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Using Post-Analyses of Optimisation Processes as an Active Computational Design Tool

T. Kipouros[1], T. Ghisu[2], G. T. Parks[2] and A. M. Savill[3]

Summary

Design optimisation techniques have proved to be very effective in the engineering design process. Turbomachinery is one of the fields with distinctive applications of such approaches. Apart from the improved efficiency of the process, significant advancements to the generic behaviour of engineering products have been recorded. Post-analyses of the optimisation processes and the optimal designs can reveal the physical mechanisms responsible for optimal behaviour characteristics, obtainable by no other means. Moreover, these findings can be deployed online in a dynamic way during the progression of the design process, in order to assist and enhance the adeptness of the computational design cycle and the efficacy of the navigation to the design space. In this paper we suggest an approach based on the post-analyses of optimisation using Parallel Coordinates for reducing the dimensionality of the design space without compromising the overall efficiency of the optimisation process and the quality of the Pareto front found for a three-objective turbomachinery test case.

Introduction

Through computational design approaches it is possible to reveal innovative features of solutions to real-world engineering problems in any discipline. The value of these techniques in the industrial design context is reflected by major, successful activities in academia and industry within this field. Moreover, these approaches give insight into the design space under consideration and can identify the trade-offs between competing performance measures. Special attention has been given to the aeronautical applications of turbomachinery [1], [2], aircraft aerodynamics [3] and aerostructural applications [4].

However, the identification of previously unconsidered design configurations raises questions for traditional engineering designers regarding their validity and functionality. When the design parameters represent more direct physical quantities it might be sensible to connect them with the improved behaviour of the objective performance metrics. However, these analyses are not easy to formulate and are becoming more complicated as the number of design parameters routinely considered increases. Moreover, the level of complexity increases sharply if the design problem contains design parameters that describe and represent aerodynamic surfaces

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[1] Applied Mathematics and Computing, School of Engineering, Cranfield Univ., MK43 0AL, UK
[2] Engineering Design Centre, Department of Engineering, Univ. of Cambridge, CB2 1PZ, UK
[3] Computational Aerodynamics Design, School of Engineering, Cranfield Univ., MK43 0AL, UK

using parameterisation techniques. In this case, there is no simple direct relationship with the physical performance metrics. Hence, advanced computational tools are necessary in order to assist the post-processing of optimisation procedures.

The importance and contribution of post-processing to engineering design increases when detailed analyses are executed for the optimal designs lying on the Pareto front found from a multi-objective optimisation process. In a previous investigation [5], the physical mechanisms responsible for the improved efficiency of axial compressors are revealed. Specific geometrical characteristics are linked to desirable flow features and appropriate combinations of these lead to simultaneous improvements of multiple crucial flow metrics, such as blockage, entropy generation rate, profile losses, and endwall losses.

The full potential of this approach is investigated in the present work. The approach proposed is not restricted to post-processing analyses, but can be integrated into the computational engineering design process and used in a pro-active way, in order to guide the search of the design space more efficiently, as well as to improve the adeptness of the system.

Definition of the Design Problem

The design of a new gas turbine is a highly modular process: the complexity and dimensionality of the system favour the decomposition of the problem into smaller tasks, usually tackled by teams of specialists. This modularity, while improving the tractability of the endeavour, can be detrimental for the overall system performance, as the interfaces between the different components can act as "artificial constraints" during the design process itself. Jarrett *et al.* [6] demonstrated that significant performance gains can be achieved through the integrated design (and optimisation) of contiguous components. The increased size of the design space is what really imposes a limit on the practicability of integrated optimisation. A simplification of the design space is essential to reduce the computational time required and make the optimisation more efficient. In this study we concentrated on the simultaneous optimisation of an intermediate pressure compressor (IPC) and of the following s-shaped duct illustrated in Fig. 1.

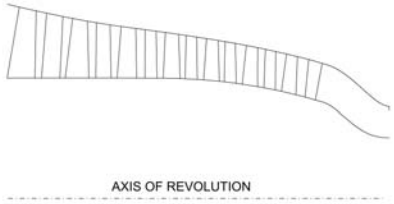


Figure 1: Meridional view of the system

The shape of the compressor annulus was specified through the definition of mean line and area distribution, expressed through fourth-order polynomials. For each blade row, the number of blades and axial chords were allowed to vary. Rather than defining camber and stagger (or blade angles) for each blade row, pressure ratios across each stage and stator exit angles were used: blade camber and stagger angles can be easily obtained by assuming minimum loss incidence. Solidities and aspect ratios can then be calculated. Thickness on chord ratios and tip clearances were kept fixed, as they involved considerations that go beyond the scope of this work.

The s-shaped duct definition reflects the parameterisation of the compressor annulus. C^1 continuity was imposed at the interface for both the mean line and the area distribution, making the two curves effectively two polynomial splines. Because of the lack of practical design rules for s-shaped ducts, the performance was evaluated through an axi-symmetric flow solver developed by Ghisu *et al.* [7] and successfully applied to the isolated optimisation of an inter-compressor duct. To reduce computational time and simplify the integration, a Radial Basis Function (RBF) response surface was built adopting the method suggested by Molinari [8].

(a) Definition of the design space (n represents the number of stages)

Variable Type	Count
compressor annulus	6
stage pressure ratios	n
stator flow exit angles	$n-1$
blade axial chords	$2n$
blade numbers	$2n$
duct annulus	2
Total	$6n+7$

(b) Definition of the optimisation problem

maximise	$\eta' = \eta \frac{\beta^{\frac{\gamma-1}{\gamma}}(1-\omega)^{\frac{\gamma-1}{\gamma}}-1}{\beta^{\frac{\gamma-1}{\gamma}}-1}$
	$SM = \frac{\beta_{SL}-\beta_{DP}}{\beta_{DP}}$
minimise	duct length
subject to	$DH_{min} \geq \overline{DH}$
	$PR_{max} \leq \overline{PR}$
	$DF_{max} \leq \overline{DF}$
	$Koch_{max} \leq \overline{Koch}$
	$H_{max_{DUCT}} \leq \overline{H}$

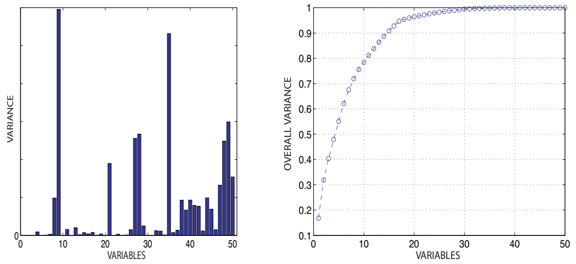
Table 1: Definition of the design space and optimisation problem

Some of the above mentioned variables were then fixed for continuity with the contiguous components, giving a total of 49 variables, two of which influence exclusively the duct (length and mid-length area) and four define the interface between IPC and duct. The system parameterisation is summarised in Table 0(a).

Three figures of merit were considered simultaneously: system adiabiatic efficiency η' (a function of duct total pressure loss coefficient ω, IPC efficiency η and pressure ratio β), compressor surge margin SM and duct length. A number of hard constraints were imposed: a safety limit was imposed on the duct to avoid flow separation (or an excessive proximity to it) by allowing a maximum boundary layer shape factor (H) of 2; the blade loading for each blade row was limited to that of the initial compressor via the Lieblien Diffusion Factor (DF), De Haller number (DH), Koch factor ($Koch$) and static pressure rise coefficient (PR). The resulting optimisation problem is summarised in Table 0(b).

Methodology

The suggested approach is based on the parallel coordinates multidimensional geometries representation, introduced by Inselberg [9]. This technique is very popular in the field of information visualisation [10], but has also been successfully applied to the post-analysis of aerodynamic optimal configurations of axial compressors [5]. The approach offered insight into the impact of the crucial blade geometrical characteristics on the overall performance of a compressor blade row. In the present work, we take advantage of this ability and use the information extracted in a pro-active way while the optimisation process progresses: the design parameters that prove to have only a small impact on the system performance (because of an active constraint, because they have reached an overall optimal value, or because they simply have little impact on system performance) can be fixed and the dimensionality of the problem thereby reduced.



(a) Variance associated with each design variable

(b) Overall variance retained

Figure 2: Reduction of the problem dimensionality through analysis of the variance

As a consequence, the optimisation accelerates significantly. One option for identifying the variables to be fixed is to calculate their variance among the Pareto optimal designs. This decision process takes place after the execution of 500 optimisation steps, in order to give the optimiser enough time to locate the most significant variables. The variance associated with each of the initial 50 variables is shown in figure 2(a): reducing the design space to 25 variables the dimensionality of the problem to be reduced significantly, while retaining 98% of the total variance observed in the Pareto front (figure 2(b)). It should be emphasised that only the ability of each design parameter to change during the optimisation process is eliminated; these variables can take different values when the search is intensified and a Pareto optimal design is selected as the next search point.

Presentation and Discussion of the Results

Figure 3 shows design parameter number on the x-axis, and the y-axis represents the value of each design parameter normalised relative to its overall allowed range of variation. Hence, each line running from left to right represents a design configuration from the Pareto front found for the turbomachinery design problem in question, in a run in which all 50 design parameters were allowed to vary throughout. It is clear already that among the Pareto optimal designs some of the design parameters appear to have fixed values.

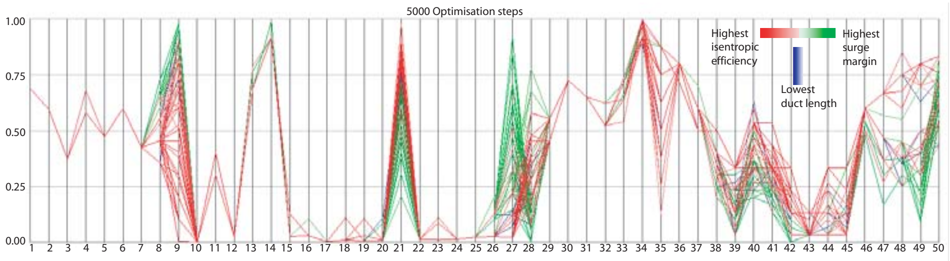


Figure 3: Parallel Coordinates representation of the Pareto front design vectors found after 5000 optimisation steps with 50 design parameters free to change

In the reduced-design-space test case we fixed parameters 1-7, 10, 12, 14, 15, 17, 18, 20, 22, 24, 25, 29-32, 34, 36, 43, and 46, based on the variance analysis after the execution of the first 500 optimisation steps. Comparing Figs. 3 and 4 we can identify very few differences between the Pareto optimal design vectors from the two optimisation runs revealed after 5000 optimisation steps. 652 designs comprise the trade-off surface for the reduced-design-space test case, and 456 designs lie on the trade-off surface found through the initial investigation of the design problem. Hence, the optimum design area of the problem was better investigated when we deployed the proposed method for reducing the number of design parameters. Similar results were also found after the execution of 20000 optimisation steps.

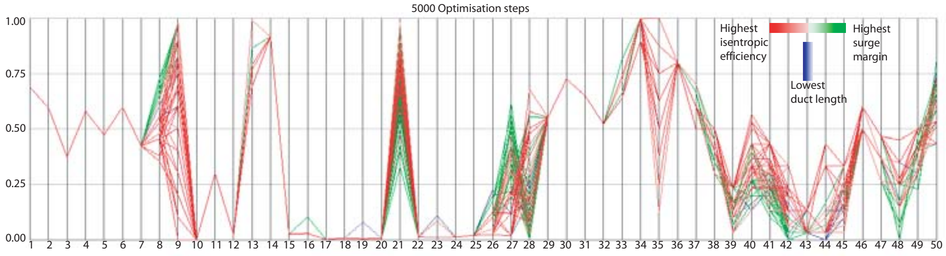


Figure 4: Parallel Coordinates representation of the Pareto front design vectors found after 5000 optimisation steps with 25 design parameters free to change

Moreover, Fig. 5 presents the two trade-off surfaces found. It is clear that the

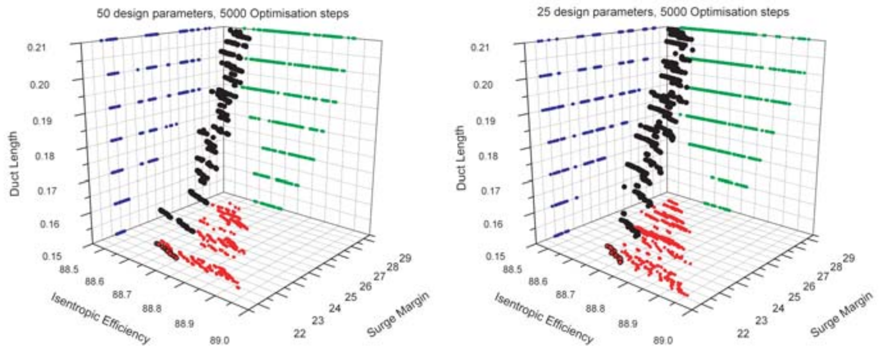


Figure 5: Comparison of the 3D Pareto trade-off surfaces found

improvement made to the intelligence of the optimisation search is directly reflected in an improvement in the quality of the Pareto front. The compromise design area of the reduced-design-space trade-off surface is richer and dominates the trade-off surface found when all 50 variables were allowed to vary.

Conclusions

In the present work we propose and apply in a dynamic way, while the design process progresses, an approach traditionally used for post-processing optimisation results. The technique is powerful not only in facilitating the visualisation of the 50-dimensional design space and the extraction of qualitative information about physical characteristics and mechanisms of optimal designs, but also in assisting the improvement of the adeptness of the design process. A 50% reduction in the dimensionality of the design space is achieved. This is then directly reflected in the computational time saved for the same optimisation design process without compromising the quality of the solutions obtained. In addition, another element in the engineering design process is underlined: the importance of the dynamic interaction between the human designer and the automated computational design cycle.

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