Aerodynamic Optimization of Centrifugal Fans Using CFD-Trained Meta-Models

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Long Abstract

Introduction

A typical optimization target in the design of centrifugal impellers is to achieve a design point (pressure rise at a specific flow rate) with the highest possible total-to-static efficiency. Typically, such optimizations are performed by coupling Computational Fluid Dynamics (CFD) with optimization algorithms. The optimization process is often accelerated by replacing CFD simulations by CFD-trained meta-models. In that case, CFD is only required to generate a dataset which is used to train the meta-models. The optimization is then performed with the meta-models which evaluate the target function several orders of magnitude faster than CFD itself. The aim of the present study is to develop meta-models which differ from state-of-the art modes in terms of universality since they can be used to optimize impellers in the complete classic realm of centrifugal fans according to Cordier's diagram. In order to avoid an explosion of the number of required CFD simulations, it is of crucial importance to use the computational resources as efficiently as possible.

1. Methods

The individual steps in order to obtain the meta-models are described in the following. The main focus of the description is on measures to reduce computational effort without compromising the applicability and accuracy of the meta-models.

Impeller Parameterization

The main objective of the parameterization is to provide a high level of geometrical flexibility with a low number of free parameters. The final selection comprises only such geometrical parameters which are of crucial importance with respect to the aerodynamic performance (see e.g. Bommes [1], Pfleiderer [2]): the number of blades, the inner diameter, the width at leading and trailing edge, the blade angle at leading and trailing edge, the blade lean, the angle at which the leading edge is cut off and the radius of the nozzle at the leading edge. All lengths mentioned are referred to the outer diameter to obtain a dimensionless description of the impeller.
Geometrical parameters with lower aerodynamic significance (e.g. the blade thickness, the contour of the inlet nozzle, etc.) are held constant at typical recommendations according to literature ([1], [2]).

Design of Experiments (DoE)

The variation of impeller geometry is based on a latin hypercube method. Two measures are performed to vary the geometry as efficient as possible. Firstly, an optimized latin hypercube method is used which leads to a more uniform distribution of points in the parameter space as compared to a random latin hypercube method. Secondly, geometry variations obtained by the DoE are simulated in an optimized sequence. The idea behind optimizing the sequence is to achieve better performance of the meta-models at a time at which only a part of the overall number of intended CFD simulations are completed.

Computational Fluid Dynamics

All geometry variations obtained by the DoE are simulated using the Reynolds-averaged Navier-Stokes (RANS) method. There are two competing objectives: On the one hand, the CFD-results must be precise and not grid dependent which suggest the utilization of a very fine grid resolution and the consideration of a huge inflow and outflow space surrounding the impeller. On the other hand, the duration of a single CFD simulation limits the affordable number of geometry variations and eventually the quality of the meta-models. The best trade-off is found by optimizing the following characteristics of the numerical grid: the overall number on nodes, the allocation of the nodes between the impeller and the surroundings, the resolution of the boundary layers at the impeller and in the surroundings and the size of the surroundings. Optimal magnitudes of these settings are obtained by an optimization algorithm aiming at the best possible adaption of the RANS results to experimental data (using three fans and three operating points each) while considering a penalty term for the overall number of grid points.

Training of Meta-Models

Two types of meta-models are trained and compared: Local model networks (LMN) and multi-layer perceptrons (MLP). The main focus is on an efficient exploitation of the CFD-results. To this end, the quality of the meta-models is enhanced by cross-validation, term selection (backwards elimination as well as forward selection) and structure optimization.

Experimental Investigations

Characteristic fan curves of axial impellers are measured on a test rig in accordance with the international standard EN ISO 5801:2009 [3]. The test series comprises three impellers with very different geometrical and operational features. These tests are used to validate the CFD model and to perform the aforementioned optimization of the numerical grid.

2. Results

Optimal Numerical Grid

The best trade-off between accuracy on the one hand and numerical cost-effectiveness on the other hand is obtained using a total of 650,000 nodes (150,000 of which are placed in the surroundings of the impeller), a wall resolution of $y^+ \approx 30$ and surroundings around the impeller which extend one impeller diameter in both positive and negative axial direction and two impeller diameters in radial direction.

Adequacy of the two Meta-Models

At the moment, the MLPs perform better than the LMNs, but the advantage decreases the more geometry variations are simulated and considered for training the meta-models. Since the CFD-dataset is continuously extended, it is too early for a final assessment. This will be part of the final paper which will furthermore discuss the suitability of the meta-models for optimization problems.

Achievable Design Points

The design points that can be realized with the present geometrical parameter space are found to fully cover the typical operating range of centrifugal impellers according to Cordier's diagram. In addition, typical design points of mixed-flow and axial fans are partly feasible, too.

References

[1] Bommes, L., Fricke, J., Grundmann, R., 2003, Ventilatoren, *Vulkan Verlag*, Essen.

[2] Pfleiderer, C., Petermann, H., 1991, Strömungsmaschinen, *Springer-Verlag*, Berlin, Germany.

[3] EN ISO 5801:2009, 2010, "Industrial Fans - Performance Testing Using Standadized Airways," *Beuth Verlag, Berlin, Germany*, Berlin, Germany.