Multi-disciplinary optimization of a compressor rotor subjected to ice impact using metamodelling

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Compressors of gas turbine engines are multi-disciplinary systems where the different disciplines are largely considered separately during the design process. 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 on each 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 not carried out until the aero design is reasonable mature. That allows usually only small changes to the rotor in order to achieve the impact requirements. Hence, the introduction of ice impact analysis in the earlier design stages provides higher flexibility for the designers and leads to better compressor performance. A fast thick-shell approach has been adopted to model the transient dynamics of the compressor rotor impacted by crystalline ice slabs from upstream stators. The aerodynamic performance is evaluated with 3D computational fluid mechanics (CFD).

The disciplines are linked using surrogate models which are built up with design of experiments (DoE) and response surface methods (RSM). The surrogate model allows identifying quickly suitable regions in the design space which is leading to improved rotor designs.

I. Introduction

Aircrafts are flying through cold and moist conditions during take-off and landing where the liquid water droplets are super-cooled which means that the water temperature is below -15C. The liquid 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 travelling downstream and impacting the downstream compressor rotor. Due to the high rotor speeds, the ice impact could cause severe mechanical damage if the impact-worthiness is not considered during the design process. 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 evaporate.[1] After a thorough literature search, a lack of suitable methods for ice impact on aeroengine rotors which are appropriate for optimisation has been identified. A model for transient impact dynamics has been developed and used for multi-disciplinary design optimisation.

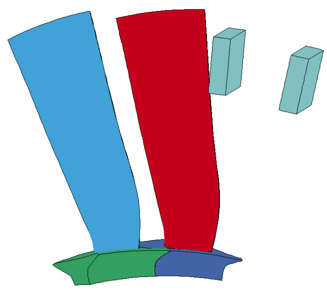

Figure 1. Ice impact model with two ice slabs and two blisk rotor blades.

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A. Ice Impact model

A thick shell approach where the blade is modelled with a one layer brick mesh has been developed in order to reduce the computational time significantly without losing much accuracy. The explicit solver of LS-DYNA[2] is used to simulate the transient dynamics of the impact. In order to avoid highly distorted elements in the lagrangian model, element erosion is applied. In addition, the element erosion helps to model the slicing process more accurate. The impact model consist of two blades and two ice slabs (fig. 1). The size and position of the ice slabs has been chosen to represent a worst case scenario.

B. Aerodynamic model

The aerodynamic performance of the blade geometries is assessed via the Rolls-Royce in-house Reynolds-Averaged-Navier-Stokes solver Hydra.[3] It is an edge-based unstructured CFD code. The turbulence closure is done by using the Spalart-Allmaras turbulence model. The flow is considered to be fully turbulent in the CFD simulations.

For the mesh generation an automatic and robust mesh generation system is necessary avoiding any user interaction. Therefore, the Rolls-Royce mesh generator PADRAM[4] is enabling high quality block-structured meshes to be generated fully automatically.

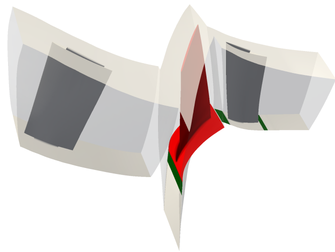


Figure 2. Rotor (red) embedded in a 1.5 stage setup with a shroud leakage model (green).

C. Parameterisation

The aerofoil section shapes are defined by the classical aerofoil parameterisation using the camberline angle Φ and thickness T distribution and the chord length c. Figure 3 shows the parameter definitions of a classical aerofoil parameterisation. The Rolls-Royce in-house tool Parablading is used to generate the aerofoils according to the prescribed parameters.

It can be imagined that the design space is large if all the available parameters for each section are used to define the aerofoil shape. In order to make the optimisation more efficient a reduction of the design parameters is necessary. An approach using B-splines to describe the design parameter distributions in radial and chordwise direction has been chosen. Overall 25 design parameters allowing to change the design with high flexibility has been used.

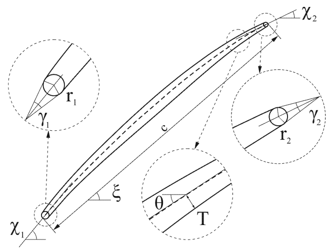


Figure 3. Classical aerofoil section parameterisation.

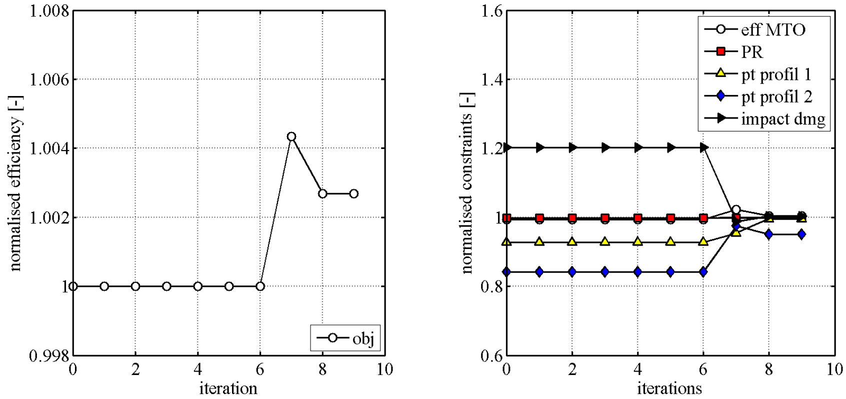
D. Optimisation method and strategy

Direct optimisation where every asked point from the optimiser is evaluated is rather expensive. Much effort has been made to develop optimisation strategies which require less amount of expensive simulations. In this study the mid-range approximation method (MAM)[5–11] has been used. The MAM is using a trust region approach where the optimisation problem is transformed to a sequence of sub-problems.

The optimisations were conducted using the Rolls-Royce SOPHY system.[12,13] The optimiser is communicating through Python scripts with the simulation codes in order to obtain the figure of merit. The Python scripts are able to execute multiple designs in parallel on a HPC cluster in order to speed up the optimisation.

II. Results

The results of the optimisation are shown in figure 4. The figure is showing the results normalised with the nominal values. The optimisation spent 8 iterations with 310 design evaluations in the aero discipline and 330 in the impact discipline. It was possible to increase the efficiency by 0.27% (fig. 4(a))) while reducing the damage due to ice impact. The figure of merit was reduced from an initially infeasible value of 1.203 to 1.003 which means that the constraint is still violated by negligible 0.3%. In addition, the constraint on the efficiency at the higher speed is also not fully satisfied in the final design being also 0.3% above the limit. All other constraints are satisfied which can be seen in figure 4(b).



(a) Objective **(b)** Constraints

Figure 4. History of the best found solutions during the optimisation iterations.

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