Turbine Tip Flow Optimization for Modern Aero-Engines

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Efficiency  

1/3 turbine losses due to tip leakage

Weight

Blade loading  
Supersonic tip gap flows

Durability

Cooling strategies for heat load control

Manufacturability & Cost
TURBINE TIP OPTIMIZATION

Exploratory Study

- Large clearances
- Tight clearances

Experimental Campaign

Numerical Optimization

1. Contoured designs
2. ‘Squealer’ designs
Turbine tip design strategies

Shrouded

Unshrouded

Rolls Royce

Siemens

Design Strategies - Numerical Optimization - Experimental Campaign
Turbine tip design strategies

Shrouded
Unshrouded

Tight running tips
Altered aerodynamics
Large clearances
Tight clearances

Altered heat transfer

Contouring
Baseline Flat
3D tip flow
Tip flow along streamlines (2D)
2D optimization
3D carved profile reconstruction

Complex squealer

J. Applied Thermal Engineering, 2014

-18% (flat)
-39% (SQ)

J. Turbomachinery, 2014

ASME TurboExpo, 2015
Turbine tip design strategies

- Over 50 patents were easily found only considering uncooled unshrouded designs
- Reveals the company strategies
Numerical Optimization

1. Contoured designs

2. ‘Squealer’ designs

\[ P_{\text{tot},r}, T_{\text{tot},r}, \alpha, \beta, \text{Tu} \]

Upperblock

Downblock

\[ P_s \]

\~ 7.5 - 9M cells
Contoured Design Optimization

- A Bezier Surface 'mapped' onto the tip region
- Parameters are the **heights of the control points**
- 40 parameters
Squealer Design Optimization

Brevet d’Invention, “Procédé de modélisation d’une baignoire d’une aube”, FR, FR1456680, July 10th, 2014
Squealer Design Optimization

Bezier Surface

Height evaluation at each cell middle point

Combined with 1 design variable

Level-Set approach - 50 parameters

Binary approach ~200 parameters

0 1 0 1 1 0 1 1 0 0 0...

PS
SS

Down > 0
Up > 1

Merged blocks

Smoothed geometry

Brevet d'Invention, “Procédé de modélisation d’une baignoire d’une aube”, FR, FR1456680, July 10th, 2014

Design Strategies - Numerical Optimization - Experimental Campaign
Numerical Optimization

Differential Evolution Optimizer

Genetic Algorithm Optimizer

CAD Creation
- Matlab - IGG - Gambit

Meshing
- Hexpress

Solving
- Fine/OPEN

Processing
- CFView

Inhouse optimizer (CADO)

Evaluation Routines

Carved tip optimization
Squealer-like tip optimization

with Level-Set approach
with binary approach

e.g. Squealer-like

Design Strategies - Numerical Optimization - Experimental Campaign
Numerical Optimization

- For every design a multitude of performance parameters was extracted:
  - Heat Transfer, Rotor performance, Downstream non-uniformity, ...

- 4 Multi-objective optimizations have been conducted (~1500 designs)

- Ran on VKI cluster
  - 320 cores
  - +/-1 month/optimization

Objectives:
1. Higher Aerodynamic Efficiency
2. Reduce Heat Load onto Tip section

Contoured designs
- @ Tight clearance
  - DoE (129 des.)
  - 20 des.
  - 9 des. along Pareto
  - DE Optimization
  - ~ 400 designs

- @ Design clearance
  - DoE (129 des.)
  - 20 des.
  - DE Optimization
  - ~ 300 designs

'Squealer-like' designs
- Level Set approach
  - DoE (114 des.)
  - 40 des.
  - Best along Pareto
  - DE Optimization
  - ~ 540 designs

- Binary approach
  - DoE (34 des.)
  - 20 des.
  - GA Optimization
  - ~ 260 designs

Design Strategies - Numerical Optimization - Experimental Campaign
Numerical Optimization - Results

- After DoE individuals move fast towards low HT and high efficiencies.
- Convergence was accelerated through inclusion of optimal profiles at tight clearance into initial database at design clearance.
- Reducing gap size by 0.5% increases efficiency by 1%.
Numerical Optimization - Results

- **Flat tip** prime design for efficiency
- **Immediate HT reduction** of 5% through opening aft part
- Further reduction HT (> 10%) possible through conv. – div. section in front part
- **Tight running tips** require more aggressive contouring
Numerical Optimization - Results

- 2-level optimization
- Squealer-like profiles twice less sensitive to efficiency
- Compared to conventional designs:
  - Efficiency increase of 0.3%
  - 30% HT reduction

Tip Heat Transfer [W] vs. Efficiency

Pareto Carved “Design”

Pareto Carved “Tight”

2. ‘Squealer’ designs
Experimental Campaign

Engine → Turbine Rig

Similarity
- Reynolds
- Mach
- $T_g/T_w$
- $P/P_{01}$, $T/T_{01}$, $\alpha$, $\beta$, ...

1. 1D
2. 3D-CFD

- Testing of 7 distinct profiles simultaneously
Rotor Casing
- Tip clearance
- $P_s$ (ST/UNST)
- Heat transfer
- Optical access

NGV
- $P_s$ and HT at 50% and 90% of span
- NGV outlet hub $P_s$

Design Strategies - Numerical Optimization - Experimental Campaign
Experimental Campaign

- **Refurbishment** of a unique turbine facility allowing simultaneous measurements of 7 distinct profiles
- **Development** of new miniaturized instrumentation
- **Experimental assessment** of flow physics for a variety of novel blade tip designs

Numerical Optimization

- **Novel optimization strategy**
- 4 consecutive optimizations (~1500 profiles) for contoured and squealer-like profiles
- +0.3% in efficiency -30% in Heat transfer

Exploratory Study

- Identified potential for innovation
- Aerothermodynamics at tight clearances
- Optimization of carved profiles using quasi-3D approach
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