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Robust Design Optimization of a Turbocharger Centrifugal Compressor

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Conventional simulation predicts the performance of only a single design point at a time. Design optimization goes one step further by automatically simulating a suitable combination of design parameters, with the goal of confidently identifying the design that will not just meet the spec but provide the highest possible level of performance while meeting other constraints. This article demonstrates a multistep method for optimizing the design of a centrifugal compressor while ensuring that it will have sufficient robustness to withstand manufacturing variation.

In the past, the only method available to develop an automated design optimization process was the time-consuming process of writing scripts. Instead, in this application, ANSYS® Workbench™ and optiSLang® served as an integrated platform to build a fast and reliable multiphysics-based robust design optimization process in much less time without scripting. The process provides automatic regeneration of the geometry, high-quality meshing for each possible design, automatic solver execution and automatic post-processing.

Geometry definition

The design geometry, including the blades and hub body, is defined in ANSYS BladeModeler™. The geometry of the blades is defined by the meridian flow path as two parametric sketches, one for hub and another for shroud. The location of the leading and trailing edges for the rotor and return guide vane are defined based on the meridian plane. The shape of the blades is defined by the angle and thickness distribution of the hub and shroud layer. There are a total of 17 input parameters, as shown in Figure 1.

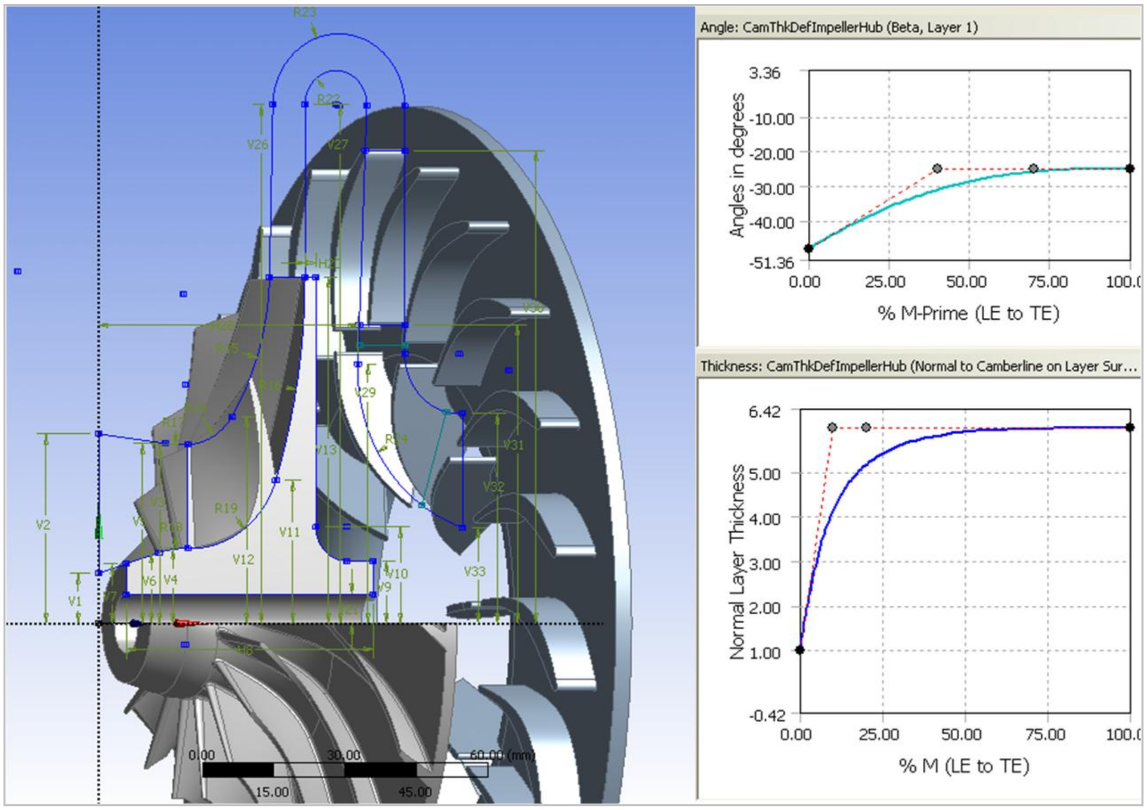

Figure 1: Parametric geometry

Computational fluid dynamics

ANSYS TurboGrid™ is used to automatically generate the mesh for the computational fluid dynamics (CFD) simulation based on the mesh resolution defined by the user. The model has one passage per component with a profile-transformation rotor–stator interface and chronologic periodic interfaces. The total pressure and temperature are defined at the inlet, while the mass flow rate is defined at the outlet. An ideal gas is used. ANSYS CFX® is used to solve the model. CFX-Post is used to define output parameters, such as total pressure/temperature ratio and isentropic or polytrophic efficiency. Figure 2 shows typical simulation results.

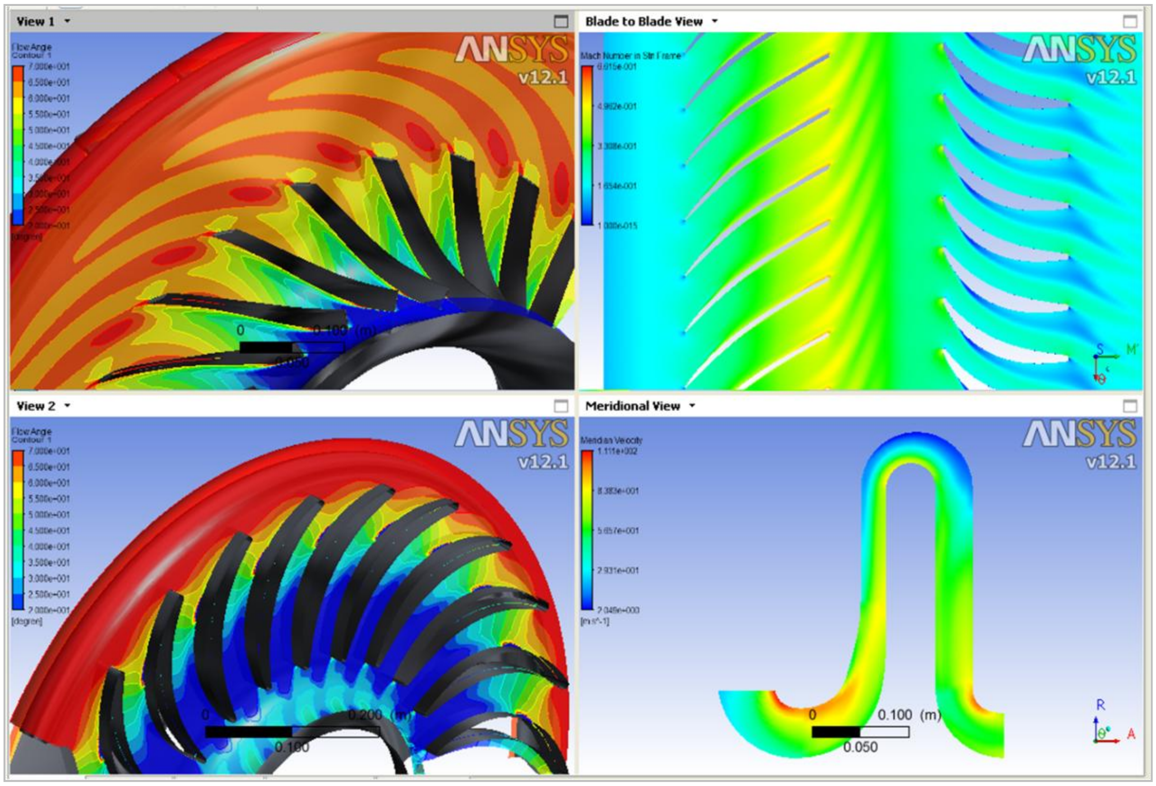

Figure 2: CFD simulation results

The mechanical model uses one segment of the rotor with cyclic symmetry, reducing computational time without sacrificing numerical accuracy. The model is fixed at the inner radius, and the rotor is loaded by centrifugal force and fluid pressure, which is taken from the CFD simulation. Data handling and fluid–structure coupling are automatically performed by Workbench, as shown in Figure 3. After the static simulation is completed, a prestressed modal analysis is performed. The results of the mechanical simulation include the maximal displacement, von Mises stress and eigen frequencies. The design requirements include an upper limit for stress and eigen values that do not match the rotational velocity to avoid resonance.

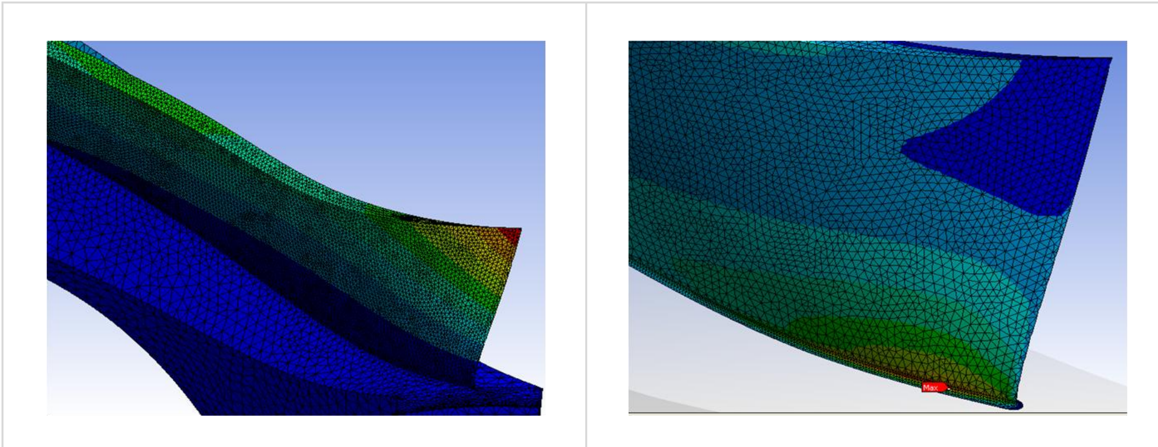

Figure 3: Mechanical displacement and stress

Sensitivity analysis

Methods of Robust Design Optimization (RDO) are conducted within ANSYS® Workbench™ using optiSLang®, a development by the Dynardo GmbH. Running a sensitivity analysis, optiSLang® evaluates the reliability of the numerical model and identifies the most important input parameters. The Metamodel of Optimal Prognosis (MoP) algorithm uses Latin hypercube sampling to scan the multidimensional space of the input parameter. Approximately 100 design points are solved simultaneously. The coefficient of prognosis (CoP) is calculated, which determines if the metamodel is reliable or not. This calculation also determines which input parameters have a strong influence on the output. The response surface graphically depicts the influence of the relevant parameters on system performance and shows where efficiency is highest. Figure 4 shows the CoP and response surface.

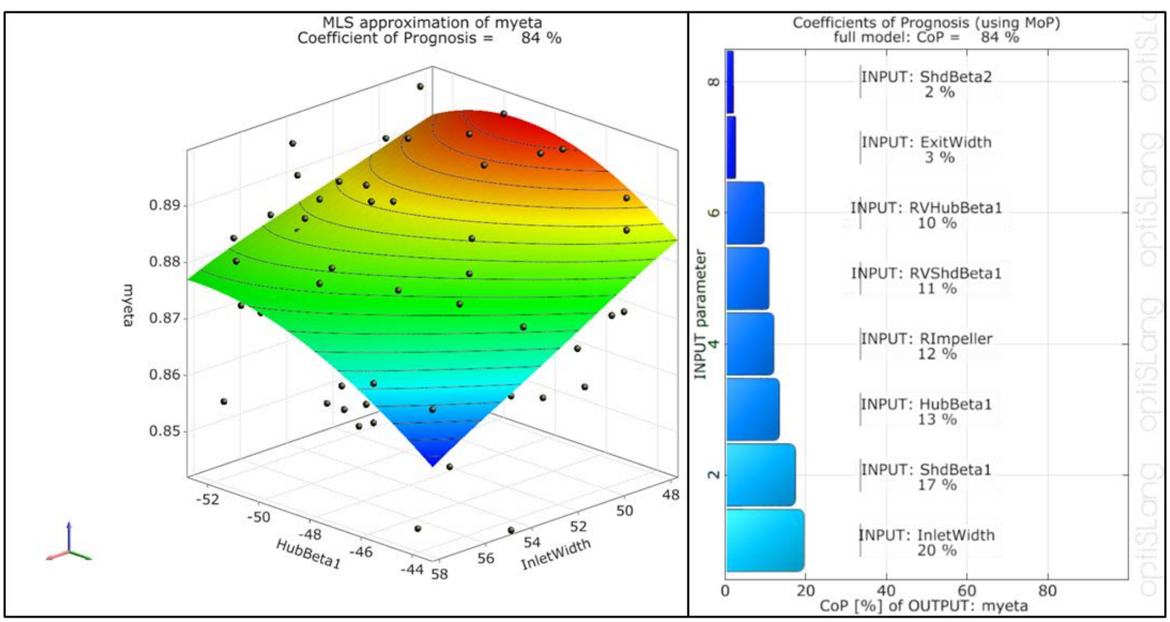

Figure 4: Coefficient of Prognosis (CoP) and metamodel

Design optimization
Fig. 4 shows that only a small number of input parameters are important. For this reason, the initial optimization strategy comprised the adaptive response surface method (ARSM) using only the important input parameters. A second optimization step with an evolutionary algorithm (EA) including all input parameters is also performed. Table 1 lists the results and computational effort required for each step.

	Initial	SA	ARSM	EA
Pressure Ratio	1.3456	1.3497	1.3479	1.3485
Efficiency [%]	86.72	89.15	90.62	90.67
# Simulations	-	100	105	84

Table 1: Design optimization

The sensitivity analysis shows a large improvement compared to the initial design, based on 100 simulations. The direct optimization with ARSM shows a further improvement, based on another 105 design evaluations. The EA does not provide additional improvement, even though it uses all input parameters, because the additional input parameters have little effect on the results. This proves that sensitivity analysis has correctly identified the critical input parameters.

Robustness evaluation
The final compressor design must achieve a specified pressure ratio. Robustness evaluation ensures that this pressure ratio will be met regardless of manufacturing variation. The statistical distribution of the input parameters produced by the manufacturing process is calculated and used to determine the distribution of the output parameters. Figure 5 shows the results for the pressure ratio.

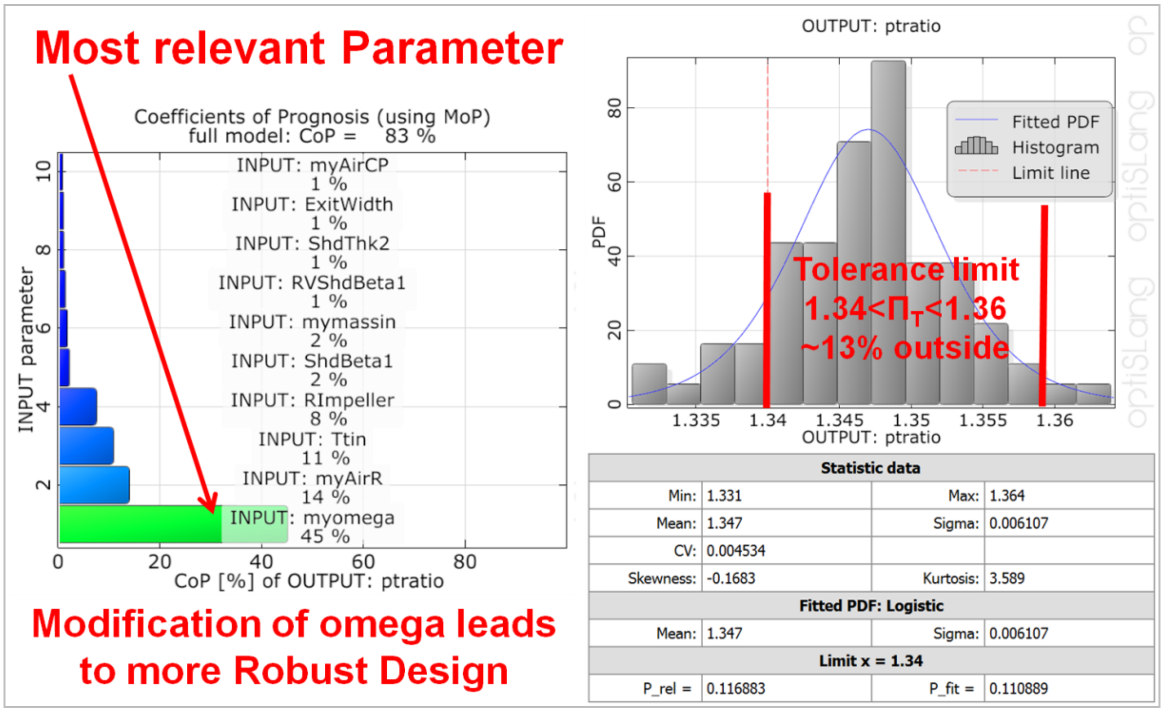

Figure 5: Robustness evaluation of pressure ratio

The robustness analysis provides results that are similar to those provided by the sensitivity analysis. The CoP is 83 percent, which indicates that the results can be trusted. The distribution function, which is also provided, shows that approximately 13 percent of the manufactured designs will not have the required pressure ratio. The robustness analysis indicates the important input parameters, the ones that, when modified, will have an effect on the variation of the results. The robustness analysis shows that the rotational velocity is the most relevant parameter for reducing statistical variation of the pressure ratio. Reducing variation of other input parameters will have little or no influence on the pressure ratio.

Conclusion

Robust Design Optimization (RDO) helps to improve the design while also minimizing the impact of manufacturing variation, resulting in a higher performing, more robust design. An automated process can be used to achieve RDO based on the ANSYS® Workbench™ and the integrated multidisziplinary and multiobjective optimization platform optiSLang®.