A Numerical Study into the Effect of Optimised Profiled End-Wall Design on High Pressure Turbine Performance

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Turbofan

HP Compressor

HP Turbine

Low Pressure (LP)
Intermediate Pressure (IP)
High Pressure (HP)
High Pressure Rotor

- 60 gram
- 800 HP (Formula 1 car)
- Temperatures up to 2000°C (half the temp. of the sun)
- Several hundred degrees above melting temperature
- Rotating at 12000 rpm (London double-decker at tip)
- Constraints from an aero, cooling, manufacturing, mechanical and cost perspective
Outline

Design  Analysis  Conclusions
Numerical Model

HP Stator
HP Rotor
IP Stator
Parametric Optimisation Study

Side-View

Top-View

TU Delft
Optimised Design

![Diagram showing efficiency improvement comparisons between FRONT, REAR, and OPT conditions.](image-url)

- Efficiency Improvement (%): 0.6
- FRONT
- REAR
- OPT

TU Delft | Design | Analysis | Conclusions | Rolls-Royce
Potential Savings (1% efficiency improvement)

**Per airplane**
160,000 €/year

**RR Order book**
2000 engines

**Lifetime**
20 years

= 100 engines

= 2 years

= 10,000 €
Main Flow
Secondary Flow

**Side-View**
- Stagnation Point

**Top-View**
- Suction Side Leg
- Pressure Side Leg

LE
Horseshoe Vortex

Traditional Figures of Merit
Framework of Analysis

- Streamlines
- Static Pressure Distribution
- Entropy Generation
- Blade Loading
Streamlines

Purge Flow

Inlet Boundary Layer Flow

Side-View
**Purge Flow**

Purge flow forms the core of the hub passage vortex.

**Inlet Boundary Layer Flow**

Emerging boundary layer flow gets injected into the cavity and wraps around the blade.

Stagnation point is aligned with blade inlet angle.
Framework of Analysis

Streamlines
- Purge flow forms core of the hub passage vortex and is forced to emerge close to the suction side
- Suction side leg is strengthened, pressure side leg is weakened

Entropy Generation

Static Pressure Distribution

Blade Loading
Static Pressure Distribution

Static pressure distribution above the hub end-wall (top-view)

Leading Edge (LE)
Pressure Side (PS)
Suction Side (SS)

Cross-passage pressure gradient is not reduced but rather made more smooth

Profiled end-wall controls local static pressure distribution at exit upstream cavity

DAT OPT
Framework of Analysis

Streamlines

- Purge flow forms core of the hub passage vortex and is forced to emerge close to the suction side
- Suction side leg is strengthened, pressure side leg is weakened

Static Pressure Distribution

- Profiled end-wall controls local static pressure distribution at exit upstream cavity
- Cross-passage pressure gradient is made more smooth

Entropy Generation

Blade Loading
Blade Loading

Axial Chord

DAT at 10%  OPT at 10%

Pressure Side  Suction Side
Blade Loading
Blade Loading
Framework of Analysis

Streamlines

• Purge flow forms core of the hub passage vortex and is forced to emerge close to the suction side
• Suction side leg is strengthened, pressure side leg is weakened

Entropy Generation

Static Pressure Distribution

• Profiled end-wall controls local static pressure distribution at exit upstream cavity
• Cross-passage pressure gradient is made more smooth

Blade Loading

• Blade loading is increased close to the hub end-wall
Entropy Generation: a Measure of Loss

\[
\text{change in the amount of entropy contained within the system} = \frac{\dot{W}_{\text{shaft}}}{\dot{W}_{\text{shaft}} + \dot{W}_{\text{lost}}}
\]

\[
\eta_t(t) = \frac{\dot{W}_{\text{shaft}}}{\dot{Q}}
\]

Thermal Dissipation

\[
\frac{\dot{Q}}{T_H} \rightarrow \frac{\dot{Q}}{T_C}
\]

Viscous Dissipation
Entropy Generation: Identifying Loss Sources

Non-Dimensional Axial Distance
Span

Side-View
(Meridional)
Entropy Generation: Identifying Loss Sources
Entropy Generation: Identifying Loss Sources

Shear Stress Work Losses

Thermal Work Losses

[Graph showing distributions of shear stress work losses and thermal work losses across different components (HP Stator, HP Rotor, IP Stator).]

TU Delft
Design  Analysis  Conclusions

Rolls-Royce
Entropy Generation: Identifying Loss Sources

Work Losses

- Thermal Work Losses
- Shear Stress Work Losses

Percentage of TWL with respect to axisymmetric end-wall (%)

- OPT

Percentage of SSWL with respect to axisymmetric end-wall (%)

- OPT

Percentage of total work loss (%)
Entropy Generation: Comparing Designs (SSWL)
Entropy Generation: Comparing Designs (SSWL)

Cumulative work losses in span-wise direction
Framework of Analysis

Streamlines

- Purge flow forms core of the hub passage vortex and is forced to emerge close to the suction side
- Suction side leg is strengthened, pressure side leg is weakened

Entropy Generation

- Specific entropy generation has shown to be a powerful tool to identify loss sources and compare designs
- Most of the work loss reduction takes place in the area of the hub passage vortex

Static Pressure Distribution

- Profiled end-wall controls local static pressure distribution at exit upstream cavity
- Cross-passage pressure gradient is made more smooth

Blade Loading

- Blade loading is increased close to the hub end-wall
Localising the Impact

Vortical character has been reduced

Passage vortex is spread out over suction surface
Localising the Impact

Large temperature gradient is removed

Reduced interaction with main flow
Localising the Impact

Top-View

PV-SS flow is absent

Reduced radial velocity gradient
Conclusions
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Propulsive Efficiency \times \text{Thermal Efficiency} = \text{Total Efficiency}
Potential Savings

\[ \text{savings} = \Delta \eta \times SFC \left( \frac{\text{lbs}}{\text{hr} \cdot \text{lbf}} \right) \times P_{\text{fuel}} \left( \frac{\text{€}}{\text{lbs}} \right) \times t_{\text{flight}} \left( \frac{\text{hr}}{\text{year}} \right) \times T_{\text{cruise}} \left( \text{lbf} \right) \]

- \( SFC = 0.5 \)
- \( P_{\text{fuel}} = 0.33 \)
- \( t_{\text{flight}} = 4000 \)
- \( T_{\text{cruise}} = 25000 \) (110 kN)

Potential savings per airplane

\[ 1\% = 160,000 \frac{\text{€}}{\text{year}} \]
Objective & Constraints

Objective
Maximise component (isentropic) efficiency

Constraints
Capacity
(mass flow through stage, affects whole engine)

Reaction
(ratio of static enthalpy drop in the rotor to the total enthalpy drop in the stage, influences the loading of the blade)
Design Space

$$\Delta r(x, \theta) = a_0 + a_1 \sin \left( \frac{2\pi \theta}{p} \right) + a_2 \cos \left( \frac{2\pi \theta}{p} \right)$$
Multi-point Approximation Method (MAM)

Steps:

- Determine initial trust region

- Generate sampling points: Design of Experiment (DoE)

- Build (local/mid-range) response surface for all responses (cheap)

- Perform optimisation on response surface (cheap)

- Check convergence, update trust region

- Repeat from second point

Min # of points, max information (coverage)
Streamlines

Inlet Boundary Layer Flow

Purge Flow
Static pressure distribution above hub end-wall

LE: Leading Edge
PS: Pressure Side
SS: Suction Side
PSL: Pressure Side Leg
SSL: Suction Side Leg
Blade Loading

MAC TIP

MAC

MAC HUB

Span

Non-Dimensional Axial Chord

High

Zero

Low

High

Zero

Low

High
Thermodynamic Cycle

The diagram illustrates a thermodynamic cycle on a T-s (temperature-entropy) diagram. The cycle is composed of four processes:

1. Process 1-2 (isothermal expansion): $p = c$
2. Process 2-3 (isobaric process): $p = c$
3. Process 3-4 (isothermal compression): $p = c$
4. Process 4-1 (isobaric process): $p = c$
Using Entropy Generation as a Performance Parameter

\[ \eta_t(t) = \frac{\dot{W}_{shaft}}{\dot{W}_{shaft} + \dot{W}_{lost}} \]

\[ \dot{W}_{shaft} = \int_{A_{walls}} p \vec{n} \cdot (\vec{\Omega} \times \vec{R}) \, dA \]

\[ + \int_{A_{walls}} \vec{t} \cdot (\vec{\Omega} \times \vec{R}) \, dA \]

\[ \dot{W}_{lost} = \int_V \left( \tau_{ij} \cdot \frac{\delta u_i}{\delta x_j} \right) \, dV \]
Analysing the Full Stage