage

$$\eta_T = \left[1 + \frac{1}{2} \frac{\xi_N v_2^2 + \xi_R w_3^2}{(h_1 - h_3)} \right]^{-1}$$

where ξ_N & ξ_R are the nozzle & rotor blade enthalpy losses, v_2 & w_3 are the nozzle & rotor exit velocities and (h_1-h_3) is the stage enthalpy drop. For a typical 50% reaction stage (with flow & work coefficients 0.5 & 1.0) with typical blade exit angles this formula reduces approximately to $\Delta\eta_T \sim -\Delta\xi$ where ξ is the enthalpy loss coefficient for a single blade row. (In practice entropy producing losses have slightly less impact on the overall turbine efficiency if incurred at higher temperatures (the so-called "reheat" effect, see Denton [1993]) but this is neglected here.)

Hence, the change is EGT is related to the change in an individual turbine blade row performance by:

$$\frac{\Delta EGT}{T_{02}} \approx \frac{T_{04}}{T_{02}} \frac{\Delta \xi}{\eta_T}$$

This is a very simple, approximate analysis; a much more sophisticated treatment is indeed possible using engine cycle modelling software (as, for example, presented by Ebmeyer *et al* [2011]) but this approach is preferred here to clearly illustrate the direct relationship between engine degradation and component life as measured by EGT.

PHYSICS-BASED MODELLING TO REPRESENT & SUPPORT THROUGH-LIFE DEGRADATION

Digital Geometry

Geometry usually starts as "pristine" CAD emerging from a typical industrial Design & Product Life Management system. This geometry will be classical BREP-NURBS with some limited parameterisation. However, once in service, this geometry representation rapidly becomes inadequate: geometry becomes "discrete" and is derived from scans, CT or photogrammetry. To illustrate this, Figure 6 shows a rendered laser scan of a volcanic ash damaged HPT NGV (Bonilla [2012]); this "discrete" geometry is available as a (tessellated) Point Cloud – and reverse-engineering this into BREP-NURBS format (whilst not impossible) to support simulation is simply too slow & expensive to be considered. And in any case, classical CAD is still not well aligned with the needs of automated mesh generation and hence not well suited to automated simulation workflows (see for example Gammon *et al* [2018]).

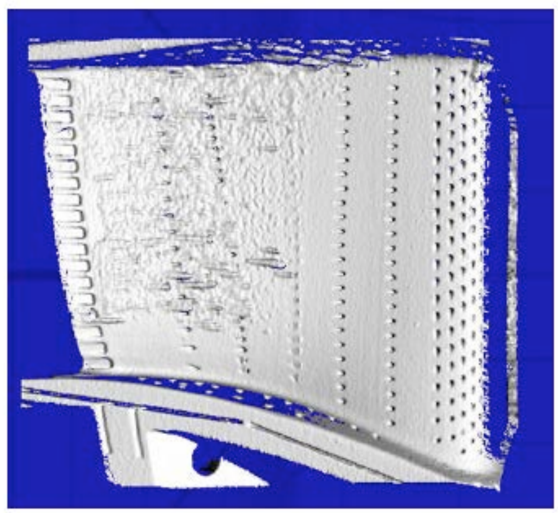


Fig.6: Rendered laser scan of a volcanic ash damaged HPT NGV (Bonilla [2012]); this "discrete" geometry is available as a (tessellated) Point Cloud

As an alternative we have for some years (Dawes et al [2005-2018]) been developing a Digital Geometry modelling kernel aimed specifically at managing efficiently, quickly & robustly difficult, complex & challenging geometries. The famous Bresenham line algorithm [1962] was developed as a way of representing a line via discrete pixels – "Rasterisation" on the newly emerging Cathode Ray Tube terminals. This is essentially the core idea in digital photography – a picture – in 3D this becomes *geometry* and the *pixels* become *voxels*.

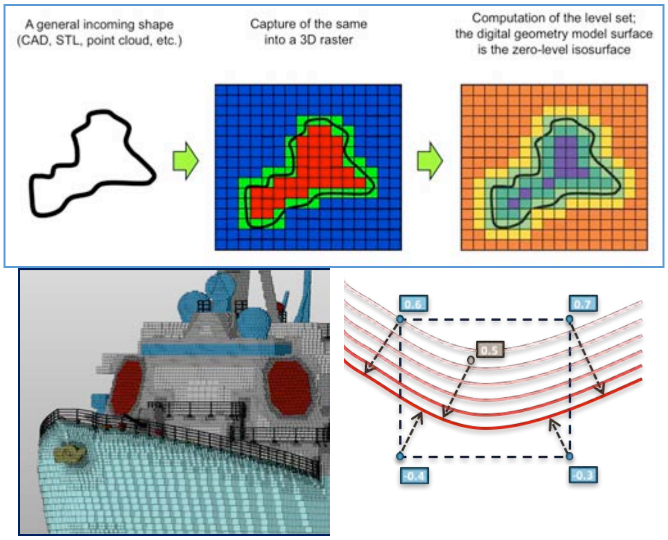


Fig.7: Our Digital Geometry Kernel; on the (top) the "Rasterisation" of the geometry; on the (lower left) a 3D voxel image; on the (lower right) the Level Set Distance Field storing sub-voxel scale geometry information

We have developed a software system (see Dawes *et al* [2005-2018]) built on Digital Geometry using generalised 3D versions of the fundamental Bresenham algorithm; Figure 7 illustrates this. This consists of an integer representation of geometry down to a chosen length scale – voxels which determine "spatial occupancy": either occupied, vacant or cut. This is combined with a local scalar Distance Field managed through Level-Set technology (Adalsteinsson *et al* [1995]) – to represent sub-voxel scale geometry. The key advantage of this approach is that geometry editing & management is supported in a very general, topology-independent way and is easily coupled with physics-based simulation.

In the Digital Geometry world, editing & managing the geometry consists of modifying the Distance Field as illustrated in Figure 8: shown on the (left), simple Boolean operations; on the (right) morphing of one shape, "A", to another, "B".

Fig.8: Digital Geometry editing the Distance Field: (left) simple Boolean operations; (right) morphing Shape "A" to Shape "B"

In more detail, the Level-Set Distance Field is defined by:

$$\phi(x,\, t > 0) \;=\; \pm d\,.$$

It is easy to show (Adalsteinsson *et al* [1995]) that there is an associated evolution equation:

$$\phi_t + F \cdot |\nabla\phi| = 0$$

where F is the *Speed Function* – setting the rate (and also the extent & location) of changes to the Digital Geometry surface $\phi = 0$. "Geometry edits" are just changes to this scalar field, defined somehow/anyhow via the function F. For example:

- standard Boolean operation is just
  - F= min (target_shape, tool_shape)
- classical morphing operation (Breen & Whitaker [2001]) is just
  - $F = (\phi_{target} - \phi_{source})$
- erosion/corrosion/burning/ablation is just
  - F=volume transfer to/from surface/s

This geometry framework provides a rich and as yet largely unexplored capability; *within this paper we explore the use of this model to support through-life degradation in gas turbines.*

Using Digital Geometry to Support Erosion Simulations

As a very simple illustration, Figure 9 shows stages in the simulation of erosion by sand of the surface of a sphere.

Fig.9: Stages in the erosion of a sphere subject to sand particle impingement; the image shows the zero distance of the Level Set geometry

The erosion simulation was performed using standard Fluent™ Discrete Particle Modelling (DPM) (see [www.ansys.com]) combined with classical erosion modelling (see for example Finnie *et al* [1992]). The erosion model takes the form:

$$ER = \sum_{trajectories} \frac{m_p C(d_p) f(\alpha) v_p^n}{A_{face}}$$

where the erosion rate (ER) of the geometry face depends on the mass of impacting particles, an empirical function of the particle diameter, an empirical function of the impact angle and the particle velocity (with an empirical exponent). The predicted surface variation in erosion rate (m^3/m^2 s) is related directly to the Level-set morph Speed Function F (m/s) and is imported directly into our software system and used to morph the Level Set Distance Field; in the Figure the zero distance (ϕ=0) is rendered.

A *new* simulation mesh is then automatically generated for this *new*, morphed geometry – see Figure 10. This is a key novelty of our approach – we morph the geometry *not* the mesh.

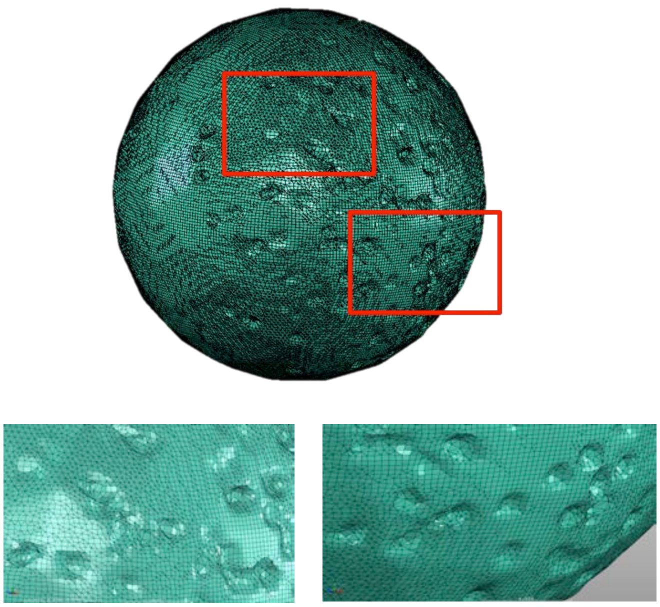


Fig.10: Simulation mesh (surface shown) generated by our simulation system for the eroded sphere generated from the morphed Level Set geometry

Our software system is very robust and to generate a mesh for a geometry like this is straightforward; the exported mesh then drives, for example, Fluent™ allowing the performance of the modified geometry to be *predicted*. Thereby, a scripted, automated "*morph-mesh-solve*" workflow can be created as sketched in Figure 11; it is this workflow which we believe is capable of supporting through-life simulations by coupling physics-based geometry degradation to predicted performance changes.

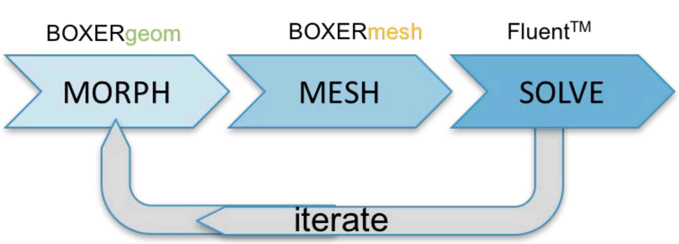


Fig.11: The automated *morph-mesh-solve* workflow

EXAMPLE 1: SIMULATED HPT BLADE EROSION

Preamble

This Section will show our first attempts at modelling blade degradation using physics-based simulation. We have chosen particulate erosion as this is one of the most severe mechanisms as discussed in the Introduction.

There are a number of approaches to particulate erosion modelling in the literature based on "dilute phase" (one-way coupling) Lagrangian particle tracking combined with an impact "bounce" or "stick" erosion model. As validation, there are many published cases: for example Tabakoff *et al* [1990], Hamed, Tabakoff *et al* [2005] or Graham *et al* [2009]. As an example, Figure 12 shows measured erosion by sand particles of an aluminium cylinder/endwall compared with a Fluent™ simulation (taken from Graham *et al* [2009]).

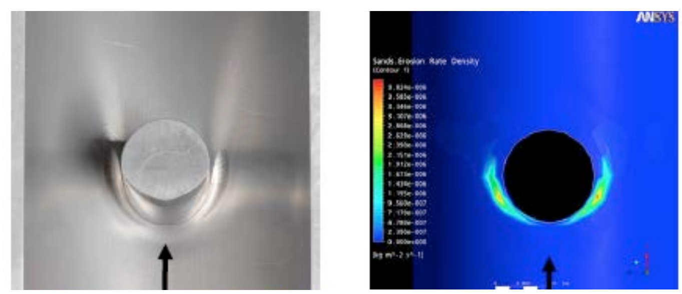


Fig.12: Measured erosion (left) by sand particles of an aluminium cylinder/endwall compared with a Fluent™ simulation (right; taken from Graham *et al* [2009])

Accordingly, we use in this paper the basic DPM/erosion model available in Fluent™ (based on Finnie *et al* [1992]) and have reproduced the results in Figure 12 to verify our approach. We have studied both the stator vanes and the downstream rotor blades and results are presented in the following Sections.

Stator vanes

The stator blades are typical of those used in an aero-engine HPT stage. A standard unstructured mesh was generated by our software system and then exported to Fluent™ to produce the baseline solution with standard inlet & outlet boundary conditions. Then the DPM/erosion simulation was performed by Fluent™ injecting sand particles with a "Rosin-Rammler" distribution (Rosin *et al* [1933]) and specifying the sand mass flow rate / number of particles & the distribution of particle diameters as shown in Table 3. The particles were injected in the same direction and with the same velocity as the bulk air flow. Quantitative data on particulates in aero-engine turbines is rarely available in the public domain; for this study the particle size & burden were selected based on the information in Hamed, Tabakoff *et al* [2005] and is representative of "runway sand".

Blade inlet angle [^{o}C]	0
Blade exit angle [^{o}C]	70
Re [-]	0.5-1x10^{6}
Sand/air mass flow ratio [%]	0.21
Sand: min; mean; max diam.[μm]	60; 250; 1000

Table 3: Basic stator vane simulation parameters

Different particle sizes take different paths through the flow with small ones following the flow and larger ones having a more "ballistic" trajectory. Figure 13 illustrates this.

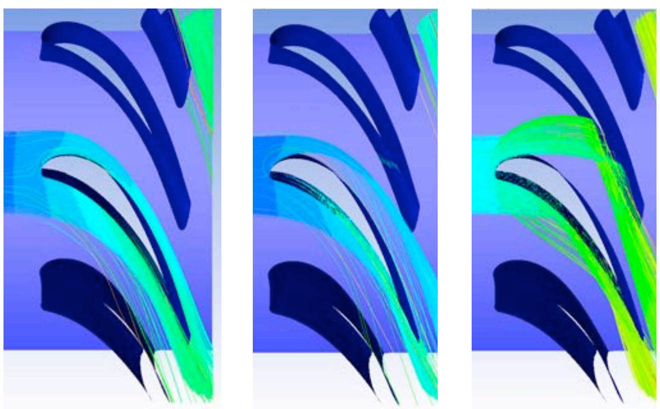


Fig.13: Predicted trajectories of different sizes of particle: (left) 2 μm; (centre) 20 μm; (right) 200 μm

An overview of the predicted erosion rates is shown in Figure 14. The particles in the simulation input are relatively large and their trajectories tend towards "ballistic" so the majority of the particle-blade impacts occur on the blade pressure side.

Notable in Figure 14 is the tendency for particles to collect in the pressure side/endwall corner and for their path-lines to roll up into a vortical structure (see zoom view in Figure 15). This leads to greatly increased local erosion rates compared to the general blade background level of around 0.5mm/10,000h; the predicted maximum erosion rate is around 2.3mm/10,000h. (10,000h is about half the Flight Hours expected before a Restoration Shop Visit (see Table 1).)

The next step in the *morph-mesh-solve* workflow is for the erosion rate to be imported into our software system and for the blade geometry to be morphed using the Speed Function "*F*" mapped onto the local erosion rate. Once the *new* geometry is generated it is exported to our simulation system and a *new* simulation mesh created and exported in turn to Fluent^{TM}. Figure 16 illustrates this simulation mesh (surface shown) for the eroded stator blade; particularly evident is the erosion pattern associated with the particulate vortical structure formed in the pressure side/endwall corner. It is important to emphasize that this is a body-fitted mesh generated for a degraded geometry – *not* a morphed mesh – and that classical BREP-NURBS CAD would have difficulty in representing this degraded geometry.

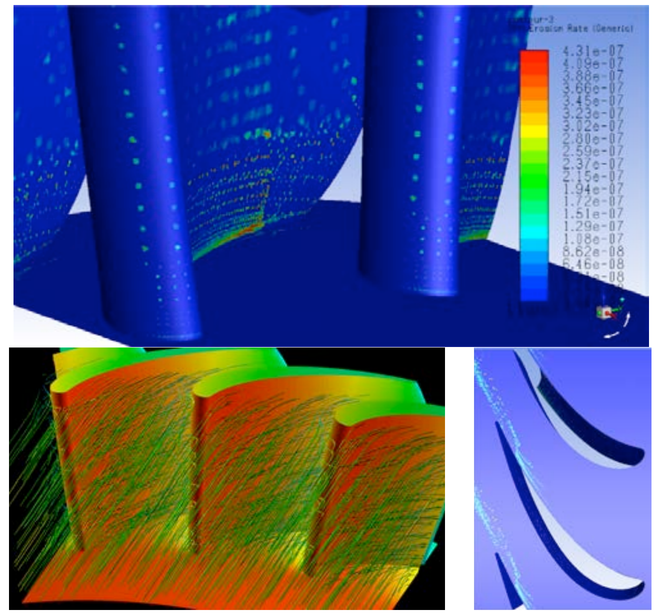


Fig.14: Overview of predicted erosion rates in kg/m^{2} s for the HPT stator vane

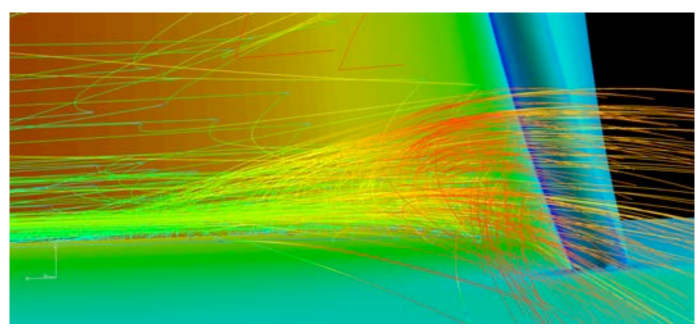


Fig.15: Particle trajectories in the pressure side/endwall corner showing a vortical structure (view upstream from the blade trailing edge)

A *new* flow simulation is run using Fluent^{TM} and the result is illustrated in the next Figure which shows total pressures plotted in a constant streamwise cut near the stator vane TE plane for both the pristine and eroded geometries. The differences are relatively small but nevertheless the extra loss generated by the pressure side/endwall erosion is detectable.

degradation and hence the associated changes in monitored quantities like EGT.

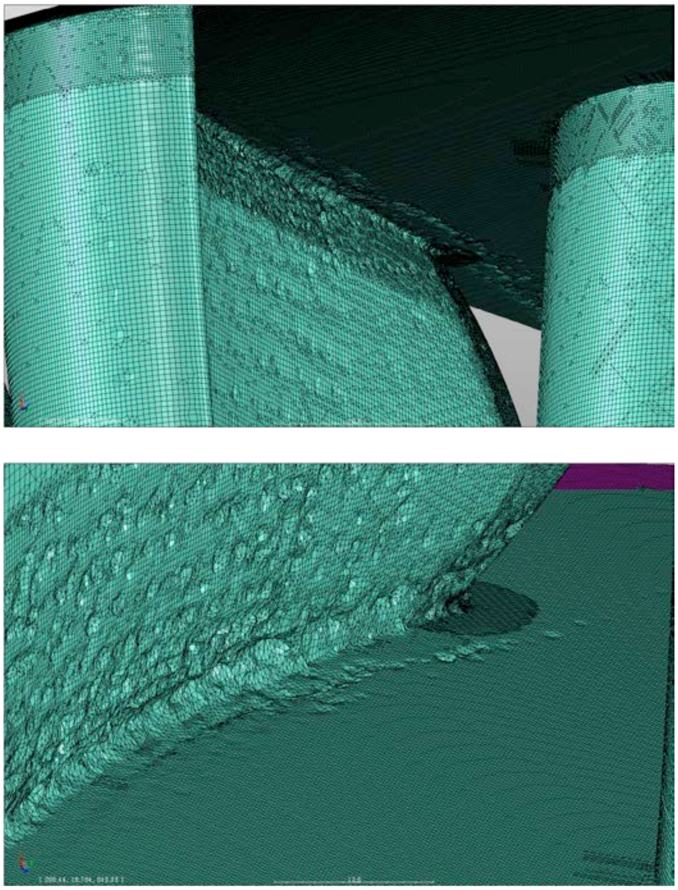


Fig.16: Simulation mesh (surface shown) for the eroded stator blade; particularly evident is the erosion pattern associated with the particulate vortical structure formed in the pressure side/endwall corner.

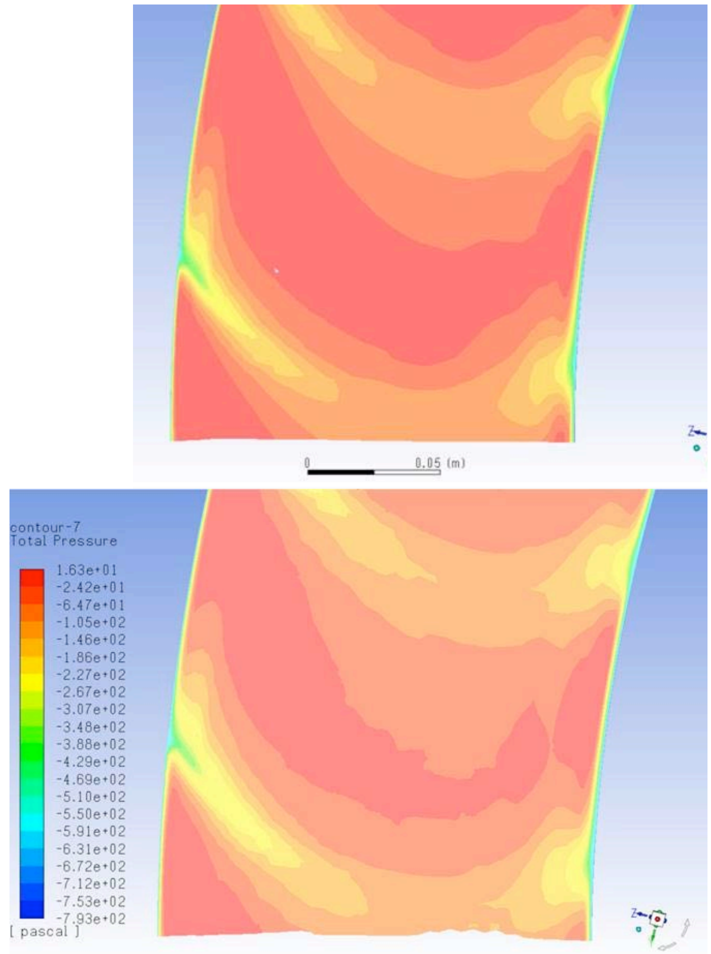


Fig.17: Predicted total pressures near the vane TE for the pristine (top) and eroded (bottom) geometries.

To make this more quantitative, Table 4 shows the predicted loss coefficients for both pristine and eroded geometries together with an estimate of the impact of this on the Exhaust Gas Temperature using the very simple analysis described earlier and for the nominal case of a modern by-pass turbofan engine at cruise (31,000ft, M=0.85, T_{02}=256K and T_{04}/T_{02}=6 ; see Figure 5).

As can be seen from Table 4, the loss coefficient is significantly impacted during the simulated degradation event by the geometry changes. When imagined to be a blade in a by-pass turbofan at cruise, this increase in loss coefficient is estimated to cause a significant increase in EGT of 5.1 ^{o}C per 1000FC (1FC=2FH) – the magnitude compares well with Ackert [2011] who quotes 4-5°C per 1000FC.

This example has successfully demonstrated how physics-based simulation might be applied to estimate through-life performance changes associated with component geometry

Stator Vane	Pristine	Eroded
Loss Coefficient, ξ	0.093	0.106
$\Delta\xi$	-	0.013
$\Delta\eta_T$	-	-0.013
ΔEGT	-	+22.1 °C
ΔEGT/1000FC	-	+5.1 °C

Table 4: Predicted loss coefficients and associated estimated changes in EGT for a nominal by-pass turbofan at cruise for the pristine & eroded geometries

Rotor blade

The next example is rotor blades typical of those used in an aero-engine HPT stage. A standard unstructured mesh was generated by our software system and then exported to Fluent™ to produce the baseline solution with standard inlet & outlet boundary conditions. Then the DPM/erosion simulation was performed by Fluent™ in the same way as for the stator vane.

Blade inlet angle [°C]	+56
Blade exit angle [°C]	-65
Re [-]	2x10^{6}
Sand/air mass flow ratio [%]	1.4
Sand: diameter [μm]	200

Table 5: Basic rotor blade simulation parameters

As before, the predicted general background erosion level is around 0.5mm/10,000h with the maximum rate is around 2.3mm/10,000h. This is imported into our Digital Geometry model, mapped onto the Level Set morphing Speed Function "*F*" and the Digital Geometry modified accordingly. As shown in Figure 18 the Level Set geometry can be morphed to interpolate between the pristine & eroded geometry and within our software can be controlled by a "slider": (left) slider at 36%, (right) slider at 96% - so allowing a physics-based interpolation between the start & end of the particular erosion event. This allows an approximate time history to be interpolated.

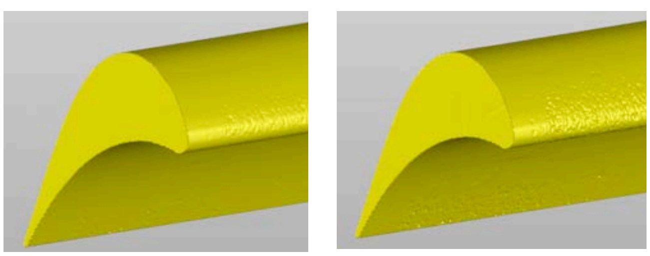


Fig.18: The Level Set geometry can be morphed to interpolate between the pristine & eroded geometry and controlled by a "slider": (left) slider at 36%, (right) slider at 96%

Any selected geometry can be exported to our software system and a simulation mesh generated (see Figure 19); this mesh in turn can be exported to Fluent™. It is important to emphasize again that our approach morphs the geometry *not* the mesh.

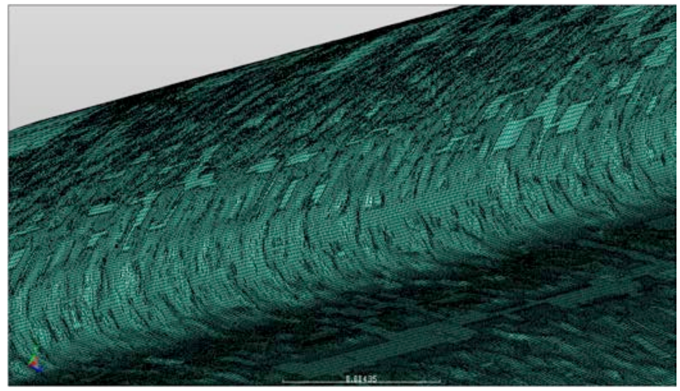


Fig.19: A simulation mesh can be generated for any selected geometry and exported.

The particles are relatively large and tend to have "ballistic" trajectories and so emerge from the stator either with much less turning than the stator vane turning angle or rather slower than the bulk air velocity. In either case this means that in the rotor blade relative frame the particles tend to arrive at high negative incidence and impact the blade leading edge region; this can be seen from the erosion distribution predicted. The next Figure, Fig.20, shows the predicted flowfield in the leading edge region of the blade for the pristine and eroded cases.

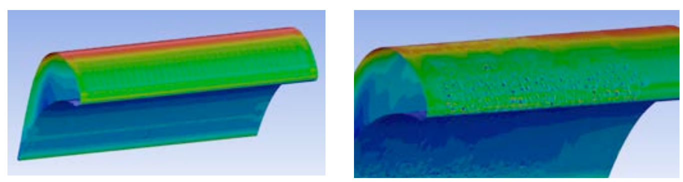


Fig.20: Predicted flowfield (pressure) in the leading edge region of the pristine (left) & eroded (right) blades

HPT Rotor Blade	Pristine	Eroded
Loss Coefficient, ξ	0.064	0.072
$\Delta\xi$	-	0.008
$\Delta\eta_T$	-	-0.008
ΔEGT	-	+13.6 °C
ΔEGT/1000FC	-	+3.1 °C

Table 6: Predicted loss coefficients and associated estimated changes in EGT for a nominal by-pass turbofan at cruise for the pristine & eroded geometries

Table 6 shows the predicted loss coefficients for the pristine and eroded blades with a cycle estimate of the impact of this degradation on EGT assuming the blade to be in a by-pass turbofan at cruise and using the simple analysis described earlier. As can be seen from Table 6, the loss coefficient is significantly impacted during the simulated degradation event by the increased roughness. This is compatible with the findings of Aligoodarz *et al* [2013] who reported increases of blade loss coefficient of 30-50% when simulations were performed with engine-representative roughness level applied via modified wall functions.

The estimated increase in EGT associated with the degraded geometry compares well with Ackert [2011] who quoted 4-5°C per 1000FC. Again, this example has successfully demonstrated how physics-based simulation might be applied to estimate through-life performance changes associated with component geometry degradation.

EXAMPLE 2: SIMULATED COOLED HPT BLADE BURN-THROUGH

The final example is the ambitious case of a simulated cooled turbine blade "burn-through" – representative of the more extreme geometric degradation illustrated earlier in Figure 3. In this example the "pristine" blade geometry, *Shape A*, comes from manufacturing CAD; the "damaged" geometry, *Shape B*, is created as a Point Cloud to mimic observed cases. Then, as before, we use the Level-set Digital Geometry capability within our software system to morph "pristine" to "damaged" geometries, modelling the time history of the degradation via the "slider bar". We then automatically export CFD simulation meshes from our system for each of the geometries at selected stages during the *morph-mesh-solve* workflow. Currently we have used the classic Breen-Whitaker [2001] morph; our next aim is for the morph (and associated speed function "*F*") to be taken from a physics-based aero-thermal-mechanical-material simulation. Figure 21 shows the geometry during stages of the simulated burn-through of the cooled turbine blade.

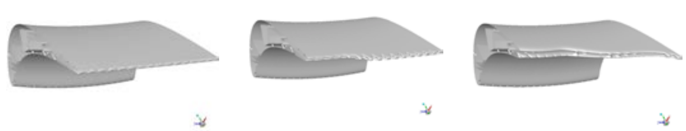


Fig.21: Stages during the simulated burn-through of the cooled turbine blade: *geometry*

Figure 22 shows a detail of the blade leading edge geometry and associated mesh in the later stages of the burn-through simulation. The geometry is by now very complex but both the Digital Geometry model and associated mesh generation are perfectly happy handling this: every mesh exported from our software system solves straightforwardly in Fluent™.

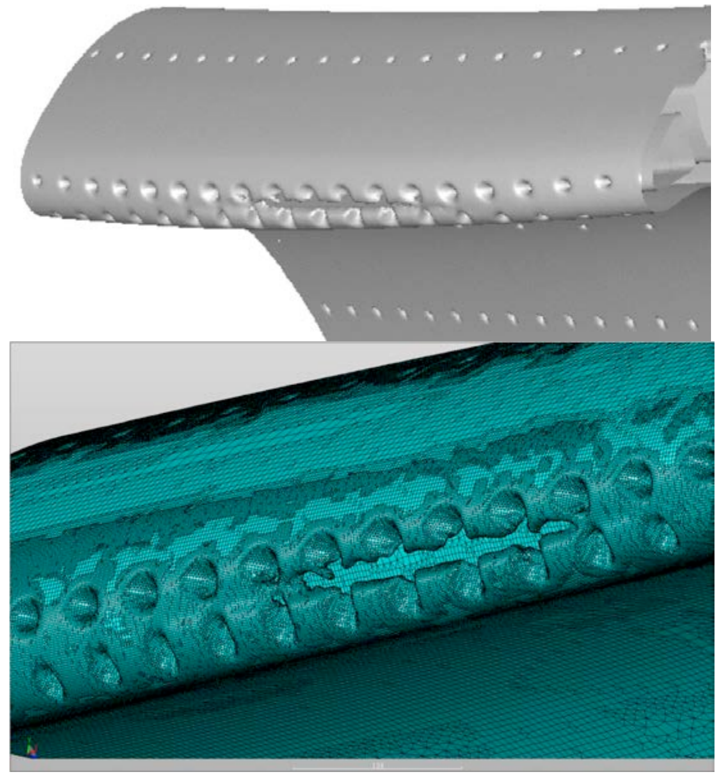


Fig.22: Geometry (top); the zero distance of the Digital Geometry Level Set and associated mesh (bottom) in the later stages of the burn-through simulation.

Figure 23 shows flow simulation results at stages during the simulated burn-through of the cooled turbine blade. The progressive – and increasingly serious – degradation of the performance is clear. Finally, in terms of stage matching and coolant load: as the throat opens, there is more primary mass flow; as the coolant holes "burn" there is more coolant flow also (fixed pressure ratio boundary conditions); see Figure 24. There is no experimental data currently in the public domain with which comparisons of our simulations can be made.

CONCLUDING REMARKS & FUTURE DIRECTIONS

In this paper we have described the three different strands of modelling which need to be brought together to support through-life modelling: the financial implications; the engine cycle coupled to component degradation; and a physics-based simulation approach. The core of the simulation is a novel Digital Geometry model which is capable of supporting typical – even extreme – gas turbine through-service geometry changes caused by degradation. The changing geometry can straightforwardly be represented by simulation meshes which can then support CFD etc. which can then in turn predict the

changes in component performance associated with degradation.
There are several potential future directions for this work. One is for this *physics-based* prediction to support the current *data-based* approach, based on condition monitoring & correlated fleet averages, to enable better physical understanding of degradation; more help with concessions & sentencing for damaged parts would be very valuable.

A second direction would be to help manage through-life economics better – for example to manage the fleet so that degradation is synchronised more closely with the Life Limited Parts so less stub life is lost.

And finally, physics-based degradation prediction should support better up-front design with life-cycle costs added to the list of design metrics – design to mitigate degradation.

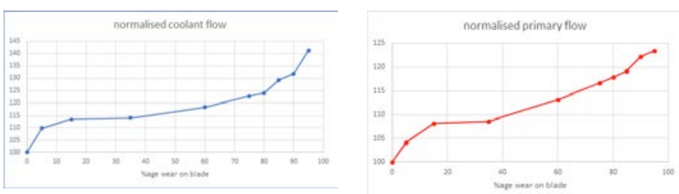


Fig.24: Predicted variation in cooling flow & primary flow during the simulated "burn-through"

ACKNOWLEDGMENTS

We are very pleased to acknowledge partial financial support from Innovate UK via the GHandI, GEMinIDS and AuGMENT Consortia and also to our Development Partners. The authors are grateful to Cambridge Flow Solutions Ltd. For permission to publish this paper.

REFERENCES

Ackert S "Engine Maintenance Concepts for Financiers" www.aircraftmonitor.com, Second Edition, Sept.2011

Adalsteinsson D & Sethian JA, "A level set approach to a unified model for etching, deposition & lithography II: three dimensional simulations" J.Comput.Phys, 122, pp348-366, 1995

Aligoodarz MR & Derakhshan FE "Numerical study of blade deterioration effects on an industrial gas turbine stage performance & flowfield" Proc.IMechE, Part A, J.Power & Energy, 227(4), 515-527, 2013

Batalha, Eucledes da Conceicao Pereira "Aircraft Engines Maintenance Costs and Reliability" Masters Thesis, University of Lisbon, 2012

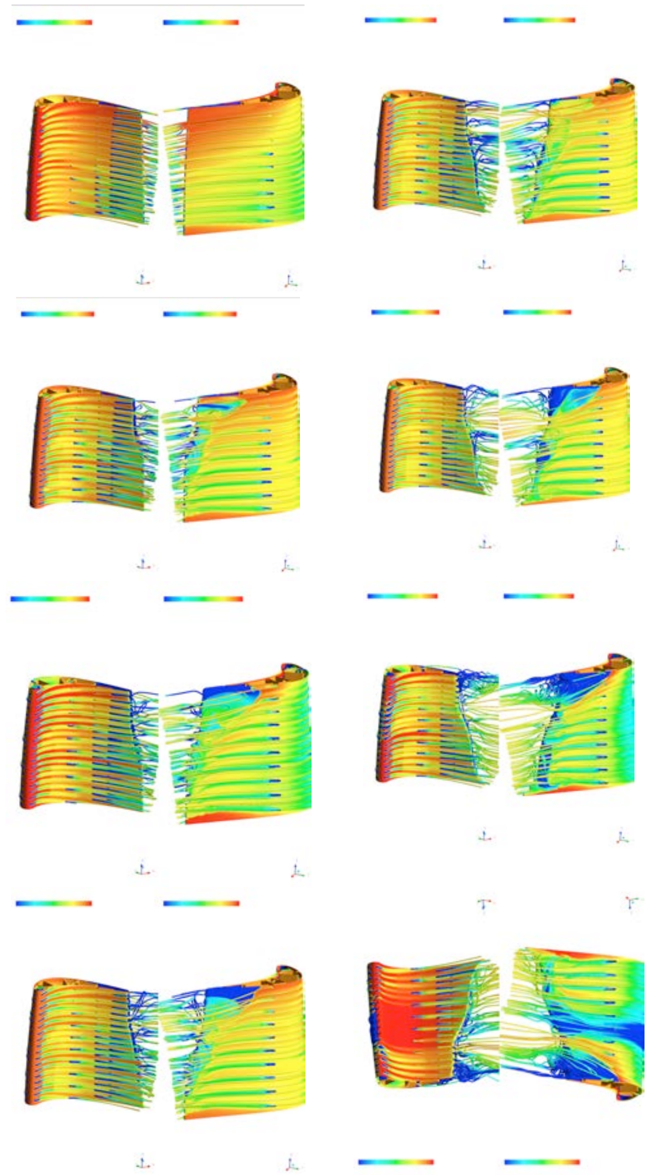


Fig.23: Stages during the simulated "burn-through" of the cooled turbine blade: *flow simulation*

Bonilla CH "The effect of film cooling on nozzle guide vane ash deposition" MSc Thesis, Ohio State University (Mike Dunn), 2012

Breen DE & Whitaker RT "A Level-Set approach for the metamorphosis of solid models" IEEE Transactions in Visualisation & Computer Graphics, vol.7, no.2, April-June 2001

Bresenham, 1962: see
https://en.wikipedia.org/wiki/Bresenham%27s_line_algorithm

Campora U, Carretta M & Cravero C, 'Simulation of a Gas Turbine Engine with Performance Degradation Modelling' - IMECE 2011, Proceeding of the ASME 2011 International Mechanical Engineering Congress & Exposition, Denver, Colorado, US, November 11-17, 2011

Cumpsty NA "Jet propulsion" Cambridge University Press, 2003

Dawes WN "Building Blocks Towards VR-Based Flow Sculpting" 43rd AIAA Aerospace Sciences Meeting & Exhibit, 10-13 January 2005, Reno, NV, AIAA-2005-1156.

Dawes WN, Kellar WP & Harvey SA "Viscous Layer Meshes from Level Sets on Cartesian Meshes" 45th AIAA Aerospace Sciences Meeting & Exhibit, 8-11 January 2007, Reno, NV, AIAA-2007-0555.

Dawes WN, Kellar WP, Harvey SA "A practical demonstration of scalable parallel mesh generation" 47th AIAA Aerospace Sciences Meeting & Exhibit, 9-12 January 2009, Orlando, FL, AIAA-2009-0981.

Dawes WN, Meah N, Hunt M, Evans R, Tacz T, Verdicchio J & Kudryavtsev A "Digital geometry & morphing to support analysis & design" ASME Paper GT2018-76862, Oslo, June 2018

Dawes WN, Kellar WP, Verdicchio J, Racz T, Meah N, Kudryavtsev A, Evans RO, Hunt M, Tiller M, Vasco C, Lu Yi & Kai Liu "Contributions Towards the NASA 2030 Vision for Simulation " SciTech AIAA-2018-1499, Kissimmee, FL, 2018

Dawes WN, 2018: the BOXER software system – see
www.cambridgeflowsolutions.com

Denton JD "Loss mechanisms in turbomachines" 1993 IGTI Scholar Lecture, ASME J.of Turbo., 115, pp 621-, Oct.1993

Dixon SL "Fluid mechanics, thermodynamics of turbomachinery", Pergammon Press, 1971

Ebmeyer C, Friedrichs J, Wensky T & Zachau U "Evaluation of total engine performance degradation based on modular efficiences" ASME Paper GT2011-45839, Vancouver BC, June 2011

Finnie I, Stevick GR & Ridgeley JR "The influence of impingement angle on the erosion of ductile metals by angular abrasive particles" Wear, 152, pp91-98, 1992

FluentTM CFD & DPM erosion modelling: see
https://www.ansys.com/blog/erosion-fluid-dynamics-modeling

Gammon M, Bucklow H & Fairey R "A review of common geometry issues affecting mesh generation" AIAA SciTech 2018-1402, Kissimmee FL, Jan.2018

Graham LJW, Lester D & Wu J "Slurry erosion in complex flows: experiment & CFD" Seventh International Conference on CFD in the Minerals & Process Industries, CRIRO, Melbourne, 9-11 Dec., 2009

Hamed AA, Tabakoff W, Rivir RB, Das K & Arora P "Turbine blde surface deterioration by erosion" ASME J.of Turbo., 127, pp 445, July 2005

Justin CY, Garcia E & Mavris DN "Aircraft valuation: a network approach to the valuation of aircraft for fleet planning & strategic decision making" AIAA Conference Paper 2010

Kennet DM "Structural model of aircraft engine maintenance" Journal of Applied Econometrics, vol.9, 351-368, 1994

Kurz R, Meher-Homji C & Brun K "Gas Turbine Degradation" 43rd Turbomachinery & 30th Pump Users Symposia, Houston TX, Sept.2014

Ntantis EL & Botsaris PN "Diagnostic methods for an aircraft engine performance" Journal of Engineering Science and Technology Review, 8 (4), 64-72, 2015

Rosin P & Rammler E "The laws governing the fineness of powdered coal" Journal of Institute of Fuel, 7, pp.29-36, 1933; see also
https://en.wikipedia.org/wiki/Weibull_distribution

Tabakoff W, Hamed A & Metwally M "Effect of particle size distribution on particle dynamics and blade erosion in axial flow turbines" ASME Paper 90-GT-114, 1990

Von Moll A, Behbahani AR, Fralick GC, Wrbanek JD & Hunter GW "A review of exhaust gas temperature sensing techniques for modern turbine engine controls" AIAA Conference Paper, July 2014

Wing RG & McGill IR "The protection of gas turbine blades" Platinum Metals Review, 25, (3), 94-105, 1981

Yildrin MT & Kurt B "Aircraft gas turbine engine health monitoring system by real flight data" International Journal of Aerospace Engineering, 2018

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