Performing Multi-Point, Multi-Objective Pump Optimizations with 3D Inverse Design

Carrying out complex multi-point, multi-objective optimizations is prohibitively expensive with conventional design methods. A 3D Inverse Design approach makes this type of optimization possible by drastically reducing the computational cost.

By Mehrdad Zangeneh, Founder and Managing Director, Advanced Design Technology

Pump Design

The hydrodynamic design of rotodynamic pump stages usually involves quite complicated multi-point and multi-objective trade-offs. At the simplest level, designers have to meet the duty points of the pump, while maximizing its efficiency at the design point and improving cavitation performance. Normally what is good for cavitation performance (e.g. longer blade chords) makes skin friction loss and efficiency worse. This means there is a natural trade-off between these two requirements.

What makes the design of pumps complicated is that the pump is required to operate over a very wide range of flow rates; from shutdown conditions to upwards of 130% flow conditions. In addition to meeting the maximum power requirement for the motor, the pump also has to meet certain targets and requirements on the continuously rising head characteristics, on the maximum power ratio and on certain NSPH requirements.

In order to meet these complicated multi-point/multi-objective requirements, the designers must explore a large design space. Improving off-design performance and 'flattening' the efficiency envelope is a difficult task for any experienced pump designer. Improving the design manually requires producing many iterations via trial and error. By using 3D inverse design-based automatic optimization, pump stages can be rapidly designed to achieve improvements in efficiency, cavitation and shape of head curve at multiple operating points.

Multi-Point Optimization for Pumps

Using a conventional design approach, automatic optimization is computationally very expensive as parametrizing the blade shape in a 3D model requires a large number of design parameters and hundreds of geometries evaluated at multiple operating points. It is also difficult to ensure that the required head is met by the geometry created at the correct flow rate, so this must be specified as a constraint and Computational Fluid Dynamics (CFD), flow analysis software, used to evaluate it. These processes add to computational costs.

In order to reduce the computational costs, a Design of Experiments (DOE) approach can be utilized. This approach works well when coupled with surrogate models such as a Response Surface Method (RSM) or Kriging. Optimization can be run on the surrogate model to find the best trade off solution for the multiple operating points. In this approach, multi-point CFD only needs to be run on a small number of geometries in the design matrix. The key to the effectiveness of this approach is the accuracy of the surrogate model, or more specifically, to what extent the efficiency predicted by the surrogate model matches the actual values obtained from CFD of that specific geometry. Generally, it is very difficult to obtain accurate surrogate models by using geometry parametrization (a conventional design approach) as the DOE method creates some designs with low head and some with high head.

In the inverse design approach, the blade shape is parametrized by using blade loading distribution. The code automatically ensures that all designs satisfy the specified head at the correct flow rate. As a result, it is possible to create accurate surrogate models by using the DOE method. A large design space can be covered by as little as four design parameters, which means it is possible to use this approach for multi-point design optimizations under industrial time scales. Typical optimization of an impeller at three operating points would only require about 45 to 60 CFD computations (i.e. a design matrix of 15 to 20 geometries computed at three operating points).

Case Study

The Challenge

A DOE multi-point optimization process was applied to the redesign of a mixed-flow pump impeller. This impeller was designed to meet the following specifications at the Design Point:

Parameter	Design Point value
RPM	1000
Flow rate (m3/min)	6.42
Impeller head (m)	10.0

Table 1: Design specifications for the pump impeller.

The impeller needed to be redesigned for improved performance across its full operating range; from design point flow rate down to 40% of design flow rate. In addition, cavitation performance is important and so NPSHr needed to be minimized. The redesign was also subject to some constraints controlling the available design space:

- The impeller needed to be a drop-in replacement and so no meridional geometry changes could be made.
- Leading edge sweep had to be <10 degrees to ensure good castability.
- The BEP had to remain with ±5% of Design Point.

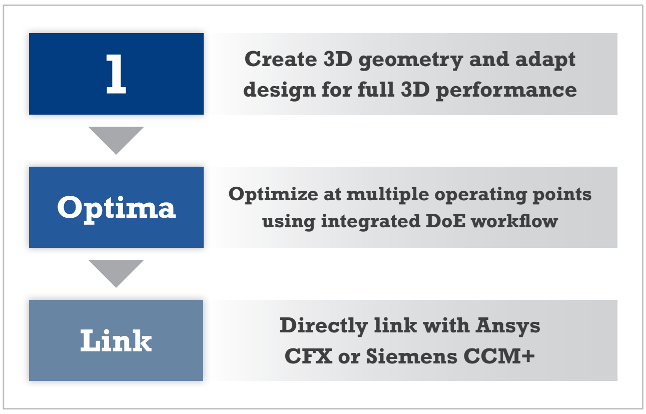

Figure 1: TURBOdesign Suite workflow used for inverse design based multi-point optimization.

For this project the following design process, shown in Figure 1, was used.

The Solution

The DOE only required five input parameters to control the 3D blade geometry. Four design parameters were used to vary the blade loading at the hub and shroud. These were the DRVT parameters that control the incidence on the blade at the leading edge, and the SLOPE parameter that controls whether the blade is fore-loaded or aft-loaded, see Figure 2. When the DRVT at leading edge is positive that means there is a positive pressure jump across the blade at the leading edge. When DRVT is zero that mean zero pressure jump and hence zero incidence at the leading edge. In the inverse design approach this is how the incidence on the blade is controlled.

The blade loading at each streamline is parametrized by using the parabolic section from leading edge to a point NC and then a straight-line section where the slope can be specified. This is then followed by a parabolic section to bring the loading to zero at the trailing edge. At the trailing edge the blade loading should always be zero to satisfy the Kutta conditions. In this case NC and ND locations were kept fixed during optimization and only the DRVT and SLOPE parameter were varied. These four parameters can give quite a large variation in design space. A fore-loaded distribution as shown by red line in Figure 2 would mean that the pressure jump across the blade is highest near the leading edge. An aft-loaded distribution as shown by the blue line in Figure 2 means the maximum pressure jump across the blade occurs close to trailing edge of the impeller.

By varying just these four parameters, which are inputs of the inverse design method TURBOdesign1, large variations in geometry corresponding to these blade loadings can be generated. Since all viscous behavior in pump impellers depend on the pressure field, this means impeller geometries with very different viscous behaviors are generated, while each design will still satisfy the specified head requirement. In addition to these parameters the stacking condition was also varied at the trailing edge.

To achieve a very high-quality response surface, engineers targeted 4x the number of input parameters for the number of design points. Using these five input parameters, a design matrix of 20 impeller geometries was created by using Optimal Latin Hypercube and TURBOdesign1. These 20 geometries were then analyzed in CFD at 40% and 100% of design flow rate. In addition, the minimum pressure was recorded from the inverse design flow solution to give a very rapid calculation for the Net Positive Suction Head Required (NPSHr), which is important for suction performance, along with throat area to ensure that BEP flowrate can be constrained in the later optimizations.

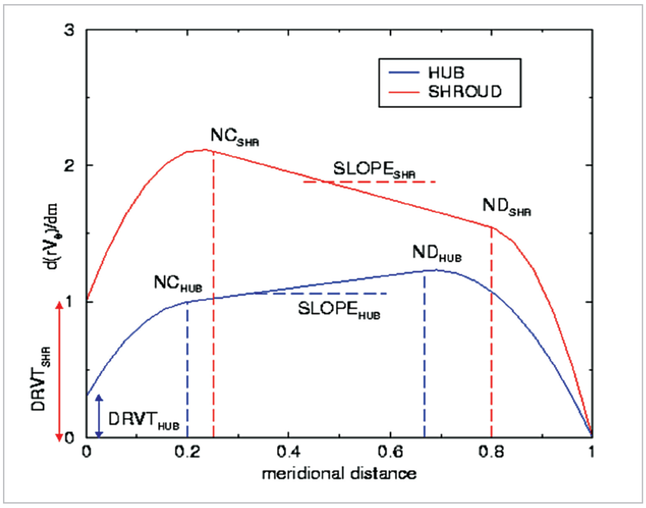

Figure 2: Blade loading parameterization used in inverse design method.

All CFD was done automatically by using a link that directly runs all geometries created by TURBOdesign1 in ANSYS workbench software by using Turbogrid structured meshing and CFX flow solver. ANSYS CFX is one of the commonly used CFD codes in the pump industry. The system also allows direct coupling with another commonly used CFD code, Siemens CCM+, and can directly run CCM+ and bring all performance parameters back into TURBOdesign Optima.

Once the CFD calculations have been run, all the resulting performance parameters, such as efficiency at various flow rates, power and head, are incorporated into the Design Matrix. A Kriging response surface (a surrogate model relating design parameters to performance parameters) will be generated. Optimization studies can then be run in less than a minute using the surrogate model. In Figures 3 and 4 there are two optimization studies; one to maximize efficiency at both flow points (Figure 3), and one targeting maximum design point efficiency as well as maximum cavitation resistance (Figure 4). Both studies applied a constraint to the throat area of the pump within ±5%, relative to the existing design, to control the BEP flowrate.

The Result

Since the optimization studies are only being performed on the response surface approximation, two points from each optimization were analyzed for verification. The results are shown in the Table 2. As can be seen, errors between prediction and validation are very small. The cases that the optimization suggested as having highest performance in a certain aspect do indeed have highest performance. As such, designers can have faith that the design chosen from the optimization will provide the highest performance possible.

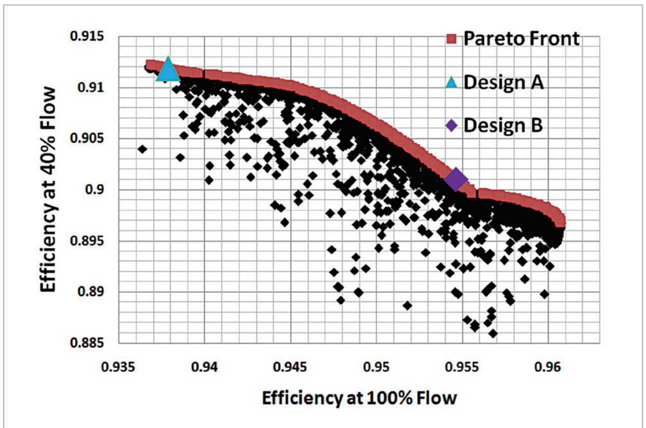

Figure 3: Pareto front obtained from surrogate model.

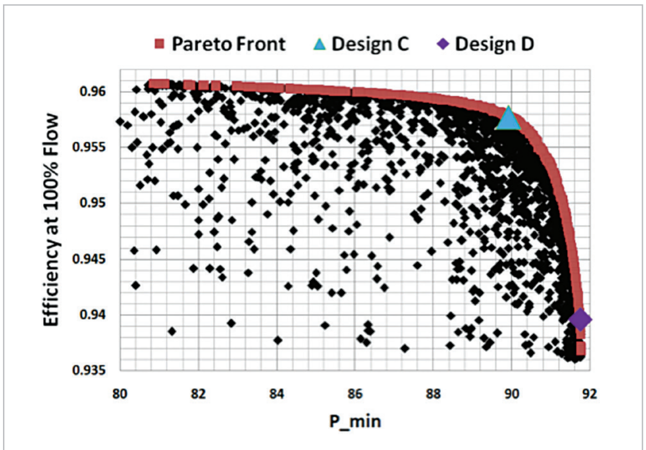

Figure 4: Pareto front obtained from the surrogate model.

Design		Eff at 100% flow	Eff at 40% flow	Max power (kW)	Pmin (kPa)
A	Prediction	0.938	0.912	11.10	89.0
	CFD	0.930	0.907	10.98	89.1
	Error	**0.89%**	**0.49%**	**1.11%**	**-0.20%**
B	Prediction	0.955	0.901	11.66	80.7
	CFD	0.955	0.905	11.67	78.6
	Error	**-0.05%**	**-0.39%**	**-0.1%**	**2.63%**
C	Prediction	0.958	0.886	11.68	89.9
	CFD	0.959	0.882	11.7	90.0
	Error	**-0.09%**	**0.47%**	**-0.18%**	**-0.10%**
D	Prediction	0.940	0.903	11.06	91.7
	CFD	0.936	0.903	11.08	92.4
	Error	**0.41%**	**0.03%**	**-0.16%**	**-0.74%**

Table 2: Results from the optimization compared with CFD verification.

This case showed that using the inverse design based optimization process, it is possible to perform a complicated multi-point, multi-objective optimization with high levels of accuracy using only a small number of analysis points, making optimization as a part of the design process feasible for all companies and all projects.

Final Thoughts

The inverse design based optimization method can create an accurate surrogate model for optimization of pump stages, and can be used to quickly solve some of the most difficult multi-point, multi-objective problems faced by the pump industry.

About the Author

Mehrdad Zangeneh is Professor of Thermofluids at University College London and Founding Director of Advanced Design Technology, Ltd (www.adtechnology.com). He has been involved in the development of advanced turbomachinery design codes based on a 3D inverse design approach for the past 30 years. His research has resulted in important breakthroughs in radial turbomachinery and he has been granted 7 international patents. He is recipient of Japan's Turbomachinery Society's Gold Medal and the Donald Julius Grone Prize by the Institution of Mechanical Engineers in UK. He has published more than 120 papers in journals and refereed conferences.