Component-specific Engine Design Taking into Account Holistic Design Aspects

Marco Hendler, Engineering Mechanics and Vehicle Dynamics, Brandenburg University of Technology, Cottbus, Germany
Dieter Bestle, Engineering Mechanics and Vehicle Dynamics, Brandenburg University of Technology, Cottbus, Germany
Peter Flassig, Rolls-Royce Deutschland Ltd & Co KG, Blankenfelde, Germany

Long Abstract

Introduction

Efficient aero engine operation requires not only optimized components like compressor, combustor and turbine, but also an optimal balance between these components. Therefore, a holistic coupled optimization of the whole engine involving all relevant components would be advisable. Due to its high complexity and wide variety of design parameters, however, such an approach is not feasible, which is why todays aero engine design process is typically split into different component specific optimization sub-processes, where fixed aerodynamic interface parameters predefined by simplified thermodynamic performance calculations are used to connect the components. In order not to miss the optimization potential of variable interface parameters, a new design process is proposed enabling an exchange of information between components. Especially, a compressor design process is extended by combustor design criteria to account for the influence of interface parameters on the compressor design and its aerodynamics.

Design Strategy

As already mentioned, the current procedure for aero engine component design is based on fixed interfaces used as boundary conditions to be achieved. In case of compressor (C) and combustor (CC), the interface is located between both components at the flow channel section behind the last stator blade of the high pressure compressor (Figure 1). The interface parameters are

$$\mathbf{y}_{C|CC} = [\,p_{30}, T_{30}, Ma_{30}, \alpha_{ex}, \dot{m}_{30}]^T \in \mathbb{R}^5 \text{ and } \mathbf{p}_{C|CC} = [\,h_{PD}, r_{PD}]^T \in \mathbb{R}^2 \quad (1)$$

where $\mathbf{y}_{C|CC}$ simultaneously represents results from compressor calculation and input to the combustor analysis, and $\mathbf{p}_{C|CC}$ represents predefined geometric parameters at the interface between both components. Interface state $\mathbf{y}_{C|CC}$ strives to be equal to the predefined state $\mathbf{y}^g_{C|CC}$, which is given by the thermodynamic performance calculation. Feedback from the combustor to the compressor $\mathbf{y}_{CC|C}$ is not taken into account. A combined compressor and combustor design determining both compressor parameters $\mathbf{p}_C \in \mathbb{R}^{d_c}$ and combustor parameters $\mathbf{p}_{CC} \in \mathbb{R}^{d_{cc}}$ would then e.g. read as

$$\min_{\mathbf{p}\in P} \begin{bmatrix} -\eta_C\eta_{CC} \\ EI \end{bmatrix} \; s.t. \;\; P = \left\{ \mathbf{p} = \begin{bmatrix} \mathbf{p}_C \\ \mathbf{p}_{CC} \end{bmatrix} \in \mathbb{R}^{d_c+d_{cc}} \middle| \begin{bmatrix} \mathbf{h}_C \\ \mathbf{h}_{CC} \end{bmatrix} \le \mathbf{0},\; \left\| \mathbf{y}^g_{C|CC} - \mathbf{y}_{C|CC}(\mathbf{p}_C) \right\| \le \varepsilon,\; \mathbf{p}^l \le \mathbf{p} \le \mathbf{p}^u \right\} \quad (2)$$

with constant interface parameters $\mathbf{p}_{C|CC}$. The objectives of the optimization are reduction of emission index EI describing the amount of emissions from burning one kilogram of fuel and maximization of the overall efficiency $\eta = \eta_C \cdot \eta_{CC}$ assumed to be the product of compressor and combustor efficiencies. The component sub-processes are subject to some inequality constraints $\mathbf{h}_C(\mathbf{p}_C) \le \mathbf{0}, \mathbf{h}_{CC}(\mathbf{p}_{CC}) \le \mathbf{0},$ and meeting the interface state within a small tolerance is enforced by condition $\left\| \mathbf{y}^g_{C|CC} - \mathbf{y}_{C|CC}(\mathbf{p}_C) \right\| \le \varepsilon$.

If only the compressor shall be designed for the predefined interface states $\mathbf{y}^g_{C|CC}$ with $\mathbf{p}_{C|CC} = \text{const.}$ and $\mathbf{p}_{CC} = \text{const.}$, the combustor calculation needs to be performed only once, because the objectives EI and η_{CC} are constant and have no influence on minimization (2). Therefore, the optimization problem of the compressor with constant combustor parameters reduces to

$$\min_{\mathbf{p}_C\in P_C} (-\eta_C) \; s.t. \;\; P_C = \left\{ \mathbf{p}_C \in \mathbb{R}^{d_c} \middle|\, \mathbf{h}_C \le \mathbf{0},\; \left\| \mathbf{y}^g_{C|CC} - \mathbf{y}_{C|CC}(\mathbf{p}_C) \right\| \le \varepsilon,\; \mathbf{p}^l_C \le \mathbf{p}_C \le \mathbf{p}^u_C \right\}. \quad (3)$$

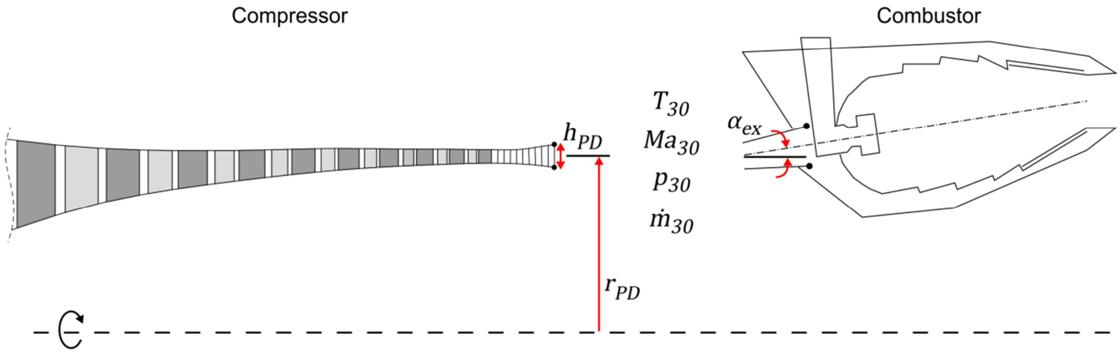

Figure 1. Compressor and combustor interface parameter.

This problem definition essentially represents the compressor design processes described in [1] and [2], which are slightly adapted here. These original processes are limited to the bladed compressor part only. For use in a holistic design approach, they are extended by a swan neck inlet duct and the pre-diffusor geometry. With these modifications, the design process is able to achieve the prescribed boundary conditions at the interface and serves as reference here.

In the new approach, also just compressor optimization is carried out, but the interface parameters are not preset to values of the performance calculation. Instead, interface parameters are taken as variables, whereby influence of compressor changes on the combustor is taken into account. The variable entry conditions to the combustor now influence its aero- and thermodynamics resulting in modified objectives EI and η_{CC}. The extended problem for the compressor now reads as

$$\min_{\mathbf{p}_C^e \in P_C} \begin{bmatrix} -\eta_C \eta_{CC} \\ EI \end{bmatrix} \; s.t. \;\; P_C^e = \left\{ \mathbf{p}_C^e = \begin{bmatrix} \mathbf{p}_C \\ \mathbf{p}_{C|CC} \end{bmatrix} \in \mathbb{R}^{d_C+2} \middle| \; \mathbf{h}_C \leq \mathbf{0},\; \mathbf{h}_{CC} \leq \mathbf{0},\;\; \mathbf{p}_C^{e,l} \leq \mathbf{p}_C^e \leq \mathbf{p}_C^{e,u} \right\}. \tag{4}$$

Due to accounting for changing interface parameters and states, the associated inequality constraints can be deleted from the optimization problem, hence leading to a simplification of the problem. The previously assumed constant design parameters in $\mathbf{p}_{C|CC}$ are integrated in the extended design vector $\mathbf{p}_C^e$ and modified as well. For changing boundary conditions, the combustor analysis program recalculates the internal air flow distribution by using a 1D flow solver and it automatically performs the necessary geometry adjustments. In contrast to [3], the interface parameters defined earlier by the performance calculation are continuously updated by higher fidelity design tools to create an optimally coupled system. The recalculation of the combustor process and the estimation of the efficiency η_{CC} as well as the emission index EI can be accelerated by use of previously trained response surfaces.

The investigation of both optimization strategies with differently interpreted coupling parameters (fixed and variable) has shown that it is advisable to use variable interfaces and to better adjust them during the design process based on higher-fidelity information than available from a preliminary performance calculation.

References

[1] T. Rühle: *Ein Beitrag zur optimalen, mehrkriteriellen Axialverdichterauslegung auf Basis der Meridianströmungsrechnung*, Dissertation, BTU. Aachen: Shaker, 2013.

[2] F. Pöhlmann: *Optimization and Coupling Strategies for Codes of Different Fidelity to Automate an Aerodynamic Compressor Design Process*, Dissertation, BTU. Aachen: Shaker, 2015.

[3] J. Kurzke: *Gas Turbine Cycle Design Methodology: A Comparison of Parameter Variation with Numerical Optimization*. In: Proc. of ASME International Gas Turbine and Aeroengine Congress and Exhibition, Stockholm, 1998, Paper No. 98-GT-343.