Design and Optimization of Non-Axisymmetric Endwalls in Turbine Cascades: Postprint

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Abstract

The NURBS surface modeling method is employed to construct non-axisymmetric endwalls by superimposing radial height variations on axisymmetric endwalls. The optimal Latin hypercube design method is adopted, and through two rounds of experimental design, a design scheme with superior performance is sought. Results analysis demonstrates that the experimental design method based on optimal Latin hypercube is feasible for directionally searching for non-axisymmetric endwall optimization design schemes for turbine cascades. Compared with the cylindrical endwall, the optimized turbine cascade passage exhibits a 5.48% reduction in area-averaged secondary flow kinetic energy at the exit, a 1.63% reduction in total pressure loss coefficient, and local improvement in endwall heat transfer conditions. The non-axisymmetric endwall weakens the strength of the horseshoe vortex and passage vortex in the turbine cascade passage by altering the static pressure distribution on the endwall. The non-axisymmetric endwall weakens endwall heat transfer near the inlet and outlet sections within the passage, while heat transfer in the wake region is somewhat enhanced.

Full Text

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Abstract

Non-Uniform Rational B-Spline (NURBS) surfaces are employed to design non-axisymmetric endwalls by adjusting the radial protrusion of axisymmetric endwalls in turbine cascades. A design of experiment (DOE) approach using optimal Latin Hypercube sampling is applied to construct non-axisymmetric endwall scenarios for a high-pressure turbine rotor. Results demonstrate that a two-step direct search within the design space constructed by the optimal Latin Hypercube method provides an efficient approach for obtaining optimal endwall contours. Compared with the axisymmetric endwall, the non-axisymmetric design reduces the area-averaged secondary kinetic energy by 5.48% and the relative total pressure loss by 1.63% at the passage exit. The heat transfer coefficients on the endwall are also reduced in certain regions. The non-axisymmetric endwall alters the pressure distribution on the endwall surface and weakens the strength of both the horseshoe vortex and passage vortex within the turbine cascade. Heat transfer decreases in the forward portion of the passage while increasing in the aft portion, with elevated heat transfer observed near the trailing edge.

Keywords: Non-axisymmetric endwall; NURBS; DOE; Optimization

1. Introduction

Secondary flow losses in turbomachinery represent a significant source of aerodynamic inefficiency. Denton [?] identified secondary flow loss mechanisms as critical contributors to overall turbine losses. In response, non-axisymmetric endwall contouring has emerged as a promising technique for reducing these losses. Harvey et al. [?] and Hartland et al. [?] developed a three-dimensional linear design system for non-axisymmetric turbine endwalls and validated it experimentally, demonstrating substantial performance improvements. Subsequent applications to the Trent 500 high-pressure turbine by Brennan et al. [?] and Rose et al. [?] confirmed the practical viability of this approach. Germain et al. [?] and Schuepbach et al. [?] further extended the methodology to high-work turbines, achieving efficiency gains of 1.0% and 0.4% respectively. Praisner et al. [?] successfully applied non-axisymmetric endwall contouring to both conventional and high-lift turbine airfoils.

The underlying flow physics involves modification of the endwall pressure distribution to weaken secondary vortical structures. Saha and Acharya [?] conducted computational studies of turbulent flow and heat transfer in three-dimensional non-axisymmetric blade passages, while Mahmood and Acharya [?] measured endwall flow and heat transfer in linear blade passages with endwall modifications. Lynch et al. [?] specifically investigated heat transfer characteristics for turbine blades with non-axisymmetric endwall contouring. These studies collectively demonstrate that properly designed endwall contours can mitigate secondary flows while managing thermal loads.

The present work employs NURBS-based parameterization combined with optimal Latin Hypercube design of experiments to systematically explore the design space and identify optimal non-axisymmetric endwall geometries for a high-pressure turbine rotor.

2. NURBS Parameterization of Endwall Geometry

The non-axisymmetric endwall surface is parameterized using NURBS, which provides flexible control over complex geometries through manipulation of control points and weights. The NURBS surface is defined as:

$$S(u,v) = \frac{\sum_{i=0}^{m}\sum_{j=0}^{n} N_{i,p}(u)N_{j,q}(v)w_{i,j}P_{i,j}}{\sum_{i=0}^{m}\sum_{j=0}^{n} N_{i,p}(u)N_{j,q}(v)w_{i,j}}$$

where $N_{i,p}(u)$ and $N_{j,q}(v)$ are B-spline basis functions of degree p and q, $w_{i,j}$ are weights, and $P_{i,j}$ are control points. The knot vectors U and V are defined as:

$$U = \{0, \dots, 0, u_{p+1}, \dots, u_{r-p-1}, 1, \dots, 1\}$$

$$V = \{0, \dots, 0, v_{q+1}, \dots, v_{s-q-1}, 1, \dots, 1\}$$

The design variables consist of the vertical displacements of $(m+1) \times (n+1)$ control points, constrained to $\pm 10\%$ of the blade span to maintain mechanical feasibility. An optimal Latin Hypercube design generates 25 scenarios spanning the design space, enabling efficient surrogate modeling and optimization.

3. Optimization Methodology and Results

A two-step direct search strategy is employed within the Latin Hypercube-constructed design space. Computational fluid dynamics (CFD) simulations using TurboGrid and CFX evaluate each design scenario. The optimization objectives include minimization of secondary kinetic energy (SKE) and total pressure loss at the passage exit.

Figure 3 [Figure 3: see original paper] illustrates the control point distribution on the endwall surface. **Figure 4** [Figure 4: see original paper] shows static pressure coefficients on the cylinder endwall for baseline and contoured configurations. The non-axisymmetric contouring produces favorable pressure gradients that suppress secondary flow formation.

The optimal design achieves a 5.48% reduction in area-averaged SKE and a 1.63% reduction in relative total pressure loss compared to the axisymmetric baseline. **Figure 8** [Figure 8: see original paper] presents the geometric parameters and final contoured shape. **Figure 9** [Figure 9: see original paper] shows the radial distribution of pitchwise-averaged total pressure coefficients, confirming improved pressure recovery.

Figure 10 [Figure 10: see original paper] and **Figure 11** [Figure 11: see original paper] compare blade static pressure distributions at 5% and 20% span, revealing how the endwall contouring modifies the near-wall pressure field. **Figure**

12 [Figure 12: see original paper] displays SKE contours at the passage exit, visually confirming the reduction in secondary flow intensity.

4. Heat Transfer Characteristics

The thermal impact of non-axisymmetric endwall contouring is assessed through Stanton number distributions. **Figure 13** [Figure 13: see original paper] shows Stanton number contours on the endwall surface. Heat transfer coefficients decrease in the forward passage region but increase in the aft portion, particularly near the trailing edge. This redistribution results from altered vortex trajectories and modified boundary layer development. The overall effect is beneficial, reducing thermal loads in critical upstream regions while maintaining acceptable levels downstream.

5. Flow Physics Analysis

The non-axisymmetric endwall modifies the static pressure distribution, which weakens the horseshoe vortex formation at the leading edge and reduces the strength of the passage vortex. The contoured surface creates favorable pressure gradients that redirect secondary flow vortices away from the blade suction surface, thereby reducing energy loss. The weakened vortical structures exhibit lower SKE values throughout the passage, as confirmed by **Figure 12** [Figure 12: see original paper].

6. Conclusions

This study demonstrates that NURBS-based parameterization combined with optimal Latin Hypercube DOE provides an efficient framework for non-axisymmetric endwall optimization. The optimal design yields:

1. A 5.48% reduction in area-averaged secondary kinetic energy at the passage exit
2. A 1.63% reduction in relative total pressure loss
3. Reduced heat transfer coefficients in the forward passage region
4. Weakened horseshoe and passage vortices through modified endwall pressure distribution

These improvements validate the effectiveness of non-axisymmetric endwall contouring for enhancing turbine aerodynamic performance while managing thermal loads. The methodology is readily extensible to other turbomachinery applications.

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Note: Figure translations are in progress. See original paper for figures.