Flow Optimization Design Tool for the Rotordynamics of Impellers and Seals (New)

Paul Cizmas

Introduction and Background

Computational Fluid Dynamics (CFD) is currently an important tool in the design of turbomachinery. While most interest lies in the aerodynamic shape optimization of compressor and turbine blades, CFD can also be used to assess and improve the designs of pumps (Takemura and Goto, 1990), seals (Liliedahl et al., 2011), and swirl brakes (Baldassarre et al., 2014; Matula and Cizmas, 2017). However, due to the tremendous cost of high-fidelity CFD simulations, their use in design work is relegated to late-stage design evaluation and improvement, with the earlier parts of the design process focusing instead on lower-fidelity models and designer experience. In order for CFD to take a more central role in turbomachinery design, it is critical to embed optimization methods in the flow solver itself.

An optimization methodology begins by defining an objective function $f(\boldsymbol{\alpha}, \boldsymbol{\lambda})$ whose extremum is sought, subject to constraints $\mathbf{g}(\boldsymbol{\alpha}, \boldsymbol{\lambda}) = \mathbf{0}$ and $\mathbf{h}(\boldsymbol{\alpha}, \boldsymbol{\lambda}) \leq \mathbf{0}$. Herein, $\boldsymbol{\alpha}$ is the vector of operating conditions, $\boldsymbol{\lambda}$ is the vector of design variables, and $\mathbf{g}$ and $\mathbf{h}$ are vector-valued functions that represent constraints on the allowable combinations of $\boldsymbol{\alpha}$ and $\boldsymbol{\lambda}$. Using the design of pre-swirl brakes as an example, $\boldsymbol{\alpha}$ will contain information such as rotor speed and seal pressure ratio, while $\boldsymbol{\lambda}$ will contain variables such as vane thickness, chord length, pitch, and stagger angle, shown in Fig. 1. In this example, f will be the pre-swirl at seal inlet, shown in Fig. 2. The constraints that must be satisfied are (1) the residual of the spatial discretization must be below a prescribed tolerance, and (2) for any operating condition $\boldsymbol{\alpha}$ in the given range, the design variables $\boldsymbol{\lambda}$ must have acceptable values for manufacturing.

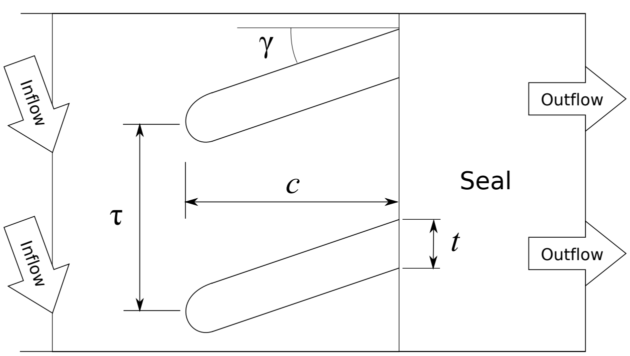

Figure 1: Design variables for pre-swirl brake: vane angle, thickness, chord length, and pitch.

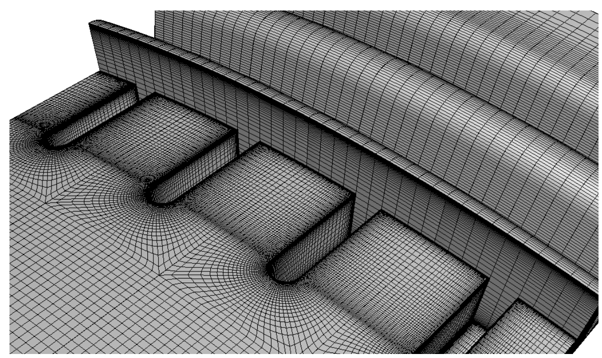

Figure 2: Computational grid for combined pre-swirl brake and labyrinth seal.

We propose herein to use two methods for design optimization: Automatic Differentiation (AD) and Adjoint Methods (AM). The fundamental idea of automatic differentiation is that any computer program can be thought of as a mapping of input variables to output variables (Hodson et al., 2017). As an example, the input variables could be geometric parameters and operating conditions, while the output variables could be integral quantities such as drag or pre-swirl. Furthermore, since every subroutine within the program can also be thought as a mapping between input and output variables, the program is therefore a composite mapping. A smooth composite function is differentiable by the chain rule of elementary calculus. Hence, it stands to reason that software can be written to automatically differentiate an entire computer program by applying the chain rule to each constitutive subprogram. This is the premise of Automatic Differentiation. While this approach is often confused with finite differences, AD can evaluate gradients at a computational cost comparable to that of the original function, which is usually far cheaper than using finite differences. Further, AD evaluates these gradients with a precision comparable to that of the original function, while finite differences require a carefully chosen step size to balance truncation and round-off error. Finally, AD synergizes well with implicit solvers within the simulation software itself.

Adjoint methods are a promising technique for evaluating sensitivities when the objective function is evaluated with complicated simulation software. The premise is to use the Jacobian of the residual of the spatial discretization with respect to the discrete unknowns to calculate the gradient of the objective function at a modest cost (Mavriplis, 2007). Like AD, this approach works well with implicit solvers already embedded within the simulation software. The adjoint approach is more sophisticated and likely more computationally efficient than the AD approach, but requires extensive code modifications.

We propose to update our in-house flow solver, UNS3D, with optimization capabilities using automatic differentiation and adjoint methods. We further propose to use these new capabilities to improve the designs of a pre-swirl brake (Childs et al., 2016; Matula and Cizmas, 2017), an impeller eye labyrinth seal (Wagner et al., 2009), and a stepped labyrinth seal (Tyacke et al., 2011), with the goals of improving flow coefficients and rotordynamic stability.

Deliverables

1. Updated CFD solver UNS3D with optimization capabilities using automatic differentiation and adjoint methods.
2. Computational grids, UNS3D input files, simulation results, and accuracy assessment for the simulations of pre-swirl brakes and labyrinth seals.
3. Geometry of optimal pre-swirl brakes and labyrinth seals.

Costs

Support for graduate student (20 hours/week)	$26,400
Fringe benefits and insurance	$ 5,450
Tuition and fees	$ 4,630
Software	$ 1,200
Hardware	$ 2,320
Travel to technical conferences	$ 2,500 × 2
Total	$45,000

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