DESIGNING THE FLOWPATH

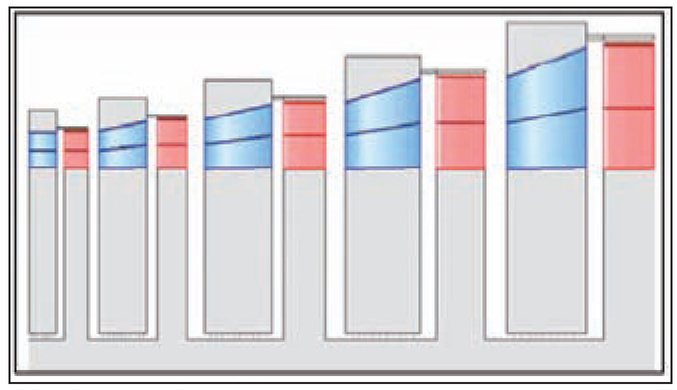
ROBUST AND EFFICIENT AERODYNAMIC AND STRUCTURAL SOLVERS CAN PROVIDE AN INTEGRATED SOFTWARE SOLUTION FOR PERFORMING THE ENTIRE WORKFLOW

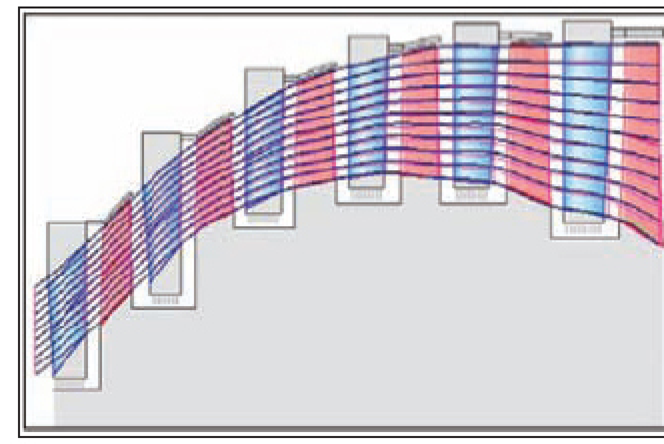
LEONID MOROZ
SOFTINWAY, INC.

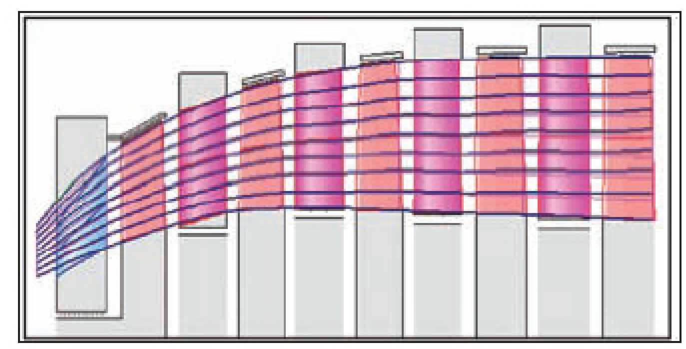
In recent years, methods for turbomachinery flowpath design have greatly improved due to the introduction of three dimensional (3D) viscous flow concepts. But one dimensional (1D) and two dimensional (2D) calculations are also beneficial, especially at the early stages of the design. This article describes the steps in a turbomachinery conceptual design, which uses 1D, 2D and 3D calculations.

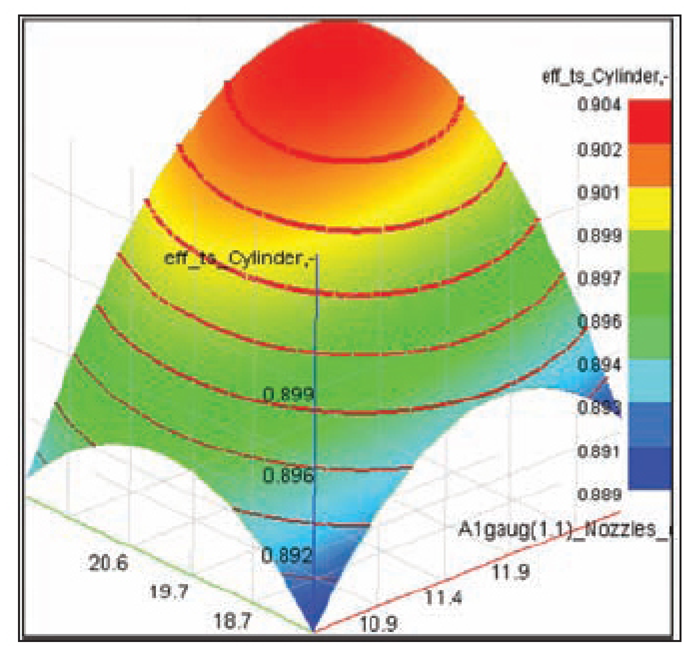
Design of new turbomachinery is a long and complex process. It can be considered as a sequence of several steps. They are:

- Preliminary design (sizing)
- Meanline and streamline flowpath analysis
- Profiling and 3D blade design
- Structural and modal analysis
- 3D flow analysis









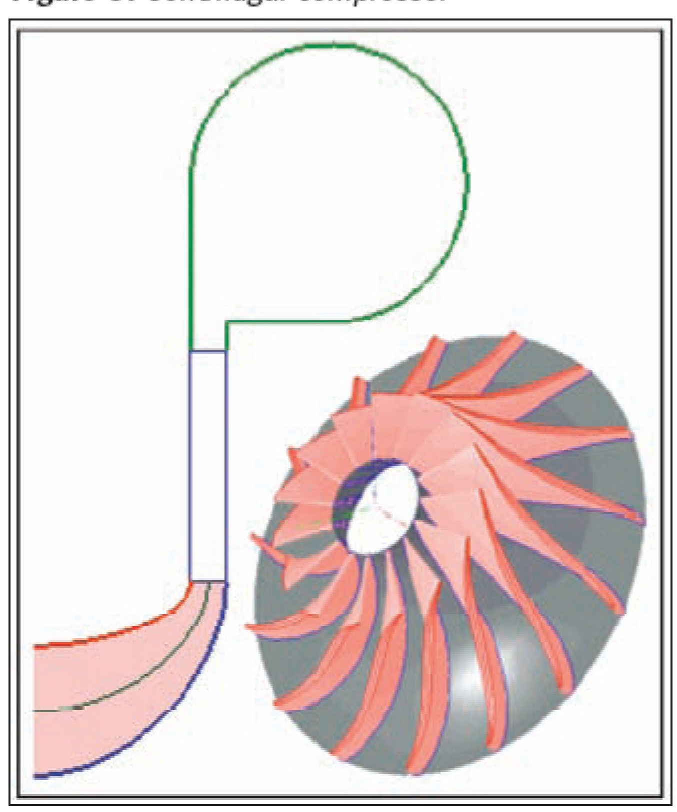


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Figure 1: *Multistage turbine flowpath after preliminary design*
Figure 2: *LP gas turbine*
Figure 3: *Contra-rotating turbine*
Figure 4: *Efficiency DoE study*
Figure 5: *Centrifugal compressor*

Preliminary design

Design from scratch (preliminary design) is the first step of the conceptual workflow. In this, the designer determines key parameters, such as the number of stages, diameters, blade heights and cascade metal angles, reactions of the future flowpath and other features that have a significant influence on the efficiency of the final design, its manufacturing cost and reliability. Results of a preliminary design are in Figure 1.

The objective of the preliminary design is to determine optimal flowpath parameters and provide the best attainable performance while staying strictly within design limits. The preliminary design process typically uses the "inverse problem formulation" in which the flowpath dimensions are selected based on given geometrical and operational constraints.

The design is refined by pitchwise and spanwise optimization on S1-S2 surfaces, taking into account general estimations of structural and modal constraints. Optimization of the S1 surface in the pitchwise direction helps find the optimum chord and pitch/chord ratio. The criterion used in this optimization is the minimization of total losses. Optimization of the S2 surface in the spanwise direction helps find optimal flowpath outline dimensions.

The next step is to validate the solution with the help of flowpath analysis through the "direct formulation" process, in which flowpath performance is estimated with known geometrical dimensions and fixed operating conditions. When the preliminary design is finished, the designer uses flowpath meanline analysis (1D) in direct formulation to validate the solution, and estimate more precisely the influence of flow leakages.

The next task in the design process is meanline and streamline flowpath analysis. Meanline analysis uses data specified for the mean cross-sections to calculate the solution. Axisymmetric analysis (2D) is used for further refinement, taking into account the distribution of metal angles in spanwise direction. This type of analysis uses data specified on several spanwise cross-sections along the blade height to calculate a solution with the help of streamline solver methods.

Meanline and axisymmetric solvers are typically given the following tasks regarding boundary condition specifications:

- Find Mass Flow Rate (MFR) for a given outlet pressure
- Find outlet pressure for a given MFR
- Find inlet total pressure for a given MFR
- Find gauging angles for a given MFR and pressure

Gauging angles are used to predict the flow discharge in the various stages of the flowpath. Outlet pressure can be taken as static or total. In this step, it is possible to minimize incidence (angles) by adjusting inlet blade angles to match flow angles.

The analysis can be carried out for multistage turbomachine stages with full blade crowns, only rotor or stator crowns, stages with contra-rotation, and mixed

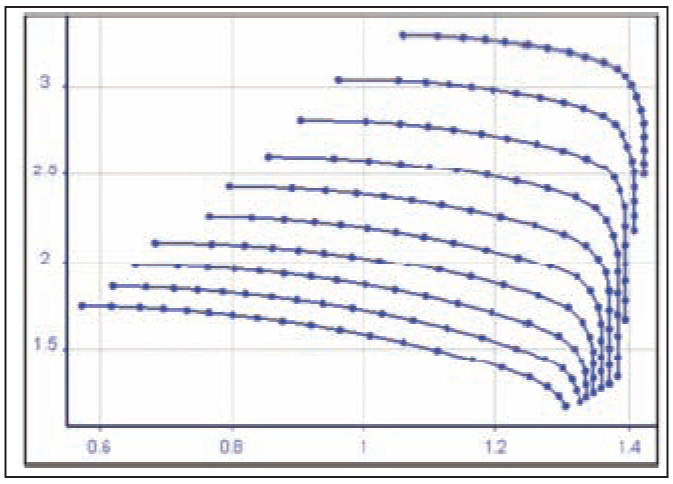

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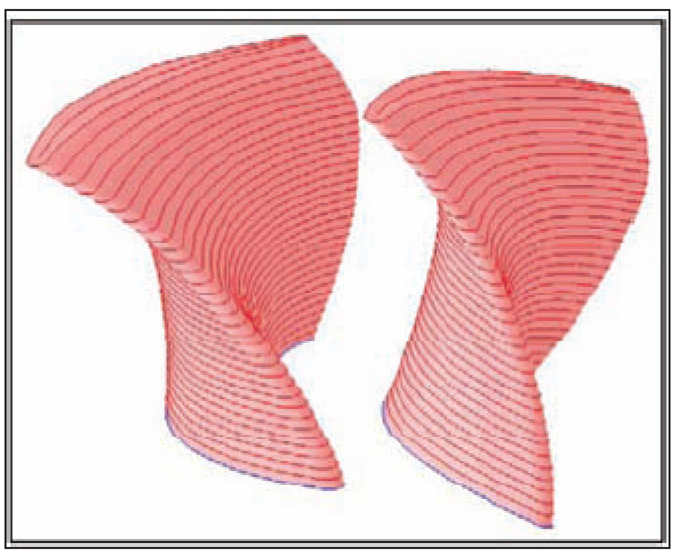
Figure 6: *Compressor performance map (pressure ratio vs. mass flow rate)*

Figure 7: *Turbine rotor blades cascade*

Figure 8: *Flow chart with relative Mach number distribution along airfoil outline*

Figure 9: *Highly twisted turbine blades*



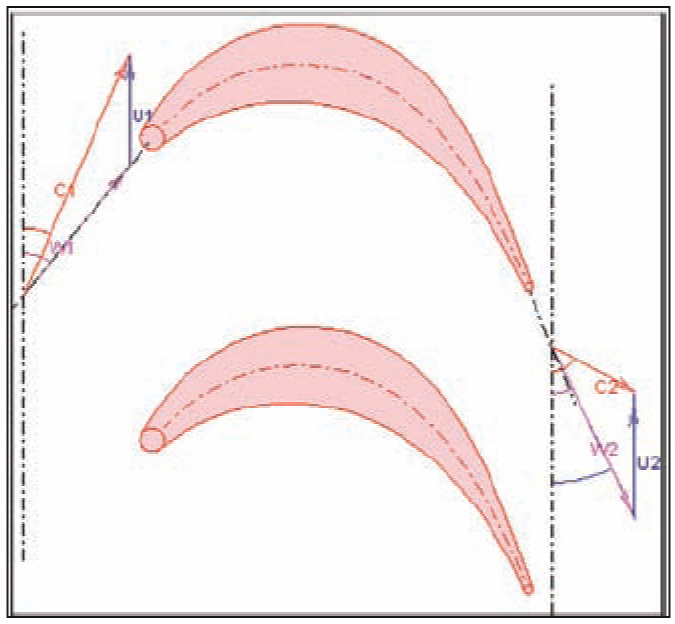
flowpaths with axial and radial stages. Examples of axisymmetric analysis calculations for a Low Pressure gas turbine and a contra-rotating turbine are given in Figures 2 and 3, respectively.

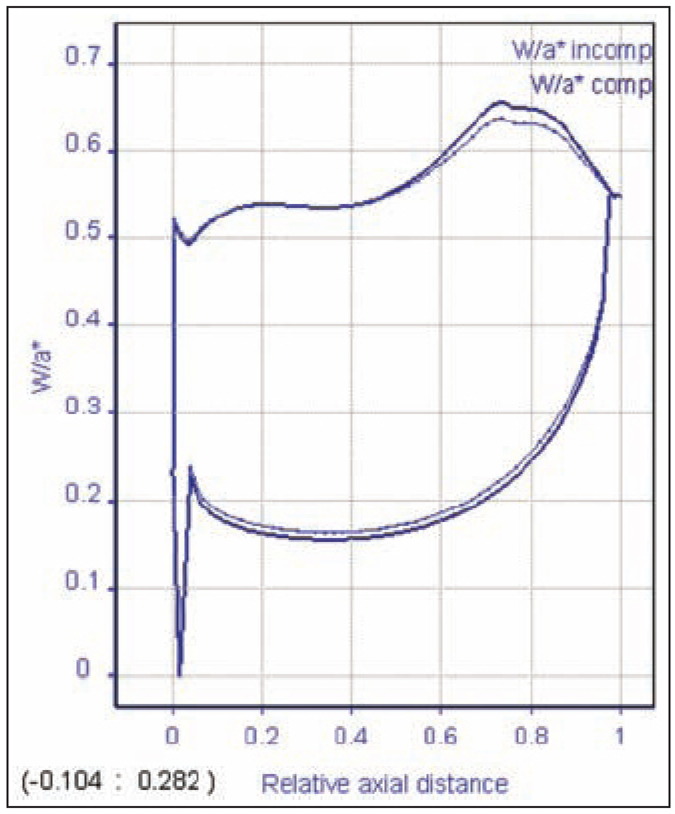
Optimization methods

The selection of blade twist low is a rather complex and challenging task. Blade twist low selects the distribution of blade angles in the spanwise direction along the blade height.

Usually, Design of Experiment (DoE) methods are used on this design step for optimal blade twist low selection. DoE methods are numerical studies that are widely used for flowpath optimization studies in different meanline and streamline problem formulations. The influence of geometrical and operational parameters variation on power, efficiency and other parameters can be estimated. Figure 4 gives an example of a DoE study with efficiency selected as the response surface in relation to stator and rotor blade angles.

Performance and efficiency maps are generated to estimate turbomachinery characteristics in offdesign points. Off-design performance calculation can be carried out using meanline and streamline formulations depending on data available for analysis. For example, a compressor map shows the range of operation, stall and surge region. Figures 5 and 6 show a centrifugal compressor design and a typical map.





Profiling of airfoil cross-sections is used to find a suitable airfoil outline on the basis of flow calculations in planar profile cascades, taking into account boundary layer and compressibility effects. Figures 7 and 8 show turbine rotor blade cascades and flow charts with the distribution of relative Mach numbers along the airfoil outline.

A flow chart gives the designer estimations of cascade losses, velocity, pressure, and so on. Knowing the distributions along the airfoil outline, the engineer can design profiles without flow separation.

Profile optimization is carried out according to geometrical and aerodynamic criteria of profile quality, such as:

- Minimum of maximal curvature
- Minimum of profile losses

Analysis of flow charts with velocity, pressure, momentum thickness values and heat transfer coefficients distributions along the profile outline is an essential part of profiling. 3D blade design involves stacking industry-approved or newly designed profiles while preserving the required level of blade surface curvature and structural constraints. The final design of highly twisted turbine blades is shown in Figure 9.

Modern 3D structural and modal analysis tools are based on Finite Element Method (FEM) calculations. A finite element mesh is generated upon 3D blade geometry created in the previous step. Boundary conditions and material properties should be specified before starting the analysis.

Stresses in blades and stress tensor components are outputs for structural analysis calculations. Values of a specified number of first natural frequencies for the blade package are outputs for modal analysis calculations. Stress contours in the turbine blade are shown in Figure 10 as an example of structural analysis results.

Finally, 3D flow effects can be examined using Computational Fluid Dynamics (CFD) tools by finite volume method calculations. The computational mesh for inter-blade channels is generated upon the 3D blade geometry. Fluid properties and boundary conditions should be specified before starting the analysis.

Outputs of CFD calculations used for turbomachinery analysis can be divided into two main categories. They are:

- Integral flow characteristics (values of mass flow rate, power and the efficiency in the performance curve)
- Partial flow characteristics (distributions of flow angles, velocities, pressures, and so on at the control stations, namely inlet, between blades and outlet)

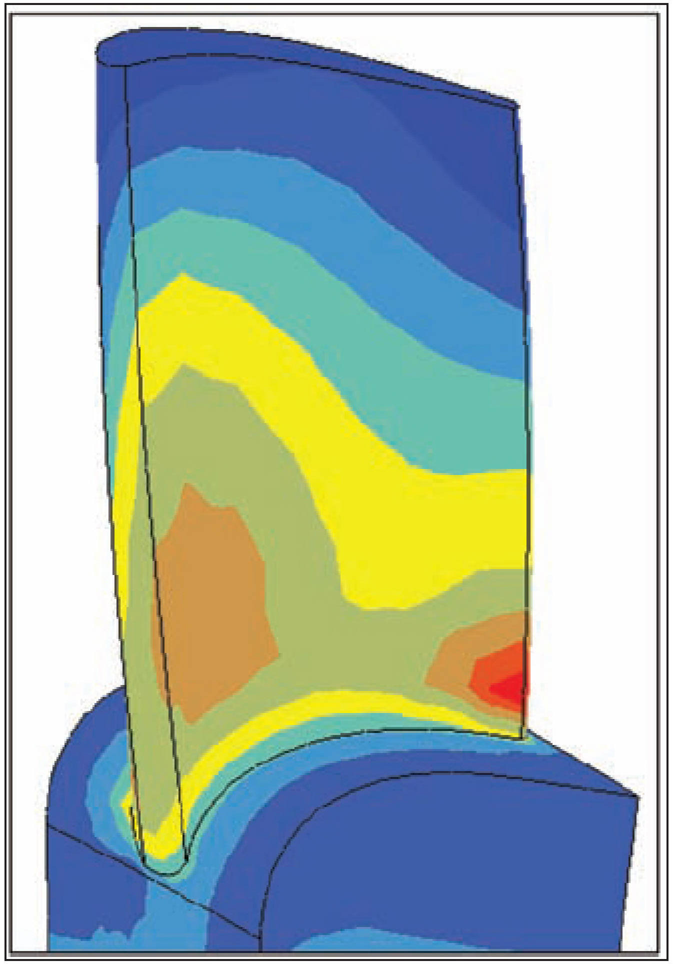
Relative Mach number contours in compressor cascade and static pressure contours in the turbine are shown in Figures 11 and 12, as examples of 3D flow analysis results.

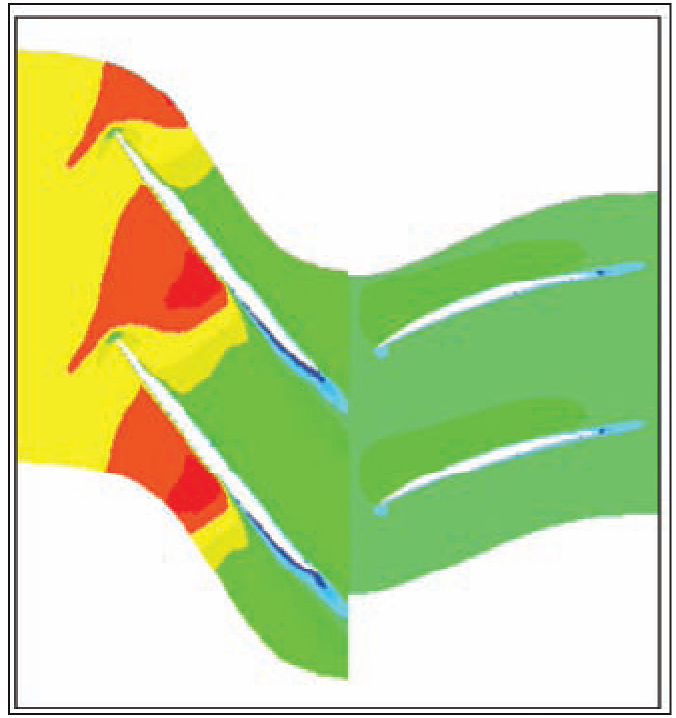
Implementing the concept

The above design workflow provides turbomachinery companies a reliable approach for performing aerodynamic and structural tasks related to flowpath design. This approach covers various types of turbomachines, such as axial turbines and compressors, centrifugal compressors, radial turbines, contra-rotating turbines and so on.

Specialized software is available to aid the workflow. These systems help to unite all the design steps under one umbrella, giving the user a centralized flowpath data storage, unified graphical interface for control of the design process, data input and output, optimization, profiling, blade design, and FEA and CFD analysis tools.

Integrated software solutions are available that provide the entire design workflow through a single package. In the past, designers used various codes and software written by different vendors and at various points of time.





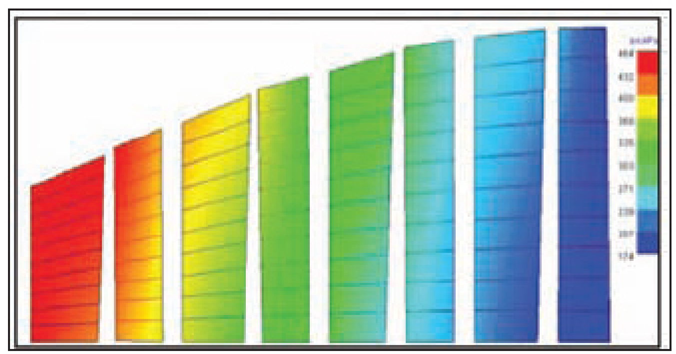


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Figure 10: *Stress contours in a turbine blade*

Figure 11: *Relative Mach number contours in compressor cascade*

Figure 12: *Static pressure contours in turbine*

The integrated solution should:

• Involve a set of design modules needed for procedures in 1D and 2D formulations with the output of 3D geometric models, which are ready for final refinement by means of 3D aerodynamic and stress calculations

• Make it possible to automate multivariate and optimization calculations

• Ensure an interactive design scenario with the opportunity to return to the beginning at the early design stages, versions support, and project integrity

• Give the user convenient mechanisms for data input, modification, output and export into other software systems

• Ensure expansibility, scalability, and maintainability

These requirements guarantee that the conceptual design approach described here can be successfully implemented.

Robust and efficient aerodynamic and structural solvers are key features of modern flowpath design. These solvers work together in a single workflow environment, allowing the designers to carry out the complete turbomachinery design, from concept to final product quickly and more efficiently than in the past.

Note

All figures in the article are from Softinway's AxStream software.

Author

Leonid Moroz is CEO of SoftInWay, Inc. (www.SoftInWay.com). Reach Moroz at L.Moroz@SoftInWay.com.