Multi-disciplinary Optimisation of a Compressor Rotor subjected to Ice Impact

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ABSTRACT
Compressors of gas turbine engines are multi-disciplinary systems whereas the different disciplines are largely considered separately. In order to produce feasible designs, the components need to be re-designed several times which is time consuming. A multi-disciplinary design process enabling an integrated approach for all discipline is described in this paper. The main disciplines considered are aerodynamics and ice impact-worthiness for the front stage intermediate pressure compressor (IPC) rotor of a modern three-spool jet-engine.

Due to long lead times, ice impact analyses are usually not carried out until the aerodynamic design is reasonably mature. Only small changes to the rotor are usually allowed in order to satisfy the impact requirements that may lead to sub-optimal designs. Therefore, the introduction of ice impact analysis in the earlier design stages provides higher flexibility for the designers and leads to an overall better compressor performance. A fast thick-shell approach has been developed to model the transient dynamics of the compressor rotor impacted by crystalline ice cuboids released from upstream stators.

The disciplines are linked using surrogate models which are based on the Kriging method. An adaptive multi-objective, multi-disciplinary optimisation approach has been used in order to increase the accuracy of the surrogate model iteratively in the areas of interest. It allows to optimise the performance of each discipline individually. The obtained Pareto front shows design trends in order to improve each discipline individually or both together.

NOMENCLATURE

Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<td>CSD</td>
<td>Computational Structural Dynamics</td>
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<tr>
<td>CGEI</td>
<td>Constrained Generalised Expected Improvement</td>
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<td>CP</td>
<td>Control Point</td>
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<tr>
<td>DoE</td>
<td>Design of Experiments</td>
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<td>DP</td>
<td>Design Point</td>
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<td>ESS</td>
<td>Engine Section Stator</td>
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<td>GPR</td>
<td>Gaussian Process Regression</td>
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<td>HPC</td>
<td>High Performance Computing</td>
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<td>LHS</td>
<td>Latin Hypercube Sampling</td>
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<td>MDO</td>
<td>Multi-disciplinary Design Optimization</td>
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<td>NSGA</td>
<td>Non-dominated Sorting Genetic Algorithm</td>
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<td>TSM</td>
<td>Thick-Shell Method</td>
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Symbols

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<tr>
<th>Symbol</th>
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<tbody>
<tr>
<td>$\rho$</td>
<td>$[kg/m^3]$ Density</td>
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<tr>
<td>$c$</td>
<td>$[m]$ Chord length</td>
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<tr>
<td>$f$</td>
<td>$[-]$ Objective function</td>
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<tr>
<td>$f_R$</td>
<td>$[1/s]$ Rotor speed</td>
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<tr>
<td>$g$</td>
<td>$[-]$ Inequality constraints</td>
</tr>
<tr>
<td>$h$</td>
<td>$[-]$ Equality constraints</td>
</tr>
<tr>
<td>$N$</td>
<td>$[-]$ Number of blades/vanes</td>
</tr>
<tr>
<td>$p$</td>
<td>$[-]$ Plastic strain</td>
</tr>
<tr>
<td>$r_i$</td>
<td>$[m]$ Impact radius</td>
</tr>
<tr>
<td>$s_l$</td>
<td>$[m]$ Slicing length</td>
</tr>
<tr>
<td>$T$</td>
<td>$[m]$ Thickness</td>
</tr>
<tr>
<td>$v$</td>
<td>$[m/s]$ Velocity</td>
</tr>
<tr>
<td>$x$</td>
<td>$[-]$ Design vector</td>
</tr>
<tr>
<td>$y^+$</td>
<td>$[-]$ Non-dimensional wall distance</td>
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INTRODUCTION

Aircraft fly through cold and moist air during take-off and landing where the liquid water droplets are super-cooled which means that the water temperature is below $-15^\circ C$. The super-cooled water droplets are entering the core engine and are freezing instantaneously when hitting cold engine surfaces such as stators and casings. The ice accretes to thick crystalline ice shells and eventually shed in presence of vibrations and warmed-up components. The ice cuboids will then travel downstream impacting the compressor rotor. Due to the high rotor speeds, the ice impact cause severe mechanical damage. Hence, it is important to consider the impact-worthiness during the design process. Only the front stages of the compressor are typically affected by the ice impact threat as the rear stages are warmer. However, recent incidents shows that also melting ice particles can accrete on rear stages (Saxena et al. (2015)). In addition, the ice ingestion can affect the compressor aerodynamics causing a shift of the working line and stall margin when the ice melts and evaporates as shown by Saxena et al. (2015).

Numerical impact analysis is common for many aircraft structures such as wings and windcreens and also fan blades. Most commonly, two kinds of foreign object damage (FOD), bird strike (soft-body) and impact from foreign object debris (hard-body), are investigated. A comprehensive review of the computational methods for FOD on aircraft structures is given by Heimbs (2011). Depending on the impact speed, the response of the impactor can be elastic for low velocities, plastic for high impact velocities where the stresses exceeds the yield stress and hydrodynamic for hypervelocities where the inertial stresses are much higher than the material strength. In the experimental work of Wilbeck (1978); Wilbeck and Barber (1978); Wilbeck and Rand (1981) and Barber et al. (1975, 1978), the hydrodynamic behaviour of the bird impact at high speeds has been studied.

Additionally, studies of the hydrodynamics during the bird impact showed that the pressure is only a function of the density $\rho_B$ and impact speed $v_B$ for soft-body impact. It is shown that the initial pressure peak at contact can be described by the Hugoniot pressure caused by a shock wave travelling reverse through the projectile (Heimbs (2011)). The shock wave is reflected at the boundaries of the impactor causing expansion waves which are also reducing the pressure getting on the blade. Hence, the initial high pressure peak lasts only a very short time ($< 1ms$). Additionally, the shock structure leads to a velocity tangential to the target surface helping to turn the travel direction of the impactor. After the decay of the shock structure, the material motion is considered to be steady with a constant pressure that can be described by the Bernoulli equation. The state of steady flow is only attained if the impactor is long enough. However, this observation has been made for a normal impact on a rigid plate. The theory has also been extended to oblique impact which has shown a good agreement with experiments in the work of Wilbeck and Barber (1978).

In contrast to the impact on a rigid plate, the bird is sliced during the bird strike event on a turbofan rotor. The forces during the slicing process at the leading edge (LE) are the highest over the whole impact process. In the case of bird strike, the most damage to the blade is done due to the turning of the bird slices. The change in the relative impact velocity normal to the blade surface together with the sliced mass defines the forces onto the blade.

For the ice impact on turbofan rotors, only a few studies are available. In the work of Reddy et al. (1992a,b, 1993) the analysis capabilities for local and root damage due to ice impact on an unswept propfan blade have been demonstrated. However, only limited progress was made where only a small part of the blade was modelled with a coarse finite element mesh. The slicing process was considered in a simplified way in order to determine the resulting impulse of the impacting slice which is applied as a load to the blade. This does not allow to capture the loads evolving in time. More work was done to model the impact of hail ice by Kim and Kedward (2000); Kim et al. (2003) and Anghileri et al. (2005). A simple isotropic elastic-plastic material model with failure was used in the numerical models which is not able to have different yield stresses in compression and tension. Additionally, the failure stresses are not considered as a function of the strain rate. Shulson (2001) showed that the failure stress under compression depends strongly on the strain rate for ice. A material formulation for
the behavior of ice at high velocities was developed by Carney et al. (2006) taking both into account. It accounts for the ice shattering during the impact due to the shock waves traveling through the ice block. In order to model the shattered ice, the tensional and deviatoric stresses are set to zero when a certain threshold is reached. This results in a material behaviour that is more like a liquid. The main difference between the bird strike and the ice impact is the greatest during the first microseconds. However, both reach a hydrodynamic state after a few microseconds.

The aim of this research is to develop a fast running model that can represent the fundamental physics of an ice impact onto a compressor rotor. This impact model is used in a multi-disciplinary optimisation allowing to reduce damage in an impact event while improving the aerodynamic performance using simultaneously high-fidelity CFD. To the author’s knowledge, it is a novelty to include the ice impact assessment into the compressor blade design process leading to better global optimum. Furthermore, the usage of multi-disciplinary optimisation techniques has not been used in this context. Both is leading to novel rotor blade design providing superior aerodynamic and impact performances.

In the following section an overview is given of the impact behaviour as well as the aerodynamics of a transonic compressor rotor. Then, the general optimisation strategy using a Kriging response surface approach is outlined. Next, the methodology for modelling the ice impact as well as the aerodynamics with 3D CFD is presented followed by a description of the aerofoil parameterisation. Finally, the results of this work are presented and discussed.

THEORETICAL BACKGROUND

Impact behaviour

Impact can cause sever damage to a compressor rotor if it is not designed to withstand such an incident. High energy impact is causing damage in the location of the impact due to the resulting high forces. Furthermore, the transferred energy forces the blade to vibrate heavily plasticising the blade edges. High levels of plasticity can cause cracking and needs to be avoided to maintain a sufficient long component life. Moreover, the plastic deformation also spoils the aerodynamic performance of the transonic rotor by changing the throat area and the metal angles. Therefore, designs which are more robust against plastic deformation are desirable. The increase of aerofoil thickness is traditionally used to achieve this by adding metal where the damage occur. Additionally, closing the blade by increasing the stagger angle can be used to reduce the impact energy by reducing the amount of caught ice especially in case of multiple impacts. Another key parameter is the chord length which affects the vibration behaviour.

Aerodynamics of transonic compressor rotor

The trend of increasing overall pressure ratio in gas turbines will ensure that Mach number in the front stages of core compressors remain transonic. In addition, there is a drive to improve compressor efficiency, not only around the design point where the specific fuel consumption (SFC) is the major factor but also at some off design conditions, particularly at high powers where turbine entry temperatures can be adversely affected by excessive compressor performance drop-off. In transonic bladerows, the curvature on the suction surface of the aerofoil is the major driver on loss and this is essentially set by the inlet and exit blade angles of the aerofoil, which set the camber, the camber distribution and the aerofoil thickness. In general, thin aerofoils with small leading and trailing edge radii are preferred to minimise losses. However, the thickness parameters are set by the stress and impact constraints. Therefore, they are usually not used in an aerodynamic optimisation. The multi-disciplinary approach eases some of the restrictions on the design space where the aerodynamic and mechanical properties are simultaneously evaluated in order to meet the requirements.

Optimisation

This subsection describes some background of an adaptive response surface optimisation strategy as it is often used for complex engineering problems.
**Optimisation Strategy**

The optimisation is carried out using the Rolls-Royce SOPHY system (SOFT, PADRAM, HYDRA) introduced by Shahpar (2005). SOFT (Smart Optimisation For Turbomachinery) introduced by Shahpar (2002) provides a library of different optimisation algorithms and communicates through Python scripts with the other codes in order to execute them in batch mode, to evaluate the results of the simulation. These computations are run in parallel on an HPC cluster in order to reduce the overall run time. A schematic overview is depicted in figure 1(a).

The optimisation problem is defined by the objective functions $f_m(x)$ to be minimised, while satisfying a number of inequality constraints $g_j(x)$ and equality constraints $h_k(x)$:

\[
\text{Minimise} \quad f_m(x) \quad m = 1, 2, \ldots, M \\
\text{Subjected to} \quad g_j(x) \geq 0 \quad j = 1, 2, \ldots, J \\
\quad h_k(x) = 0 \quad k = 1, 2, \ldots, K \\
\quad x^l_i \leq x_i \leq x^u_i \quad i = 1, 2, \ldots, N 
\]

(1)

where $x$ is the design variable vector containing $n$ design variables $x_1, \ldots, x_n$. The superscripts $l$ and $u$ define the lower and upper limit on a particular design variable $x_i$.

**Initial Design of Experiments**

In order to carry out a surrogate assisted optimisation and to explore the design space a Design of Experiment (DOE) approach is used with a Latin Hypercube sampling technique (LHS). The LHS attempts to distribute data points homogeneously within the design space in such a way that each point is the only one in each hyperplane aligned to a design variable (McKay et al. (2000), Stein (1987)). From a stochastic point of view, this method provides a good interpolation dataset for an unknown behaviour of an objective function within a defined design space.

![Scheme for an response surface based adaptive optimisation.](a)

In order to choose the number of data points for the initial DOE, the recommendation given by Baert et al. (2015) is followed: for a continuous design variable space, the authors took five times the number of design variables ($5 \times n$) for an initial DOE size. However, it would be favorable to further increase the initial RSM quality by $5 \cdot p \times n$ where $p > 1$ if affordable.

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Surrogate Based Optimisation

For complex engineering problems, the aim is to get to the optimum solution i.e. with a minimum number of expensive simulations. Mathematical or statistical approximation models are, therefore, used to speed up the optimisation and to couple different disciplines. In the technical literature, these models are known as surrogate models, metamodels or response surface models (RSM). In this study, the optimisation is conducted by using the Kriging or Gaussian Process Regression (GPR) technique which is able to replicate accurately a complex multi-dimensional function. It is out of the scope of this paper to provide the details of the Kriging method. Therefore, the reader is referred to the early literature of Krig (1951) and Matheron (1963) and for practical guidance to the book of Forrester et al. (2008).

In this work, regressing Kriging (Jones et al. (1998); Sacks et al. (1989); Forrester et al. (2006, 2008)) is used, which is based on the classical Kriging approach with an additional parameter to filter out numerical noise coming from numerical calculations such as CFD. A schematic representation of the optimisation process based on Kriging as it is implemented in SOFT. Starting from an initial LHS DOE set, the obtained initial designs are evaluated in parallel and saved in a database or in case of simulation failure, in a failure database. That allows to restart the optimisation in case of failure or change of the optimisation setup. Once the designs are evaluated, a RSM is built using Kriging and the convergence of the RSM quality is checked using the leave-one-out cross-validation method (see Brooks et al. (2011)). The initial RSM is updated by additional points in order to iteratively converge to the Pareto front.

In order to refine the DOE and to find a new set of update points, the RSM is searched using global multi-objective optimisation techniques. Therefore, the non-dominated sorting multi-objective genetic algorithm (NSGA-II) by Deb et al. (2000); Deb (2011) is chosen from the SOFT library. In order to find update or infill points, the RSM is sought for the best predictions on the Pareto front. If the maximum number of infill points is not reached, the RSM is searched in a second step for the best constrained generalised expected improvement (CGEI) that takes also the uncertainty of the RSM approximation into account. The CGEI is described by Brooks et al. (2011).

NUMERICAL METHODOLOGY

Ice impact model

The in-house model for ice impact is available to produce highly accurate results to minimise the number of required engine tests. However, a long runtime is unfavourable for the preliminary design phase where a designer wishes to explore the design space. A thick shell approach where the blade is modelled with one-layer brick meshes has been developed in order to significantly reduce the computational time. A benchmark between a full 3D model and the TSM on the same HPC showed that the TSM is about 50 times faster. Furthermore, the mesh generation is much simplified since a TSM mesh needs less effort to be produced compared to a full 3D brick mesh. The automatisation of the geometry handling and meshing process reduces the lead time even further.

The explicit solver of LS-DYNA (Hallquist (1998)) is used to simulate the transient dynamics of the impact. A typical thick-shell mesh of the rotor is shown in figure 2(a) where the discretisation issue at the LE and TE is highlighted. It is not possible to model accurately circles with a one-layer brick mesh. Hence, a bit of the elliptic LE and the circular TE needs to be cropped. The influence onto the model accuracy is later discussed in the validation section. The mesh of the TSM consists of 2,000 elements per rotor blade. The rotor blade material is a titanium alloy which is typical for front stage compressor rotors. High strain rates are expected where non-linear effects occur. Therefore, a strain rate depended yield rule is used in LS-DYNA.

There are several approaches to model the ice blocks. One way which is used here is to use a Lagrangian method where the meshes deform during the impact. In order to avoid highly distorted elements, element erosion is applied. Also, the element erosion is used to model the slicing process where the blade cuts the ice blocks in smaller pieces. The fine 3D mesh grid of the ice cuboids consists...
of 21,000 solid elements. The material properties of ice has been assigned where the brittleness of ice has been ignored, modelling the ice as a fully ductile material until erosion.

![Typical thick-shell mesh with cropped leading and trailing edge.](image)

**Figure 2:** Typical thick-shell mesh with cropped leading and trailing edge.

The impact model developed here consists of two blades and two ice cuboids (see figure 3(a)subfigure.3.1). The size and position of the ice cuboids has been chosen to represent a worst case scenario observed in various engine tests and in service incidents.

In order to assess the impact behaviour, the untwisted static aerofoil shape is needed. Therefore, the running aerofoil which is loaded with the centrifugal, gas and thermal loads needs to be transformed into the static cold shape. The process of obtaining the cold static geometry is called unrun process. The 3D FEM unrun model consisting one sector of the blisk is created in NX and iteratively solved with the in-house FEM code SC03. The overall impact analysis process is defined by the following steps:

- Generate the aerofoil geometry with the Rolls-Royce blade generator Parablanding

![Ice impact model with two ice cuboids and two blisk rotor blades](image)

**Figure 3:** Ice impact model with two ice cuboids and two blisk rotor blades 3(a)subfigure.3.1 and the model to assess the aerodynamic performance with CFD 3(b)subfigure.3.2.
• Create a CAD model of the aerofoil and disk (blisk) in CAD system NX
• Unrun process with the Rolls-Royce FE solver SC03 in order to obtain an untwisted, static blisk geometry
• Generate the thick-shell mesh of the blade and the solid mesh of the truncated disk in NX
• Set up the transient impact analysis
• Load the blisk with the centrifugal forces in LS-DYNA
• Run the impact simulation using LS-DYNA
• Removing the centrifugal load from the damaged blade to obtain the plastic deformations

After reviewing the literature regarding transient ice impact dynamics it has been identified that there is a lack of available academic test data. The model used here was validated against damage modes seen in available test data. The used thick-shell model agrees well with the available data which can be seen in figure 4. Nominal baseline geometry (dark grey) overlaid with the deformed blade (light grey) in static position figure.4 and 5. Damaged regions of the baseline geometry visualised with a contour plot of the plastic strain figure.5.

![Figure 4: Nominal baseline geometry (dark grey) overlaid with the deformed blade (light grey) in static position.](image)

Figure 4: Nominal baseline geometry (dark grey) overlaid with the deformed blade (light grey) in static position.

The deformation done by the impacting ice cuboids is visualised in figure 4. Nominal baseline geometry (dark grey) overlaid with the deformed blade (light grey) in static position figure.4. The static undeformed blade shape is overlaid by the deformed shape which allows to measure the cup size of the deformation. The shown cup size is normalised by the chord length. The TSM predicts a smaller cup size \(d_{TSM} = 0.039\) than the 3D model \(d_{3D} = 0.043\). The difference of the cup size is small, though.

The maximal plastic strains of the TSM which are used as a figure of merit for the optimisation are agreeing well with the 3D model, see figure 5. Damaged regions of the baseline geometry visualised with a contour plot of the plastic strain figure.5. The locations of damage is in both cases similar. The highest plastic strains are located in the rear part of the blade caused by the blade vibration. The radial extent at the TE covering in both cases about 30% span. However, the magnitude of the plastic strains are underpredicted in the TSM due to the cropped TE (see fig. 2(a) subfigure 2(a) subfigure.2.1). Overall, the TSM is rather conservative in its predictions which is preferable for a design tool.
The aerodynamic performance of the blade geometries is assessed via the Rolls-Royce high-fidelity in-house Reynolds Averaged Navier-Stokes solver Hydra (Lapworth 2004) which is an edge-based unstructured CFD code. The turbulence closure is done by using the Spalart-Allmaras turbulence model. The Reynolds number considered in the range of $Re \approx 0.8 \ldots 1.4 \cdot 10^6$. The flow is considered to be fully turbulent in the CFD simulations where the transition is not modelled.

For the mesh generation an automatic and robust mesh generation system that avoid any user interaction is necessary. Therefore, the Rolls-Royce mesh generator PADRAM introduced by Shahpar and Lapworth (2003) is used to enable high quality block-structured meshes to be generated automatically. The rotor mesh has about 1.2 million nodes and overall the 1.5 stage mesh consist of about 4.3 million nodes where the non-dimensional wall distance is roughly one ($y^+ \approx 1$) on all geometry surfaces. A typical PADRAM rotor mesh is depicted in figure 6(b).

In order to keep the computational costs minimal, it was decided to use a 1.5 stage setup where the rotor is embedded by the upstream variable inlet guide vane (VIGV) and the downstream variable stator. The penny gaps of the VIGV and the stator are discretised radially with 10 cells and the rotor
gap with 12 cells. Only one passage of the blade rows is modelled which is a common approach for steady-state analysis of compressors. The interfaces between the stator and rotor domain is handled via a mixing plane approach which allows to transmit radial flow variation but smears out circumferential flow variations. The stator shroud leakage is modelled using an analytical function based on empirical correlations allowing to estimate the mass flow and swirl of the injected leakage flow. The shroud cavity inlets and exits are marked in green in figure 3(b)Subfigure 3(b)subfigure.3.2. The outlet duct is extended about one chord length with a constant cross section area which is a good practice when the radial equilibrium exit boundary condition is used.

**Parameterisation**

The aerofoil section shapes are defined by the aerofoil parameterisation using the engineering parameters such as camberline angle $\Theta$ and thickness $T$ distribution, chord length $c$ and blade stacking. However, non-dimensional distributions for the camber-line angles and the thickness are used. This kind of parameterisation needs additionally a specification of the maximum thickness, the inlet and exit angle as well as the thickness at the leading and trailing edge. Furthermore, the chord length needs to be specified for each section. Also a definition of the stacking line is necessary to generate the 3D aerofoil blade using the axial and circumferential positions of all aerofoil section in radial direction. The described aerofoil parameters are shown in 6(a)Subfigure 6(a)subfigure.6.1. The Rolls-Royce in-house tool Parablading (see Graesel et al. (2004)) is used to generate the aerofoils according to the prescribed parameters.

The use of all the available parameters for each section to define the aerofoil shape can result in an excessively large design space. In order to make the optimisation more efficient a reduction of the number of design variables is necessary. The radial parameter distributions defining the design variables for each section has been described via B-splines with a small number of control points. The control points have been chosen such the datum design can be represented without penalising the design flexibility. This results in 25 design variables allowing the inlet and exit angle, chord length, leading edge, trailing edge and maximum thickness, thickness distribution as well as camberline distribution to vary in the upper 50% of the rotor. The root and lower 50% has been kept fixed in this study in order to keep the number of design variables small. Also, the influence of the geometry chances of the lower blade part onto the responses is expected to be small.

**Optimisation Setup**

The multi-objective optimisation problem is defined as follows. The first objective is the stage efficiency at cruise (eq. 2Optimisation Setupequation.0.2) and the second is the blade damage which have been identified as competing figures of merits.

$$f_1(x) = \eta_{\text{cruise}}$$  \hspace{1cm} (2)

The damage of the blade is quantified using the plastification of the material. The maximum plastic strains $p_i$, which is a measure of plastification, are taken in three main regions of the blade. A weighted sum of the maximal values as defined in equation (3Optimisation Setupequation.0.3) is used. The objective function for the impact part is referred as “averaged maximal damage”, given by:

$$f_2(x) = \sum_{i=1}^{N=3} w_i p_i$$  \hspace{1cm} (3)

In addition, several constraints, mainly on the aerodynamics, have been defined. They are used to maintain the stage performance at higher engine speeds in form of efficiency, total pressure ratio and flow capacity. This is necessary since the optimiser tends to trade efficiency at other speeds in order to increase the efficiency objective which needs to be avoided. The compressor stability is considered by putting several constraints on the radial distribution of the flow properties. The
CFD and computational structure dynamic (CSD) simulations are conducted in parallel on a high performance computing (HPC) cluster. Each CFD simulation uses three times the number of cores of the impact simulation \( n_{\text{CPU,CSD}} = 3 \times n_{\text{CPU,CSD}} \) in order to achieve a similar run time between both disciplines.

RESULTS AND DISCUSSION

The result of the multi-disciplinary optimisation is shown in figure 7(a) where only the feasible designs (open squares) have been plotted together with the obtained Pareto front (red triangles). The reference design has been indicated by a filled squared symbol. The horizontal and vertical dashed lines divide the graph into four quadrants where the fourth quadrant contains all designs which show improvements in both objectives. The optimal designs can be found on the pareto front. All of them are pareto optimal since no design can be found which has a better performance with respect to both objective functions.

![Optimisation results](image)

![Compressor map](image)

Figure 7: Pareto front showing the normalised efficiencies and blade damage and the compressor map showing the characteristics at cruise (left) and 100% speed (right) of the optimisation result.

Overall, 684 designs have been evaluated where roughly 10% of the runs in the CSD simulations failed due to issues in the unrun process. These were mainly problems with the convergence in the unrun process due to highly distorted elements. Additionally, some designs produce a highly bowed static blade geometry which caused problems in the mesh generation for the impact analysis. The CFD process has proven to be highly reliable where less than 1% of the simulations did not succeed.

Some of the constraints were difficult to fulfill since tight bounds were set and a high approximation accuracy was necessary in order to identify feasible design regions. This makes additional update iterations necessary where some of the constraints were adjusted several times which adds significantly to the optimisation run time.

The results of the multi-objective optimisation are shown in figure 7(a) where the averaged maximal damage. The initial design which represents a very good design produced manually by a highly experienced designer is illustrated as a filled black square, the Pareto front as a solid line and all feasible designs as empty squares. It should be mentioned that all the plotted points are evaluated with the described 3D CFD and CSD models. Improved solutions are located to the right and below of the reference solution. It is remarkable that only one feasible design is worse in both objectives compared to the initial design showing that the optimiser is able to search in the right spots of the design space. Even though the extremes of
Normalised plastic strains

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</table>

Table 1: Plastic strains of the four damage regions normalised to the results of the 3D model of the baseline design.

the Pareto fronts provides the highest benefits in one of the objectives, they are of less interest for a practical application. The solutions MO2 to 5 are better trade-offs since they show improvements in both objectives.

Compared to the reference design, MO2 increases the normalised stage efficiency by about 0.7% while maintaining the same damage. In contrast, the design MO5 is halving the damage caused by the impact while the stage efficiency is still increased by 0.16%. The designs MO3 and MO4 are also noteworthy. Comparing MO3 to MO2, it provides about the same aerodynamic performance, but decreasing the average maximal damage by 25%. MO4 lies in-between MO3 and MO5 providing less damage but also a lower cruise efficiency than the MO3. The off-design performance, as it can be seen in the compressor map in figure 7(b)Subfigure 7(b)subfigure.7.2, is maintained. The compressor map is showing the characteristic at cruise on the left and also the characteristic of the higher speed on the right.

Analysing the geometry changes of the obtained designs MO2 to MO5, it can be seen that the optimiser tries to close down the blade in the region of impact. More closed blades resist impact better since the first impact opens the blade less thus reducing the caught ice mass, especially during the following impact of the second ice cuboid. Additionally, the closed blade is better aligned with the flow at lower speeds thus increasing the efficiency at cruise. This has an opposing trend at higher speeds - reducing the efficiency. This trend is interesting since it is usually intended to keep the incidence at higher speeds optimal. In order to recover some of the efficiency loss at higher speed, the optimiser reduces the leading edge radii which counteracts the effect of higher stagger angles ensuring satisfaction of the performance constraints at 100% speed. This can be done since the LE damage is only increased mildly when reducing the LE radius.

Another observed trend is the increasing thicknesses at the trailing edge and tip where the damage occurs. The thickening of the blade is an intuitive measure to reduce the damage peaks. However, the increase in thickness spoils the aerodynamic performance drastically. The integrated MDO process using time-efficient impact methods such as the thick-shell approach has allowed to quickly determine the optimal thickness distribution across the aerofoil without penalising the aerodynamics.
The compressor map in figure 7(b) shows the characteristics at cruise (left) and 100% speed (right) of the reference design and designs MO 2, 3 & 5. It can be seen that these optimised designs perform significantly better at cruise condition while keeping the performance at the higher speed unchanged. Looking at the slope of the characteristics, it can be seen that it does not change much between the designs indicating that the surge margin should not have changed significantly. However, it should be mentioned that the predictability of the surge margin is limited using RANS.

Figure 8: TSM damage predictions of the blades derived from the Pareto front visualised as normalised plastic strain contours.

Figures 8 give a comparison of the optimised geometries MO2, 3 & 5 (figs. 8(b)-(d)) against the reference design (fig. 8(a)) with respect to the normalised plastic strain. The annotations in the figures show the relative values of the plastic strains to the reference blade in the four regions: LE, TE, front Tip and rear Tip. Values below one indicates that the plastic strain has improved compared to the results of the reference design with the 3D model. The values of the normalised plastic strains of the TSM as well as the 3D model are listed in table 1.

The comparison between the TSM and the 3D model shows that the low-fidelity TSM is able to pick up the trends. In general, the TSM model is more conservative in its predictions which is preferable for a design tool. Throughout the results, the TSM show lower plastic strain values at the TE which is a consequence of the cropped TE described in the model section.

The optimised designs MO2 & 3 have plastic strains double the value of the reference design at the LE. Although this looks significant, it is not critical for the component since the plastic strains are still well below its threshold.

The critical region is the rear part of the blade. In the reference design, the rear part shows extreme high plastic strains, almost double the tolerable value. The blade vibration triggered by the impact is causing the damage at the trailing edge as well as in the tip region at about 85% chord. All of the depicted Pareto optimal solutions have lower plastic strains than the reference where the

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maximal plastic strains of all optimised solutions are significantly below the tolerable limit. Even though the TSM is suggesting that the rear tip of MO2 is above the limit, the 3D model predicts tolerable values. Furthermore, the trailing edges of the optimised blade designs are less sensitive to the vibration enforced damage. This can be explained by a stiffening of the blade in the rear part. The stiffening of the rear part is considered to be achieved by a mild tip bow shown in figure 9 Changes in the blade shapes figure 9.

Figure 9: Changes in the blade shapes.

CONCLUSIONS

In this study an automated workflow has been developed enabling the use of a surrogate assisted optimisation methodology in order to couple 3D CFD analysis with transient ice impact assessments. A multi-objective and multi-disciplinary optimisation has been conducted using a aerofoil parameterisation which ensures high flexibility of the design space.

It is common to thicken the blade sections to increase its crash-worthiness and, therefore, lifting which then compromise its aerodynamic performance. The developed multi-disciplinary design approach enables to consider simultaneously the aerodynamic performance and the structural requirements. It has been shown, that there are designs which are crash-worthy while improving the aerodynamic performance significantly at cruise. In addition, the designers have now a greater freedom in the design space. This was previously not possible since each discipline had its own set of parameters which were not accessible by other disciplines.

The multi-disciplinary optimisation of a transonic compressor rotor has shown that the mature baseline design can be significantly improved when the aerodynamics and the crash-worthiness are considered simultaneously. It is possible to improve the stage efficiency by up to 0.7% or reduce the impact damage by over 50%. Designs which provide a good trade-off between the two figure of merits have also been identified. Furthermore, all pareto optimal designs have plastic strain values well below the tolerable limit which is verified by the high-fidelity impact model. This demonstrate that the TSM is suitable as a design tool.

Moreover, the TSM produce results which are conservative compared to the high-fidelity model and test data. This is in general a preferred design tool behaviour guaranteeing valid designs.

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REFERENCES

L. Baert, C. Beauthier, M. Leborgne, and I. Lepot. Surrogate-based optimisation for a mixed-variable
design space: Proof of concept and opportunities for turbomachinery applications. ASME Turbo
Expo GT2015-43254, Montréal, Canada, 2015.


J.P. Barber, H.R. Taylor, and J.S. Wilbeck. Bird impact forces and pressures on rigid and compliant

C. J. Brooks, A. I. J. Forrester, A. J. Keane, and S. Shahpar. Multi-fidelity design optimisation of a
transonic compressor rotor. 9th European Conference for Turbomachinery, Fluid Dynamics and

K.S. Carney, D.J. Benso, P. DuBois, and R. Lee. A phenomenological high strain rate model with


J. Graesel, A. Keskin, M. Swoboda, H. Przewozny, and A. Saxer. A full parametric model for tur-
bomachinery blade design and optimisation. ASME Design Engineering Technical Conferences


S. Heimb. Computational methods for bird strike simulations: A review. Computers and Structures,

D. R. Jones, M. Schonlau, and W. J. Welch. Efficient global optimization of expensive black-box

H. Kim and K.T. Kedward. Modeling hail ice impacts and predicting impact damage initiation in

H. Kim, D.A. Elch, and K.T. Kedward. Experimental investigation of high velocity ice impacts on

D. G. Krige. A statistical approach to some basic mine valuation and allied problems at the witwater-

L. Lapworth. Hydra-CFD: A framework for collaborative CFD development. Technical report, Inter-
national Conference on Scientific and Engineering Computation (IC-SEC), Singapore, July 2004
2004.


S. Saxena, R. Singh, and A. Breeze-Stringfellow. Transient behaviour in axial compressors in event of ice shed. ASME Turbo Expo GT2015-42413, Montreal, Canada, 2015.


