Multi-Objective Evolutionary Optimisation of a Compressor Stage

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UTP for design

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The design optimisation of turbomachinery blade rows is still a challenging problem: there are many design requirements, a large design space, and a large computational domain. As the actual flow in a compressor stage is very complicated because of viscous effects, high-fidelity Computational Fluid Dynamics such as Reynolds-Averaged Navier-Stokes computation has to be used for precise prediction of performance. Although improvements in computational resources and various optimisation techniques enable optimisation for complicated geometries, there are still difficulties, especially the computational effort required. Therefore, a Grid-enabled environment is highly desirable in such studies.

In this research, the aerodynamic design target is a blade row in a multi-stage low speed compressor as shown in Figure 1. The compressor rig consists of four stages, each with identical blades, parallel annulus and cantilever stators. It is currently unrealistic to optimise the four-stage compressor directly in terms of computational time. Therefore, a single stage is considered for optimisation to improve aerodynamic performance while keeping similar flow conditions and capacity to the baseline geometry that has already been designed.

Multi-Objective Evolutionary Optimisation

The simulation codes used to evaluate the compressor stage are a collection of programs developed at Rolls-Royce jointly with its University Technology Centres. The analysis is conducted by using the GEODISE computing tool box for Grid computing.

The three-dimensional blade geometry is re-designed from the baseline geometry by using the following parameters specified in PADRAM:

- XCEN: axial movement of sections along the engine axis (sweep)
- DELT: circumferential movement of sections (lean)
- SKEW: solid body rotation of sections based on trailing edge position
- PITCH: pitch angle (number of blades)

The radial profile is represented by B-spline curve. Some re-designed shapes of a blade using the above parameters are shown in Figure 2. PADRAM can also create a good quality viscous mesh based on O-H mesh topology as shown in Figure 3.

The flow solver, HYDRA, computes the steady-state Navier-Stokes equations with the Spalart-Allmaras turbulence model. HYDRA is used to study the following three objective functions:

- Maximisation of isentropic efficiency (aerodynamic performance of compressor)
- Minimisation of blockage (it causes reduction in the passage area because of viscous effects)
- Minimisation of total pressure loss (flow loss)

The following constraint functions are considered to maintain the flow and operating conditions similar to those of the baseline geometry: stage loading, mass flow rate, stage exit whirl angle, and pressure ratio.

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ARMOGA is used to solve the multiobjective constrained optimisation problem efficiently, with three objectives, four equality constraints and 30 design variables. The characteristic of ARMOGA is the introduction of range adaptation. Within the range adaptation routine held every 5 generations, a new search region is determined according to average and standard deviation of an archive which is composed of non-dominated and slightly-violated solutions. To treat the equality-constraint functions, the threshold values on the inequality constraints decrease as the optimisation proceeds. This process is implemented by making use of the feature that ARMOGA collects all the designs computed previously during the range adaptation routine as described in Figure 4.

Optimisation Result

Constrained three-objective optimisation has been conducted for 20 generations. It took nearly five hours to evaluate each design using a Grid node, and 16 different geometries at one generation were computed in parallel using the available Grid resources. In all, 320 different geometries were evaluated during the optimisation. All solutions, 4 non-dominated solutions and datum geometry are plotted in objective-function space in Figure 5. The objective-function values are normalised by the baseline data. One of non-dominated solutions, SV1, has better performance for all three objective functions compared to the datum geometry. The geometry of SV1 is shown in Figure 6.

As a compressor has to work at different conditions, it is desirable that the entire performance is reasonable. The profiles of efficiency at various mass flow rates for both baseline and SV1 are shown in Figure 7. The values are normalised based on the values at the design point of the baseline geometry. Compared to the datum profile, SV1 shows a reasonable profile over different working conditions. Therefore, SV1 is a good candidate to replace the datum configuration.

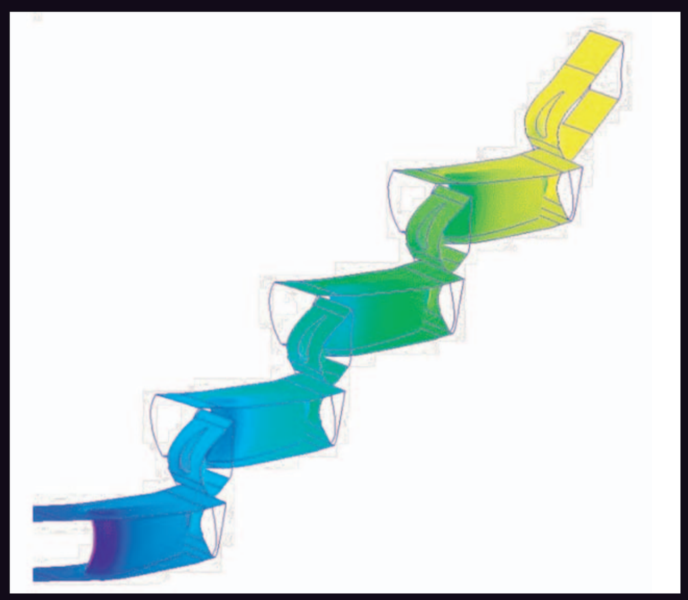

Figure 1 Four-stage low speed compressor.

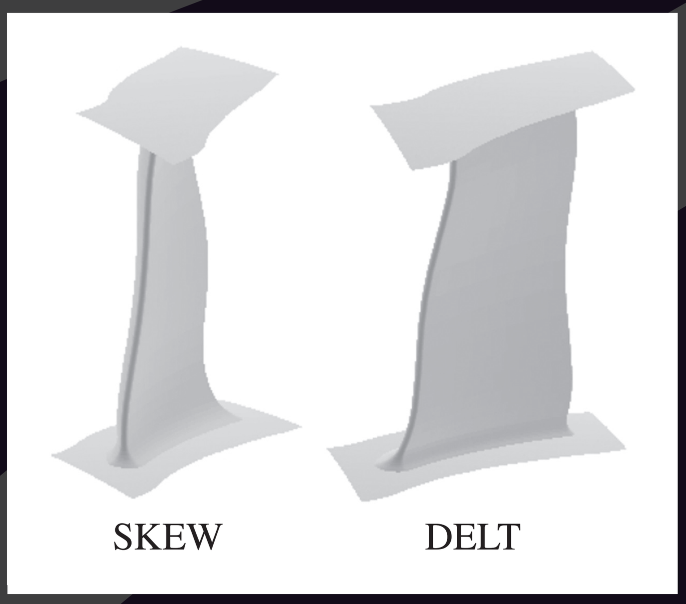

Figure 2 Geometries defined by parameters in PADRAM

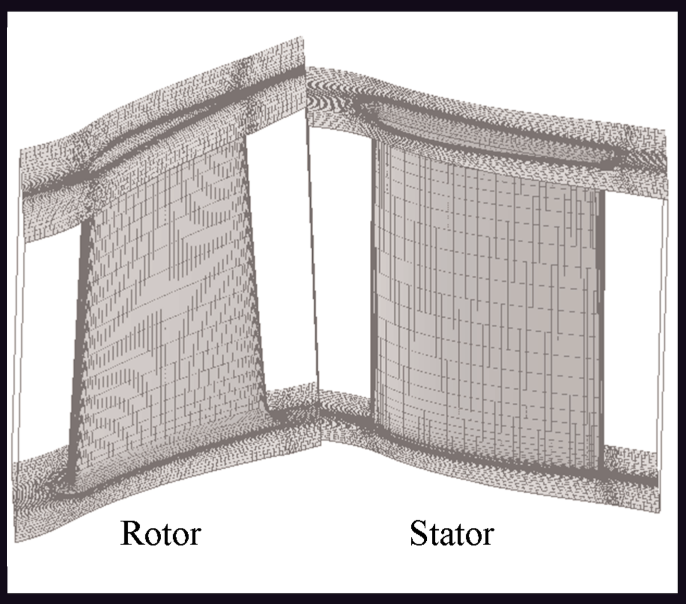

Figure 3 Datum geometry and corresponding mesh.

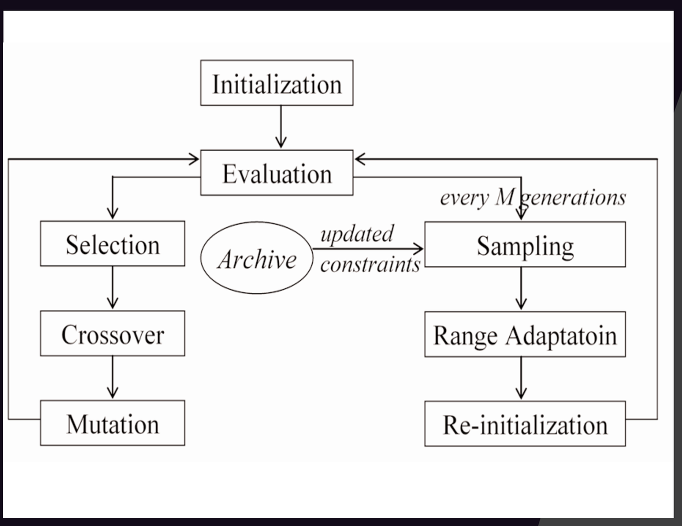

Figure 4 Flowchart of ARMOGA.

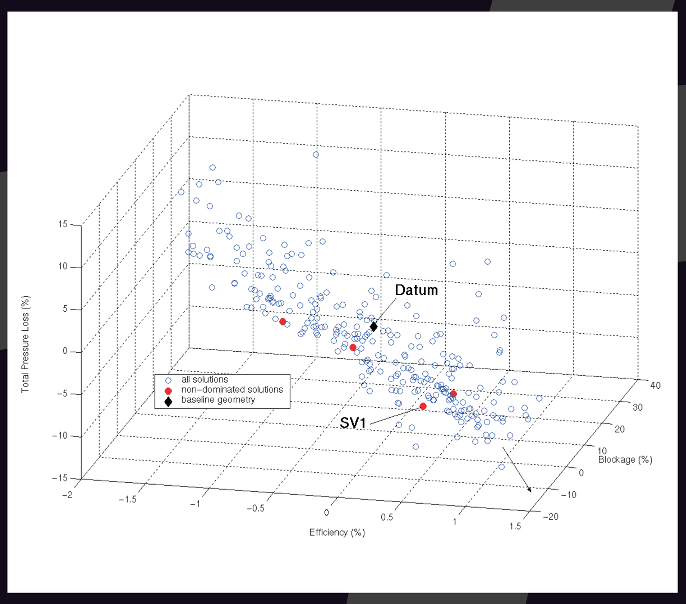

Figure 5 Objective-function space.

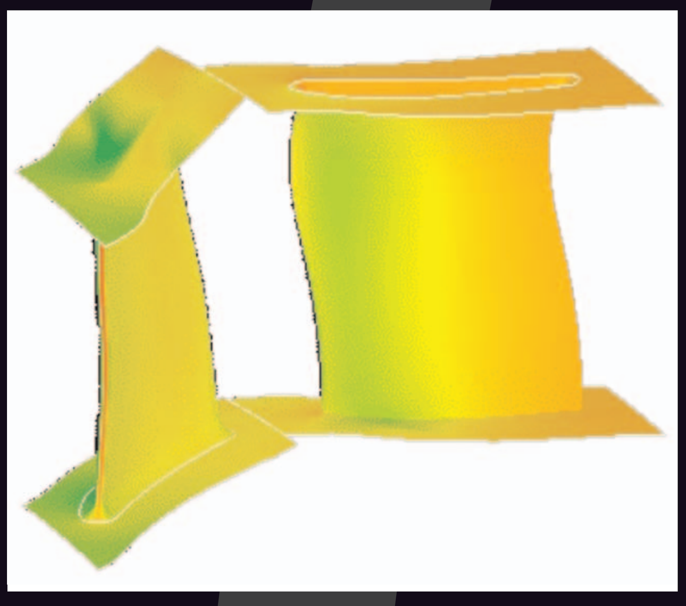

Figure 6 SV1 Geometry with pressure surface.

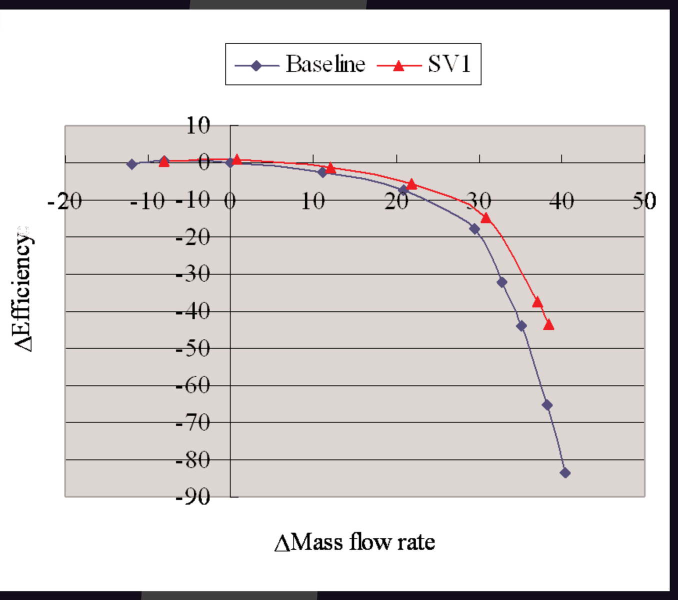

Figure 7 Profile of efficiency according to different mass flow rates.

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