Efficient stochastic modelling of an axial compressor rotor blades geometrical variability due to manufacturing uncertainties

11th Dresden Probabilistic Workshop

Chair of Structural Mechanics and Vehicle Vibrational Technology
Prof. Dr.-Ing. Arnold Kühhorn | Marco Gambitta

Table of Content

Brandenburgische Technische Universität Cottbus - Senftenberg

University Technology Centre (UTC)
Multidisciplinary Process Integration

Rolls-Royce

EUROPÄISCHE UNION
Europäischer Fonds für Regionale Entwicklung

Brandenburgische Technische Universität
Cottbus - Senftenberg

Efficient manufacturing variability stochastic modelling

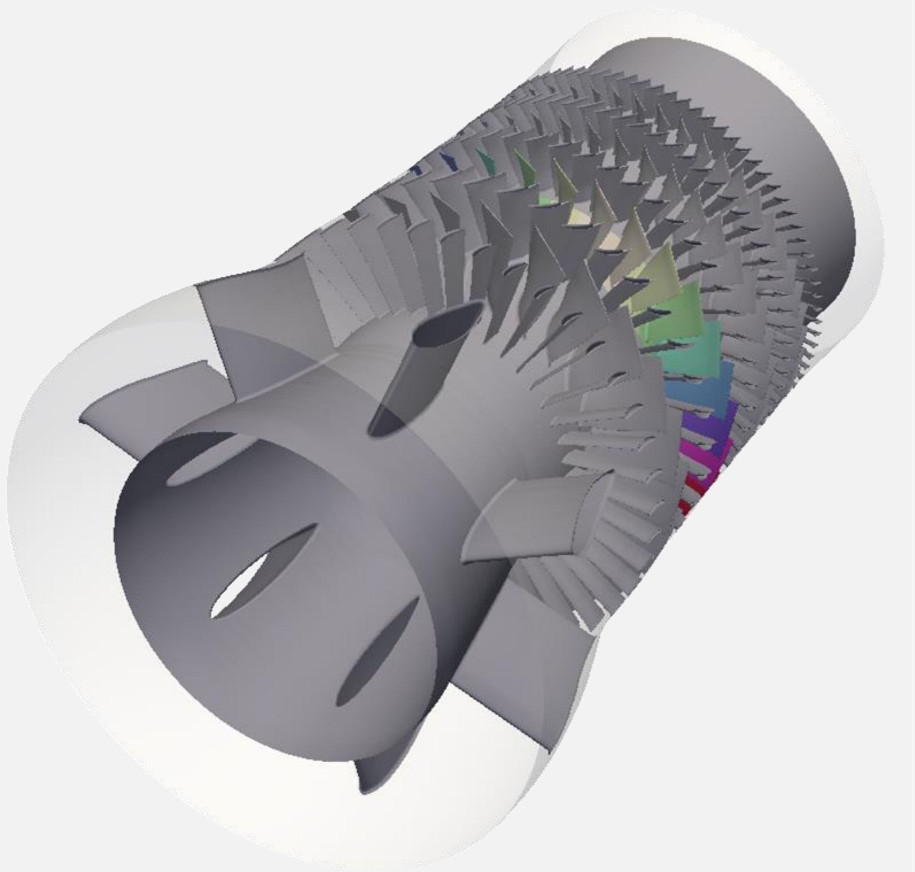
Introduction

Chair of Structural Mechanics and Vehicle Vibrational Technology
Prof. Dr.-Ing. Arnold Kühhorn | Marco Gambitta

“Efficient stochastic modelling of an axial compressor rotor blades geometrical variability due to manufacturing uncertainties.”

- Subject of study:
  - Axial HP compressor blisks and vanes (Rig250 – DLR Köln)

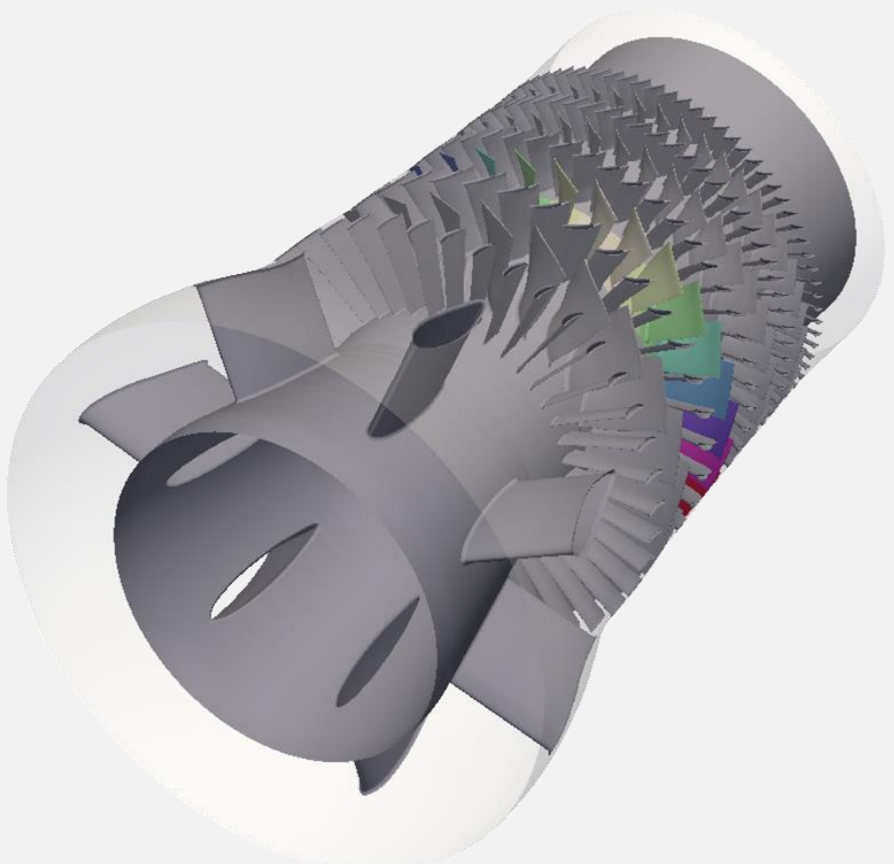
- Structure:
  - Analysis of geometric deviations from the nominal design
  - Complex CFD and FEM modelling
  - Aeroelastic analyses considering geometry based mistuning
  - Mistuning studied as blades geometrical offset from nominal design (e.g. tolerances, manufacturing variability)



Introduction

“Efficient stochastic modelling of an axial compressor rotor blades geometrical variability due to manufacturing uncertainties.”

- Objectives:
  - creation of a stochastic model representative of the measured manufacturing variability;
  - automation of a geometry based model adaptation (FEM, CFD);
  - uncertainty quantification on geometry-dependent aeroelastic analysis.



University Technology Centre (UTC) Multidisciplinary Process Integration | Rolls-Royce | EUROPÄISCHE UNION Europäischer Fonds für Regionale Entwicklung | b-tu Brandenburgische Technische Universität Cottbus - Senftenberg

Efficient manufacturing variability stochastic modelling

Geometrical Mistuning Analysis

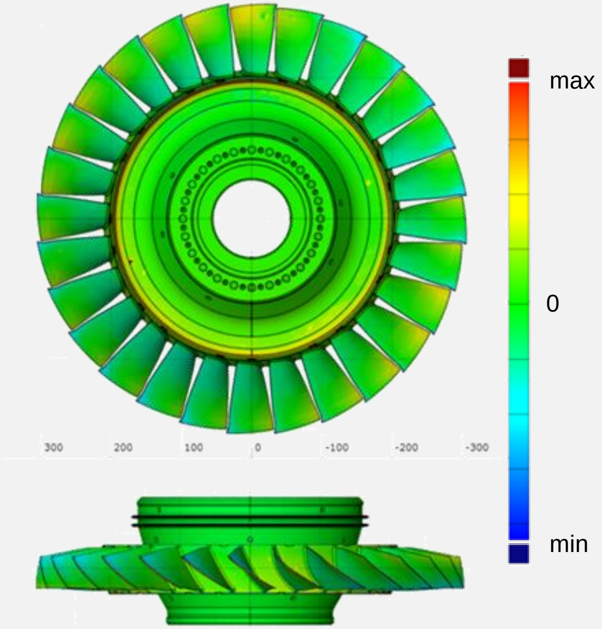
Chair of Structural Mechanics and Vehicle Vibrational Technology
Prof. Dr.-Ing. Arnold Kühhorn | Marco Gambitta

Geometrical Mistuning – Rig250 R2

Brandenburgische Technische Universität Cottbus - Senftenberg

Creation of a stochastic model which can represent through a set of variables the mistuned blades. Model based on [1] parameterization method.

- Analysis of geometric deviations for real geometries surfaces.
- Parametrization of rotor blades geometries.
- Description of surface deviations with an optimal amount of variables.
- Geometry reproduction for CFD and FEM models.

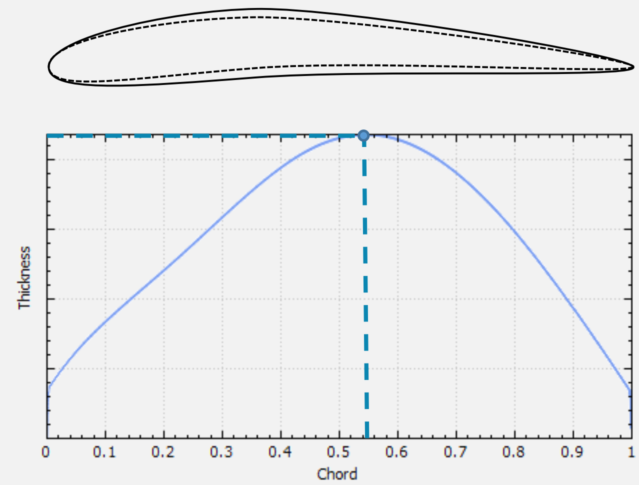


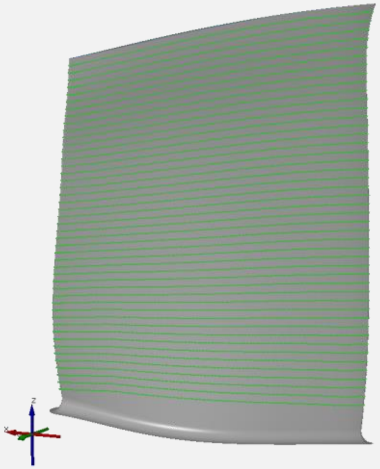
[1] Lange A., Vogeler K., Gümmer V., Schrapp H. and Clemen C. (2009). "*Introduction of a Parameter Based Compressor Blade Model for Considering Measured Geometry Uncertainties in Numerical Simulation*." Proceedings of ASME Turbo Expo. GT2009-59937.

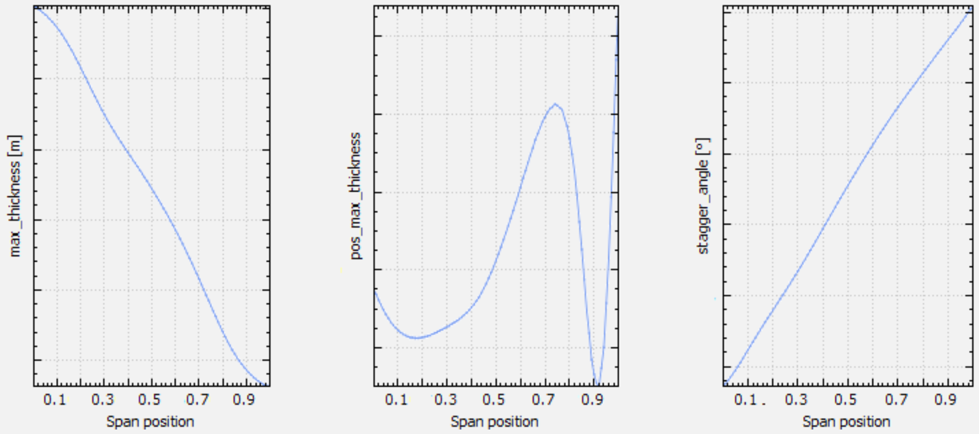
Parametrization Method

Methodology applied for the parametrization divided in the following main steps:

- radial sections definition;
- camber and thickness distributions over chord;
- distributions description with NACA-like parameters.





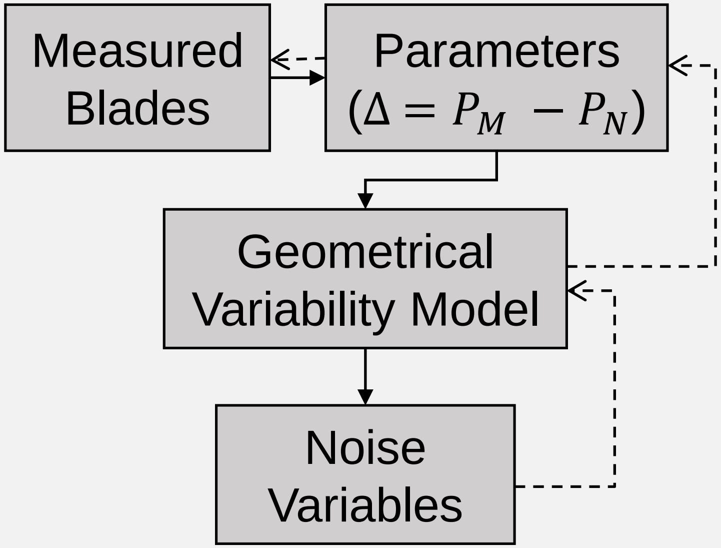


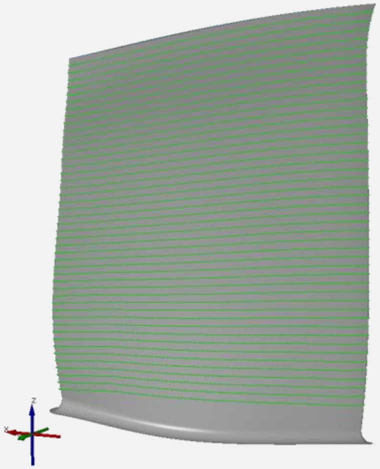
Parametrization Method

Methodology applied for the parametrization divided in the following main steps:

- radial sections definition;
- camber and thickness distributions over chord;
- distributions description with NACA-like parameters.

➢ Geometrical variability modelling.





Nominal geometry → parameters P_N

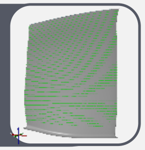
Measured geometry → parameters P_M

Geometrical Variability Model

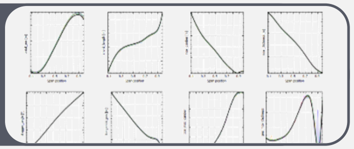
Brandenburgische Technische Universität Cottbus - Senftenberg

Measured Blades

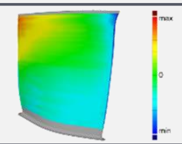
Nominal Blade



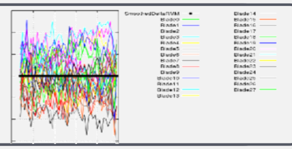
Parameterization



Reconstruction Mean Model: Δ_{RMM}



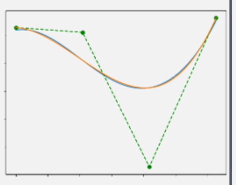
Δ_{GOM} Parameters



Δ_{GOM} spline fit

Variables reduction:

$N_{naca} \cdot N_{sec} \rightarrow N_{naca} \cdot (s_d + 1)$



PCA

$X = P\Delta Q^T \quad Y = P\Delta = XQ$

Eigenvalues of $X^T X$: Δ^2

Reduced Eigenvectors: Q_R

$\hat{Y} = XQ_R \ , \qquad \hat{X} = \hat{Y} Q_R^T$

Variables reduction:

$N_{naca} \cdot (s_d + 1) \rightarrow r$

Noise Variables

N_{naca}	number of naca parameters
N_{sec}	number of span sections
s_d	spline degree
r	number of eigenvectors used

Generic Mistuning Model

Generation of a geometrical variability model over a set of blades scans for the uncertainties representation:

- 153 total blade scans utilized;
- geometrical variability model data:

▪	spline degree:	2
▪	noise variables:	18

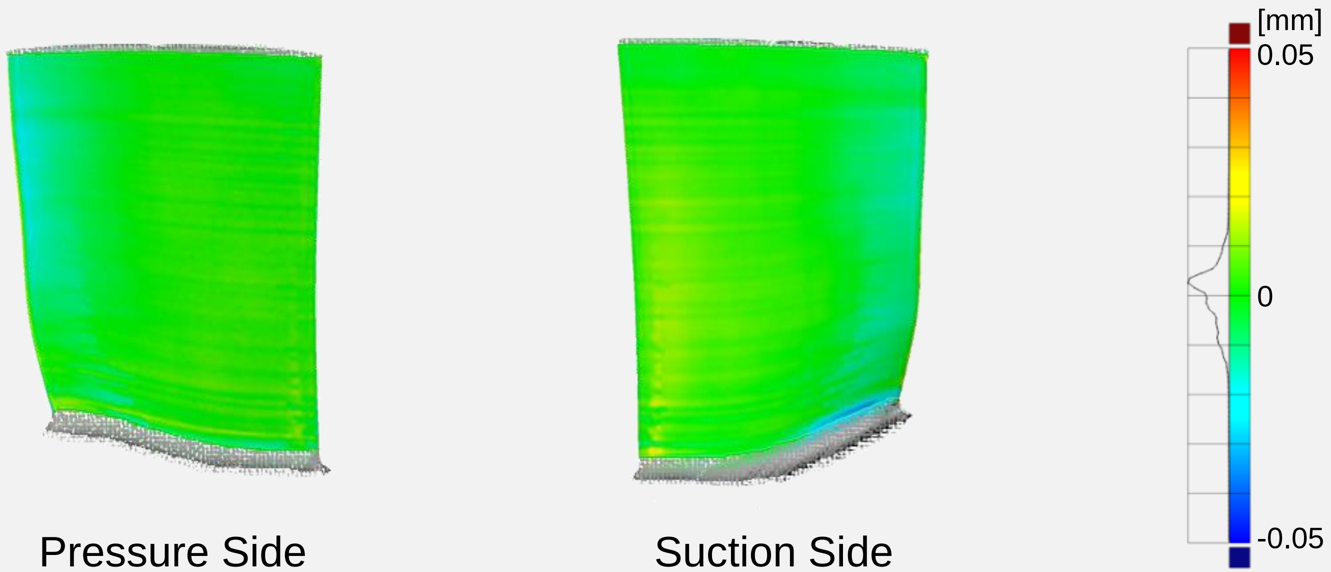
- model defined as offset from a nominal design;
- correlations between noise variables no longer present;
- possible application to any given nominal geometry;
- automated translation to CFD domain.

Rank Correlation Matrix

1	0,11	-0,02	0,02	0,04	0,01	-0,02	0,02	-0,02	-0,03	-0,02	0,03	0,00	0,03	0,01	-0,01	0,02	0,00
0,11	1	0,10	0,05	0,00	0,04	-0,01	-0,04	-0,06	0,03	0,08	0,00	-0,01	-0,02	-0,03	0,07	0,07	-0,04
-0,02	0,10	1	0,00	-0,05	0,03	0,00	0,01	-0,04	-0,02	-0,05	0,00	0,02	-0,01	0,00	0,02	0,01	-0,02
0,02	0,05	0,00	1	0,06	0,04	0,00	-0,01	0,00	0,06	0,02	0,00	0,03	-0,07	-0,02	0,00	0,02	0,02
0,04	0,00	-0,05	0,06	1	0,04	0,02	0,03	0,02	0,03	-0,02	0,00	-0,01	-0,03	-0,01	0,01	0,01	0,03
0,01	0,04	0,03	0,04	0,04	1	0,00	0,02	0,00	-0,03	-0,01	0,00	0,01	-0,05	-0,02	-0,02	0,00	0,00
-0,02	-0,01	0,00	0,00	0,02	0,00	1	0,02	-0,03	0,01	0,03	-0,04	0,00	0,00	0,00	0,00	0,03	0,03
0,02	-0,04	0,01	-0,01	0,03	0,02	0,02	1	-0,02	0,01	-0,01	0,00	-0,02	0,02	0,00	0,01	0,02	0,02
-0,02	-0,06	-0,04	0,00	0,02	0,00	-0,03	-0,02	1	0,03	0,02	0,01	0,00	0,02	-0,01	-0,01	0,07	0,06
-0,03	0,03	-0,02	0,06	0,03	-0,03	0,01	0,01	0,03	1	-0,03	0,01	0,02	0,05	0,00	0,04	0,01	0,02
-0,02	0,08	-0,05	0,02	-0,02	-0,01	0,03	-0,01	0,02	-0,03	1	-0,04	0,01	0,01	-0,01	-0,02	-0,02	-0,02
0,03	0,00	0,00	0,00	0,00	0,00	-0,04	0,00	0,01	0,01	-0,04	1	0,03	0,04	0,01	0,02	0,02	0,05
0,00	-0,01	0,02	0,03	-0,01	0,01	0,00	-0,02	0,00	0,02	0,01	0,03	1	0,03	0,03	0,05	-0,02	-0,01
0,03	-0,02	-0,01	-0,07	-0,03	-0,05	0,00	0,02	0,02	0,05	0,01	0,04	0,03	1	-0,01	0,04	-0,02	-0,02
0,01	-0,03	0,00	-0,02	-0,01	-0,02	0,00	0,00	-0,01	0,00	-0,01	0,01	0,03	-0,01	1	0,01	0,04	-0,03
-0,01	0,07	0,02	0,00	0,01	-0,02	0,00	0,01	-0,01	0,04	-0,02	0,02	0,05	0,04	0,01	1	0,02	-0,01
0,02	0,07	0,01	0,02	0,01	0,00	0,03	0,02	0,07	0,01	-0,02	0,02	-0,02	-0,02	0,04	0,02	1	-0,03
0,00	-0,04	-0,02	0,02	0,03	0,00	0,03	0,02	0,06	0,02	-0,02	0,05	-0,01	-0,02	-0,03	-0,01	-0,03	1

Model Reconstruction Error

Evaluation of the reconstruction error model-to-measure for one of the blades in the dataset:



Pressure Side

Suction Side

- consistent error for different blades;
- optimal compromise between number of variables and accuracy.

University Technology Centre (UTC) Multidisciplinary Process Integration | Rolls-Royce | EUROPÄISCHE UNION Europäischer Fonds für Regionale Entwicklung | b-tu Brandenburgische Technische Universität Cottbus - Senftenberg

Efficient manufacturing variability stochastic modelling

Fluid Solution (CFD)

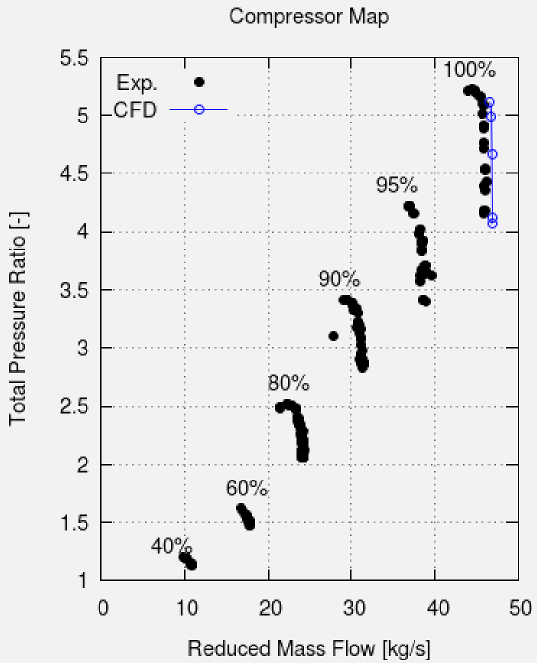
Chair of Structural Mechanics and Vehicle Vibrational Technology
Prof. Dr.-Ing. Arnold Kühhorn | Marco Gambitta

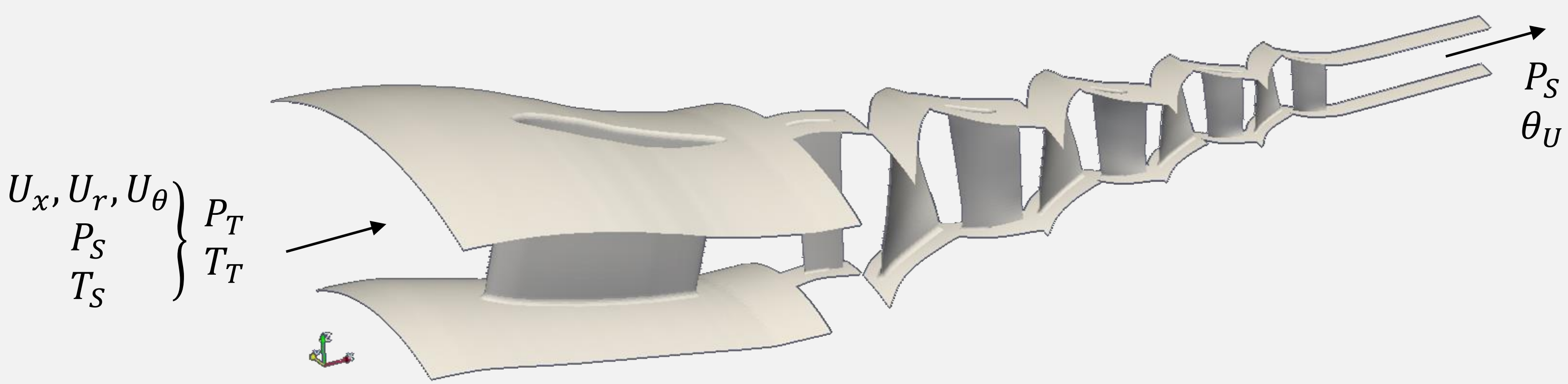
Nominal Geometry – Steady State

Brandenburgische Technische Universität Cottbus - Senftenberg

Steady state CFD computations validated using experimental measurement data:

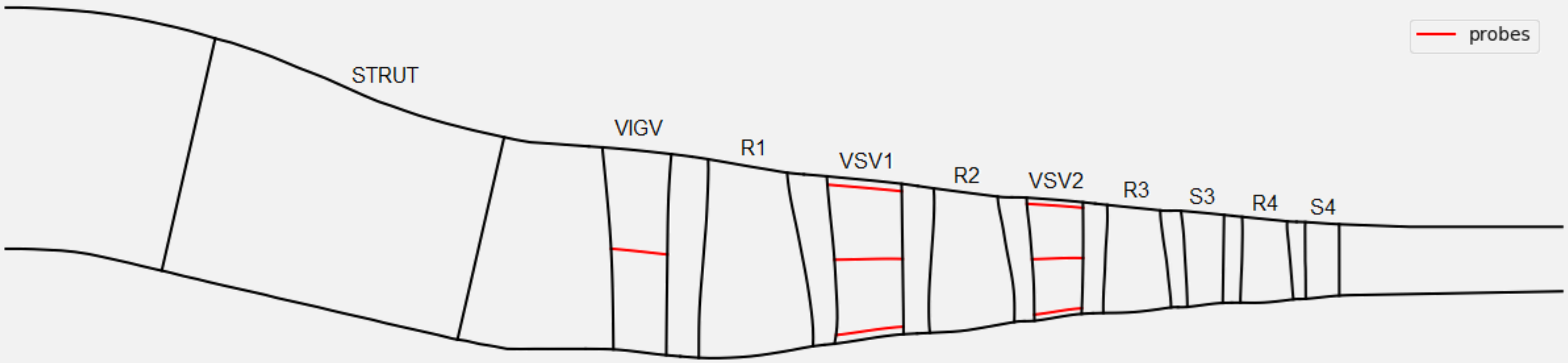
- Strut to Stator-4 geometry modelled
- ~7.7 Mln cells (single passage)
- turbulent flow with wall functions
- turbulence model: Spallart-Almaras
- boundary conditions extracted from experiments.

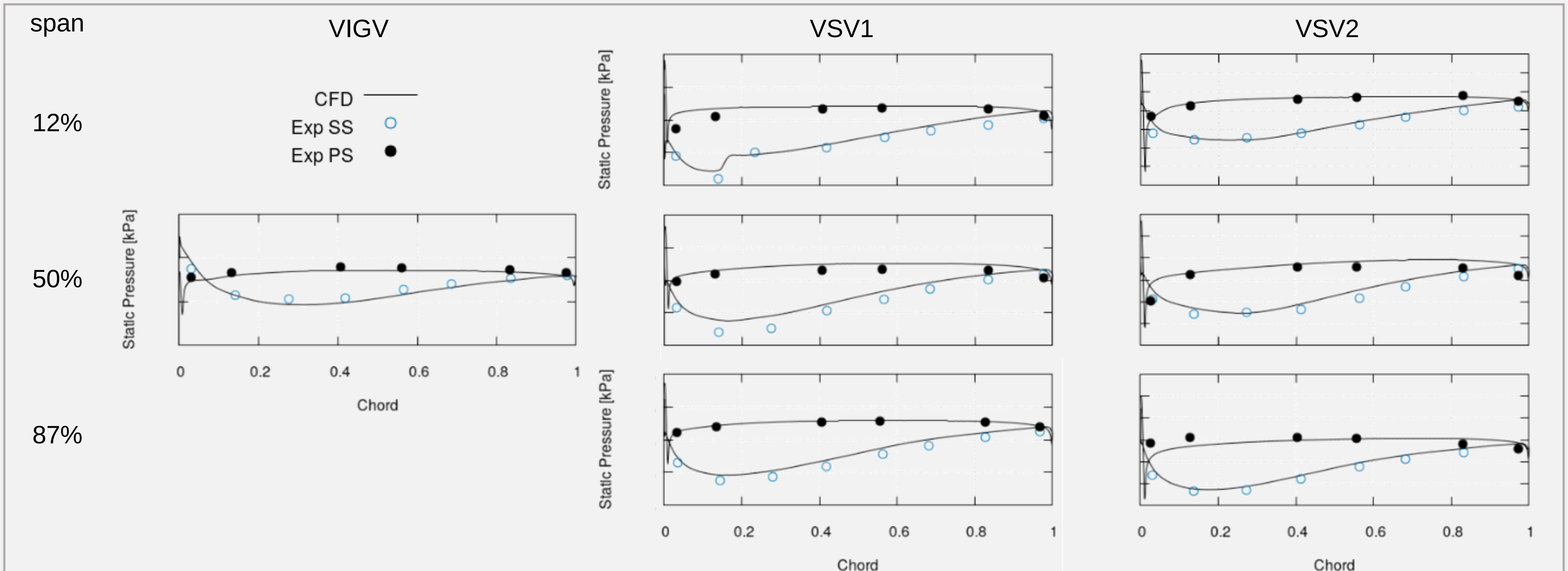




Experimental Results Comparison

Static Pressure – Variable Stator Vanes SS/PS





University Technology Centre (UTC)
Multidisciplinary Process Integration

Rolls-Royce

EUROPÄISCHE UNION
Europäischer Fonds für Regionale Entwicklung

Brandenburgische Technische Universität Cottbus - Senftenberg

Efficient manufacturing variability stochastic modelling

FEM Vibrational Analysis

Chair of Structural Mechanics and Vehicle Vibrational Technology
Prof. Dr.-Ing. Arnold Kühhorn | Marco Gambitta

FEM Analysis

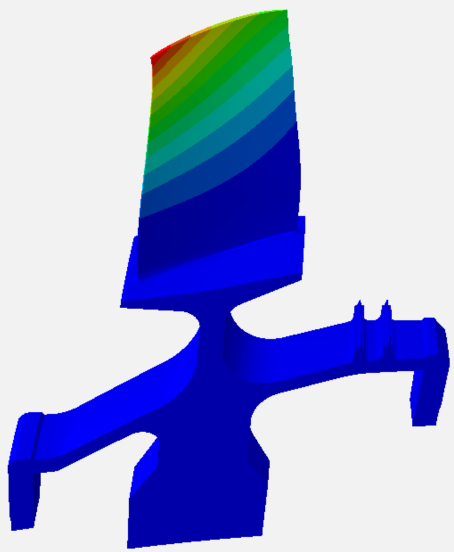
Brandenburgische Technische Universität Cottbus - Senftenberg

FEM analysis of blades vibrational modes:

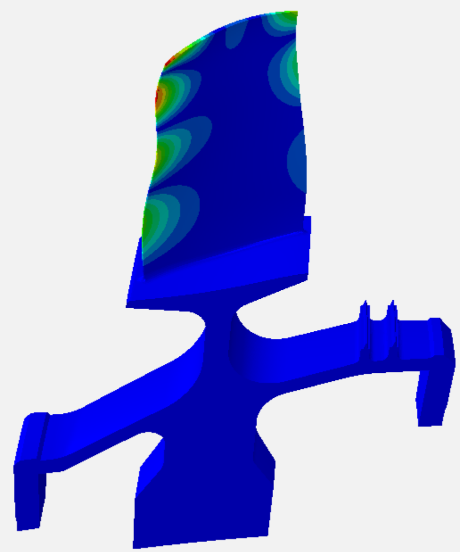
- disk structure integrated;
- engine working conditions;
- vibrational modes of interest selected.

Mode	Natural Frequency
Mode 01	742.33 Hz
Mode 11	6894.6 Hz

CAD Model (Nominal)



Mode 01

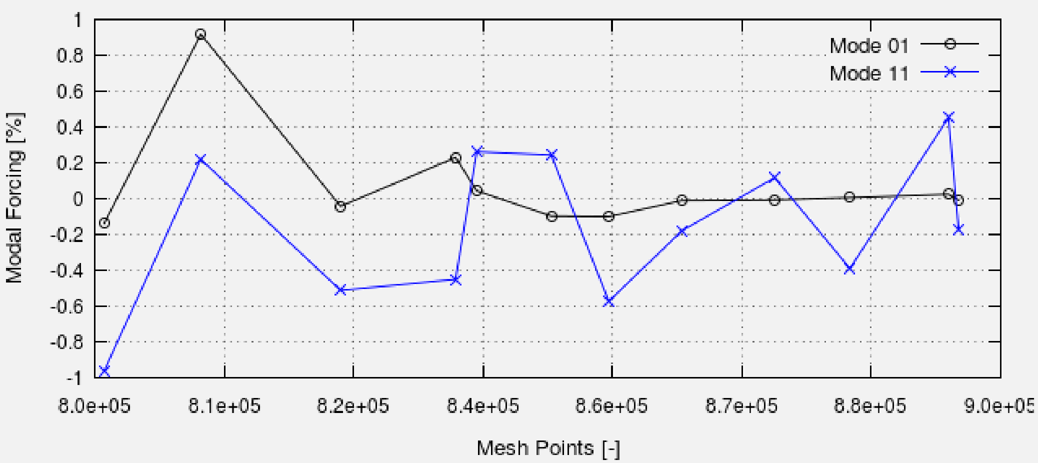


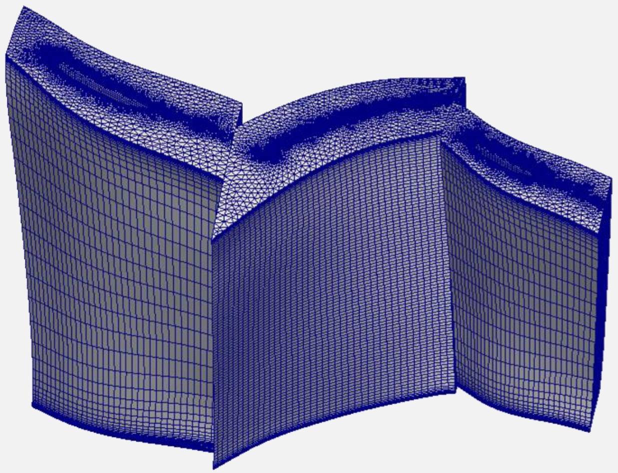
Mode 11

Mesh Study - Modal Forcing Convergence

Brandenburgische Technische Universität Cottbus - Senftenberg

Dependence upon the mesh of the steady-state modal forcing acting on the rotor blade:





- Selected mesh nodes number: ~8,730,000 points
- Relative numerical error:

Vibrational Mode	Numerical Error
Mode 01	< 0.03%
Mode 11	< 0.5%

University Technology Centre (UTC)
Multidisciplinary Process Integration

EUROPÄISCHE UNION
Europäischer Fonds für Regionale Entwicklung

Brandenburgische Technische Universität Cottbus - Senftenberg

Efficient manufacturing variability stochastic modelling

Mistuned Fluid Solution

Chair of Structural Mechanics and Vehicle Vibrational Technology
Prof. Dr.-Ing. Arnold Kühhorn | Marco Gambitta

Forced Response Analysis

Calculation of the forcing generated on the rotor-2 mode shapes from the unsteady flow pressure field:

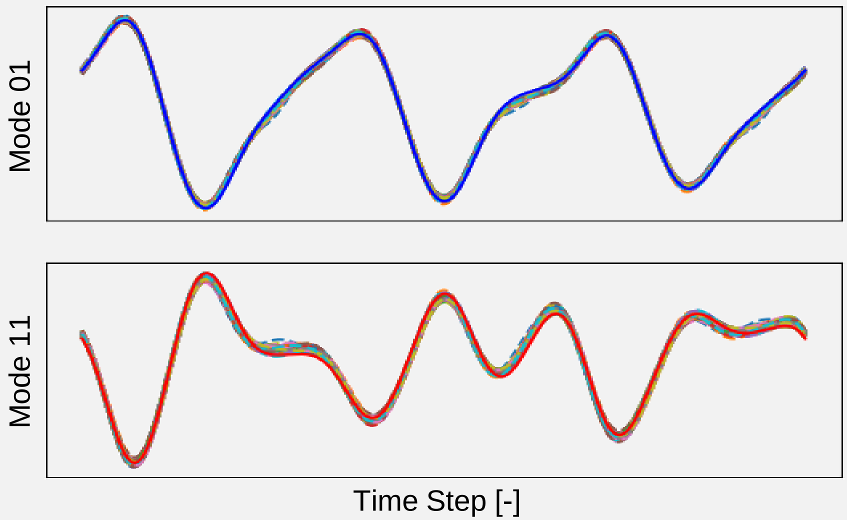
- Pressure field from unsteady CFD solution projected onto the modes shape calculated to extract the forcing in the modal domain
- Vibrational modes of interest:
  - Mode 01 (first flap mode)
  - Mode 11 (torsional mode)

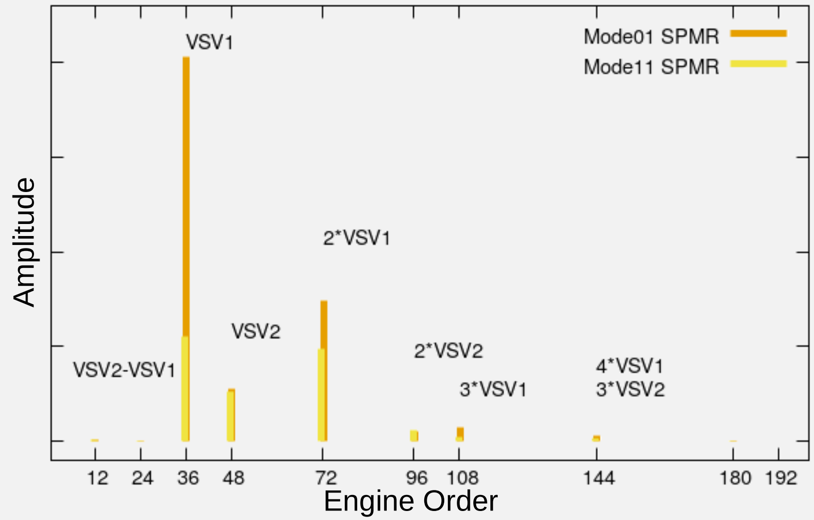
Full Annulus - FA

Single Passage Multi Row - SPMR

Modal Forcing on Rotor 2 – Nominal Geometry

Brandenburgische Technische Universität Cottbus - Senftenberg





Modal Forcing Amplitude

Projection of unsteady pressure on blade surface over vibrational mode shapes:

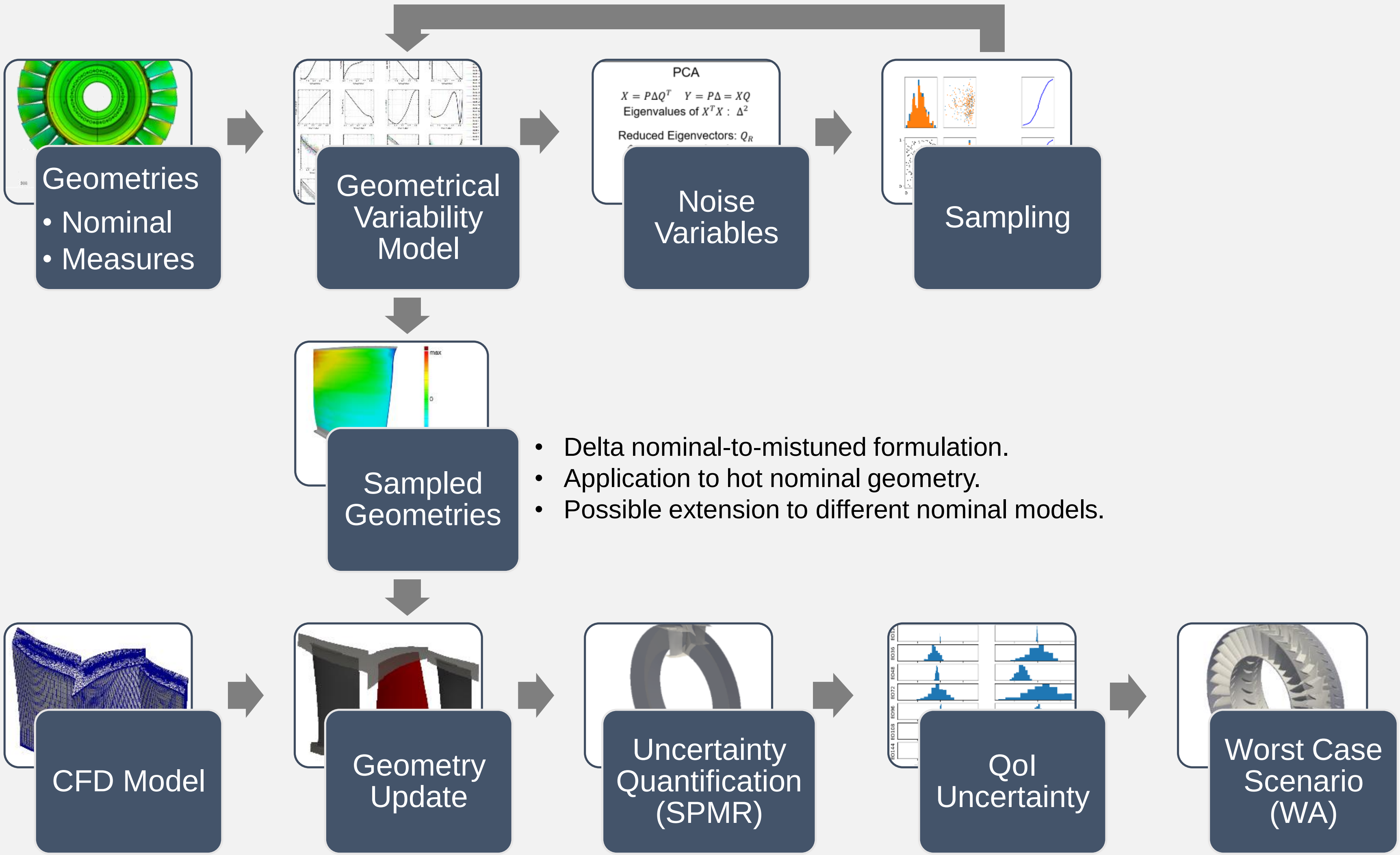
- time periodic function;
- mode specific.

Forced Response Engine Orders

Amplitude of the harmonics corresponding to the main engine orders.

Engine Orders (EO): frequencies arising from the engine working condition as higher harmonics of the shaft speed.

Uncertainty Quantification Methodology

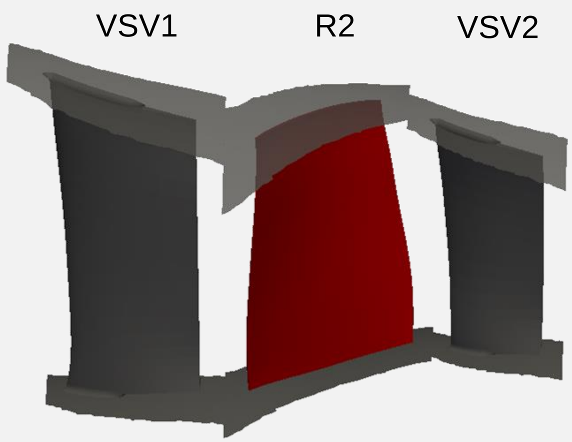


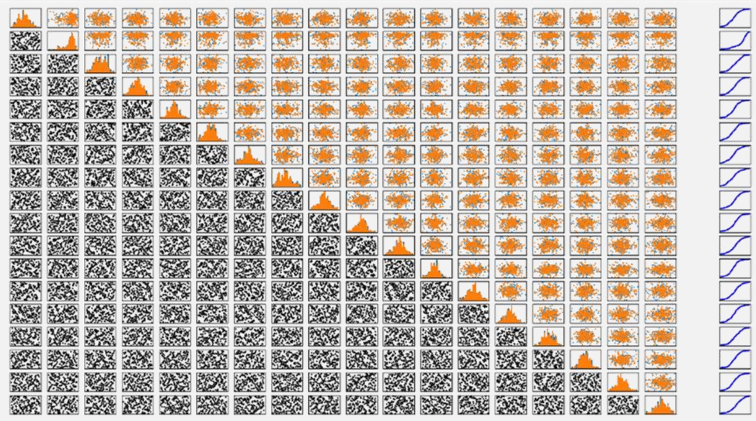
- Delta nominal-to-mistuned formulation.
- Application to hot nominal geometry.
- Possible extension to different nominal models.

Uncertainty Quantification (Mistuned R2)

Quantification of the variability of the modal forcing acting on the R2 vibrational mode-shapes:

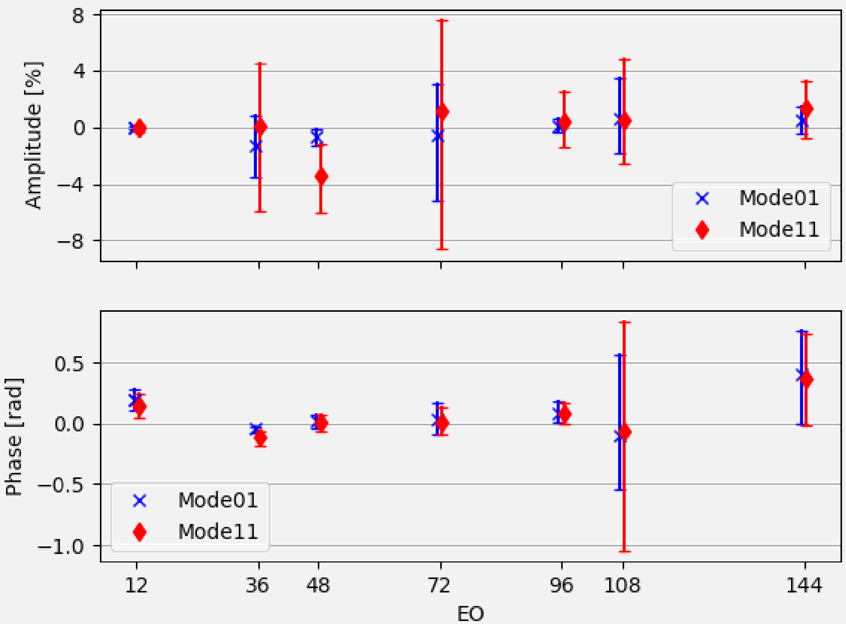
- SPMR configuration;
- geometrical variability applied on R2 geometry;
- sampling technique: Latin Hypercube Sampling;
- variables probabilistic distribution replicated from measurement data cumulative distribution function;
- no correlations present;
- 180 total samples created.



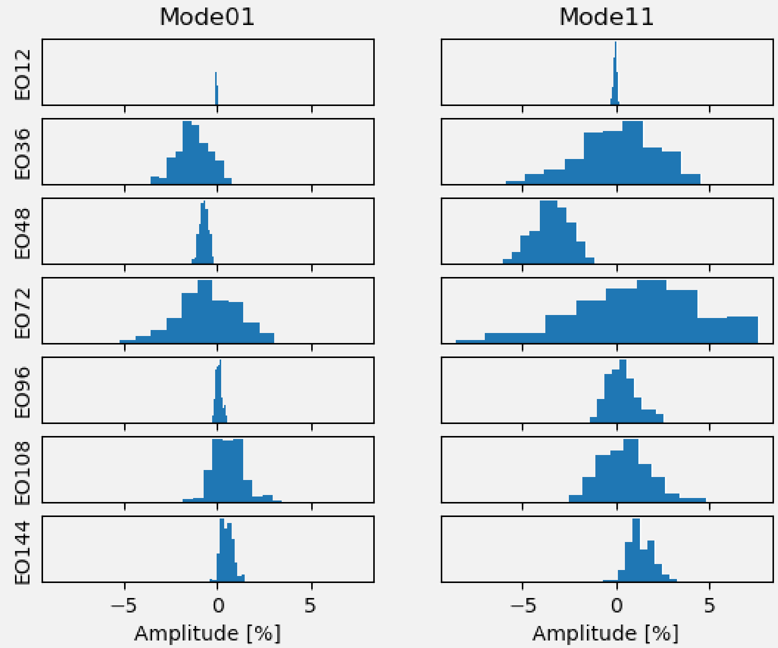


UQ Results (Mistuned R2)

Mistuned modal forcing scatter for the main engine orders:



Modal Forcing Harmonics Scatter



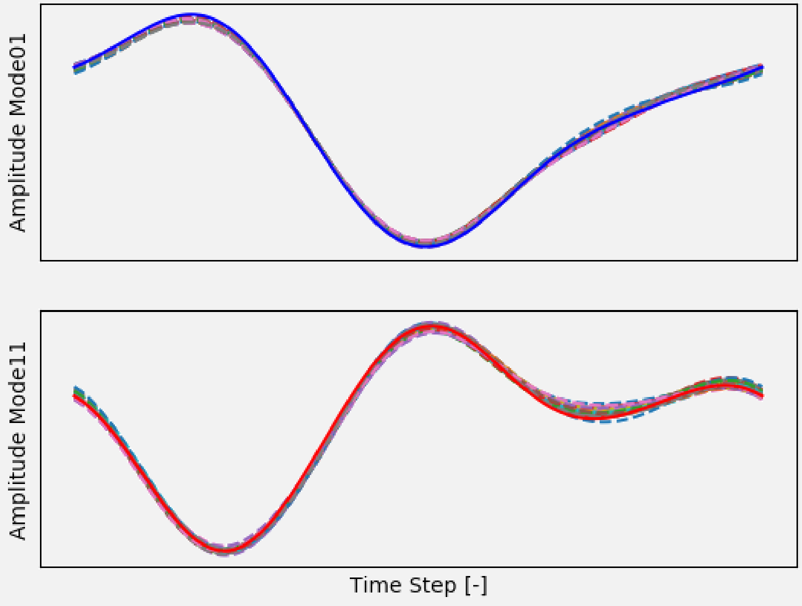
Amplitudes Probability Distribution

Delta formulation: $\Delta_F = \frac{F^M_{EO,i} - F^M_{EO,N}}{\max(F^M_{EO,N})}$, with:

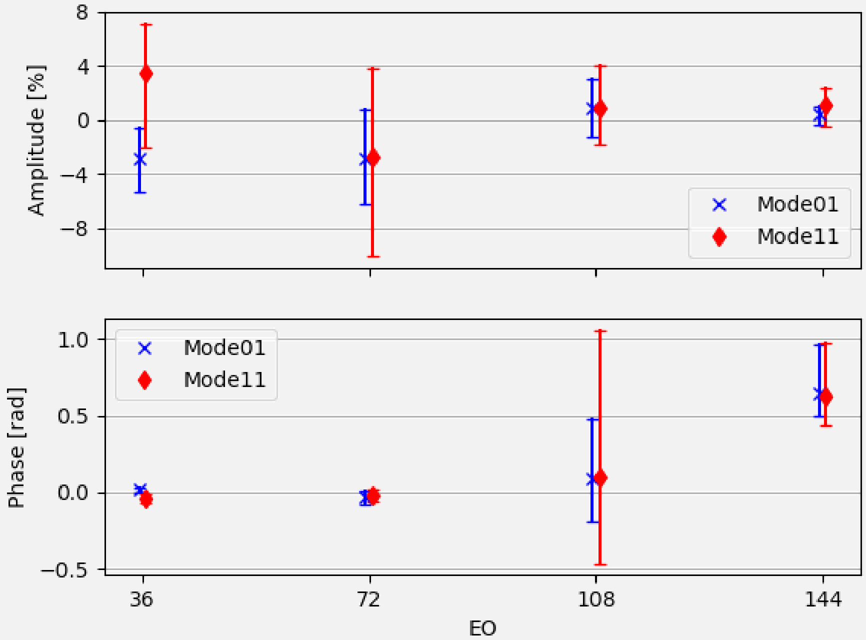
- F: modal forcing amplitude
- EO: engine order
- M: vibrational mode
- N: nominal model
- $i \epsilon [1, n_{samples}]$: mistuned blade index

Mistuned R2 – FA Analysis

Full annulus analysis (VSV1-R2) for the estimation of the mistuning effect in the assembly:



SPMR



FA

University Technology Centre (UTC) Multidisciplinary Process Integration | Rolls-Royce | EUROPÄISCHE UNION Europäischer Fonds für Regionale Entwicklung | b-tu Brandenburgische Technische Universität Cottbus - Senftenberg

Efficient manufacturing variability stochastic modelling

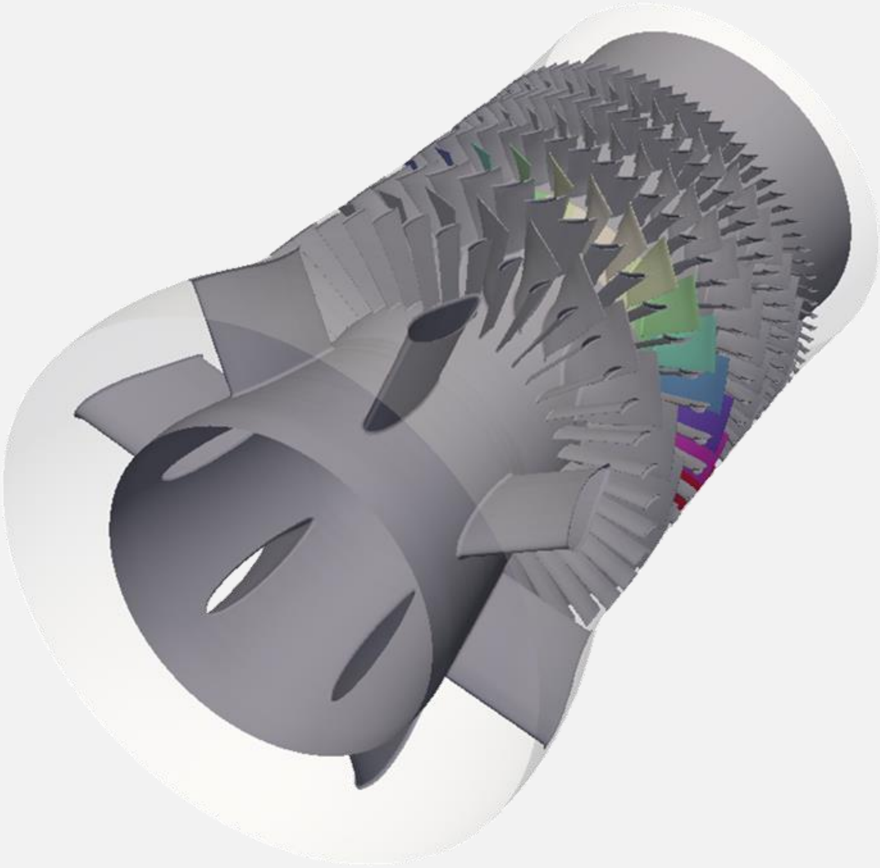
Overview

Chair of Structural Mechanics and Vehicle Vibrational Technology
Prof. Dr.-Ing. Arnold Kühhorn | Marco Gambitta

Overview

- Study of manufacturing geometrical variability on turbofan engine HPC:
  - deviations of blades geometry from the nominal design modelled for the representation in the computational models;
  - principal component analysis of geometrical variables provides an optimal subset of geometrical modes;
  - stochastic representation of the variability.
- Aeroelastic analyses considering geometry based mistuning is carried on a test-rig case:
  - focus on geometrical variability effect on blades modal forcing;
  - mode shapes extracted form blisk FEM and mapped over the CFD model nodes;
  - validated CFD model used for the computation of the unsteady pressure on the rotor blades surfaces;
  - uncertainty quantification of the geometrical variability effect on the modal forcing:
    - reduced model employed for the CFD solution (SPMR, time-space periodicity solving the governing equations in the frequency domain);
    - unsteady modal forcing is studied as amplitude and phase shift for the different engine orders;
    - results are compared to a larger computational model to assess the influence of multiple variable blades in the assembly.

Contact Page



Marco Gambitta
Chair of Structural Mechanics and Vehicle Vibrational Technology
Prof. Dr.-Ing. Arnold Kühhorn
Brandenburg University of Technology

b-tu.de/fg-strukturmechanik