Probabilistic Analysis of Regeneration-Induced Geometry Variances in a Low-Pressure Turbine

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Outline

» Collaborative Research Center (CRC) 871

» Motivation and Objective

» Analysis of Regeneration-Induced Geometry Variances

» Probabilistic Model

» Results

» Conclusions and Outlook
CRC 871 - Regeneration of Complex Capital Goods

Scientific basis for maintaining complex capital goods to...

- recondition and improve the functional properties
- refurbish high-value components
- reduce scrap rates

source: MTU

source: Siemens

source: ENERCON

source: Deutsche Bahn
Project Areas and Subprojects

Project Area A
„Inspection and Diagnostics“

Project Area B
„Interaction of the Production Process with Functional Product Properties“

Project Area C
„Production and Material Variance in Regeneration“

Project Area D
„Integral Control of the Regeneration Process“

19 subprojects and 1 transfer project

Participating disciplines: Mechanical Engineering, Construction Engineering, Industrial Engineering

Cooperation of the Institutions: Leibniz Universität Hannover, Laser Zentrum Hannover, TU Braunschweig

Funded by the DFG (German Research Foundation) since 2010

2nd funding period (2014 till 2017)
Motivation and Objective of the Present Study

- High aerodynamic, mechanical, and thermal loads cause substantial wear
- Regular overhaul and repair of turbine blades
  - Higher variance after regeneration compared to new engines
  - Modified aerodynamic and aeroelastic performance
- Efficiency changes in a low pressure turbine (LPT)
  - LPT: $\Delta \eta_{\text{LPT}} = 1\%$  → Overall: $\Delta \eta_{\text{overall}} \approx 0.7\%$
Probabilistic Analysis of Regeneration-Induced Geometry Variances in a LPT

Test-Case: Final Stage of a LPT at Cruise

- Low Re: Profile aerodynamics dominated by boundary layer transition
- Laminar separation bubble at aft-part of suction side
- High sensitivity to geometrical variances can be expected.
Determination of Regeneration-Induced Variances

- Optical 3D measurements of regenerated turbine blades
- Alignment of the measured blades with the reference CAD-model
- Extraction of blade profiles over the entire span
- Determination of characteristic profile parameters
  - Axial chord length
  - Stagger angle
  - Maximum thickness
  - Trailing edge radius
  -...

Source: www.trimetric.com
Measured Blade Geometries

- Database with 20 regenerated blades
- Data include geometry variances caused by manufacturing, operation, and repair
- 19 extracted profiles at different span locations of each blade
Parameterization to Characterize the Profile Geometry

- 12 parameters are used to describe the profile geometry.
- Camber line and thickness distribution are modeled by polynomials.
Geometry Parameter Deviation

- Nominal design geometry is used as reference (CAD-model).
- Deviations are referred to the parameters of the reference geometry.
- Delta-parameter / parameter deviation:
  \[ \Delta P_{\text{realization}} = P_{\text{realization}} - P_{\text{reference}} \]
- Excluding leading edge position and angles, all parameter deviations are normalized with respect to their reference value.
Geometry Parameter Variances at Different Span Locations

- Large scatter range e.g. of leading edge radius and trailing edge angle
- Maximum deviation of axial chord and stagger angle at 85% span due to blend repair
Correlations of Profile Parameter Deviations

Significant correlation e.g. between…

- stagger angle $\gamma$ and axial leading edge position $x_{LE}$ (positive)
- stagger angle $\gamma$ and axial chord length $l_{ax}$ (negative)
- axial chord length $l_{ax}$ and axial leading edge position $x_{LE}$ (negative)
- max. camber $c_{max}$ and circumferential leading edge position $r\theta_{LE}$ (positive)
Scheme of the Probabilistic Model

- Stochastic input parameters
- Physics-based model (CFD simulation)
- Probabilistic response

- PDF
  - chord
  - camber
  - thickness
  - ... Input n

- Output 1
  - Output 2
  - Output 3
  - ... Output n

- PDF
d  - efficiency
  - stage loading
  - ... 

- Latin Hypercube Sampling (LHS) with 100 designs
- Consideration of input parameter correlation
- Nominal vane design used for all simulations
Probabilistic Analysis of Regeneration-Induced Geometry Variances in a LPT

Tool Chain

- OptiSlang: **ALHS**
- Matlab: **create parameterized profile**
- Python script
- G3D Hexa: **meshing**
- TRACE: **CFD simulation**
- Tecplot & Matlab: **post-processing**

**Motivation**
- Geometry Variances

**Probabilistic Model**
- Results
- Conclusions

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Benedikt Ernst
Slide 14/20
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CFD Setup of the Final Stage

Computational domain
- Quasi3D(Q3D)-grid at half-span
- Radial extent: approx. 0.03 l_\text{ax}
- Each sidewall at constant radius
- Radial resolution: 4 cells
- Stator: approx. 78,000 cells
- Rotor: approx. 89,000 cells
- y^+ < 1

Finite volume code TRACE of the DLR
- 2nd order accuracy
- Including modification for stagnation point (acc. to Kato and Launder)
- Non-local correlation-based multimode transition model by Kozulovic (2007)
- Only steady computations performed
Comparison of the Original and Parameterized Blade Profile

- Isentropic efficiency
  \[ \eta_{is} = \frac{1 - \frac{T_2}{T_0}}{1 - \left( \frac{p_2}{p_0} \right)^{(\kappa-1)/\kappa}} \]

- Flow coefficient
  \[ \phi = \frac{c_{ax,2}}{U} \]

- Stage loading coefficient
  \[ \psi = \frac{\Delta h_i}{U^2} \]

Good agreement between the nominal and the parameterized reference
Scatter of Output Parameters

Deviations of isentropic efficiency, flow coefficient and stage loading coefficient are shown relative to the reference.

- Scatter range of isentropic efficiency $\Delta \eta_{is,\text{max}} - \Delta \eta_{is,\text{min}} \approx 0.25\%$
- Linear correlation between stage loading and isentropic efficiency
- No significant correlation between flow coefficient and isentropic efficiency
Correlation between Input and Output Parameters

- Significant correlation between trailing edge angle and output parameters
- No correlation between max. thickness and output parameters
Conclusions and Outlook

Conclusions
- Profiles are well characterized by means of 12 geometric parameters.
- Significant deviations of geometric parameters are found.
- High negative correlation between stagger angle and axial chord length of measured LPT blades.
- Significant correlation between leading edge angle and
  - isentropic efficiency (negative)
  - flow coefficient (positive)
  - stage loading coefficient (negative)
- Geometry variances of most designs lead to an increase in efficiency.

Outlook
- Increase the number of measured LPT blades in our database.
- Further improvement of the CFD model and automation of the tool chain.
- Analysis of local flow-related parameters.
- Variation of operation points.
Thank you for your attention!