Automatic Detuning of Steam Turbine Rotor Blades' Eigenfrequencies Away From Critical Areas

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Outline

- About DATADVANCE & UTW
- Joint project on simulation driven design and optimization
- Automated module for blades modal analysis
- Detuning as optimization problem. Adaptive DoE
- Problem statement and automated workflow
- Results and conclusion

About DATADVANCE & UTW

DATADVANCE

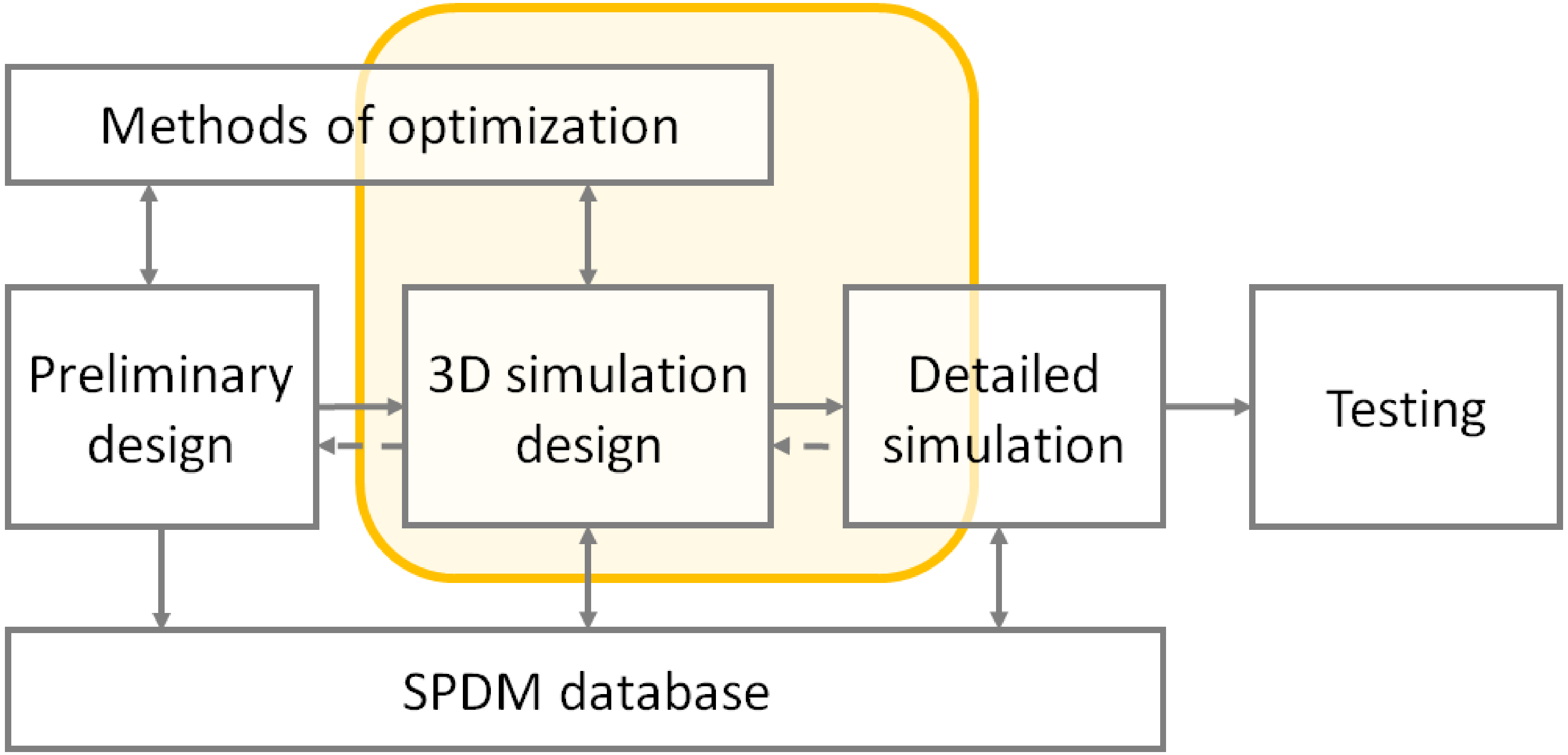
THE URAL TURBINE WORKS

- DATADVANCE provides predictive modelling and design space exploration software tools and services to customers in aerospace, automotive, energy, marine and offshore and related industries
- Company roots go to French aviation and Russian mathematics. It evolved out of a joint research program between Airbus Group and Institute for Information Transmission Problems – one of the leading mathematical centers in Russia.
- Direct office locations:
  - Toulouse, France (HQ, AE and Operations)
  - Moscow, Russia (R&D team)

- UTW products account for approximately a half of overall mounted cogeneration turbine capacity in Russia and the CIS. Steam and gas turbines made by UTW are operated in 26 countries worldwide.
- More than 70 years of experience in turbine design and a wide range of manufactured turbines enable the Ural Turbine Works to satisfy demands of different clients.
- During the development of new turbines and renovation of existing ones UTW takes into consideration modern trends in power engineering development, gas industry and metallurgy.

Automated 3D Simulations in Design Chain

- Automated module for blades eigenfrequencies detuning presented in this presentation is a part of dedicated automated solution for 3D simulation based turbine design.



Automated Modules: General Idea

Automated simulation modules allow to setup and conduct various types of analysis using the common interface.

User interface

Module

- Interactive input based on templates
- Reference to DB (optional)
- Parameter set validation
- **Fully automated geometry assembly**
- **Automated mesh setup and creation**
- **Mesh convergence checks embedded**
- **Simulation setup based on scenario**
- Preset reports with results and graphics
- Upload to DB (optional)

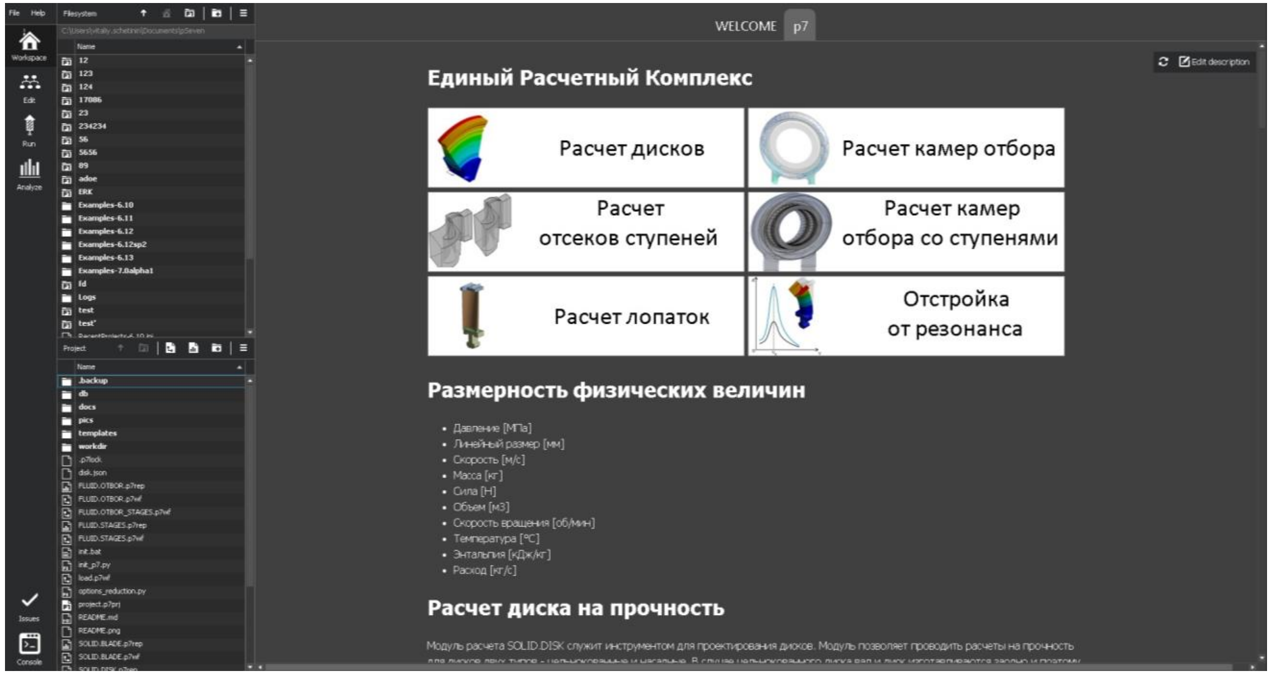
User interface

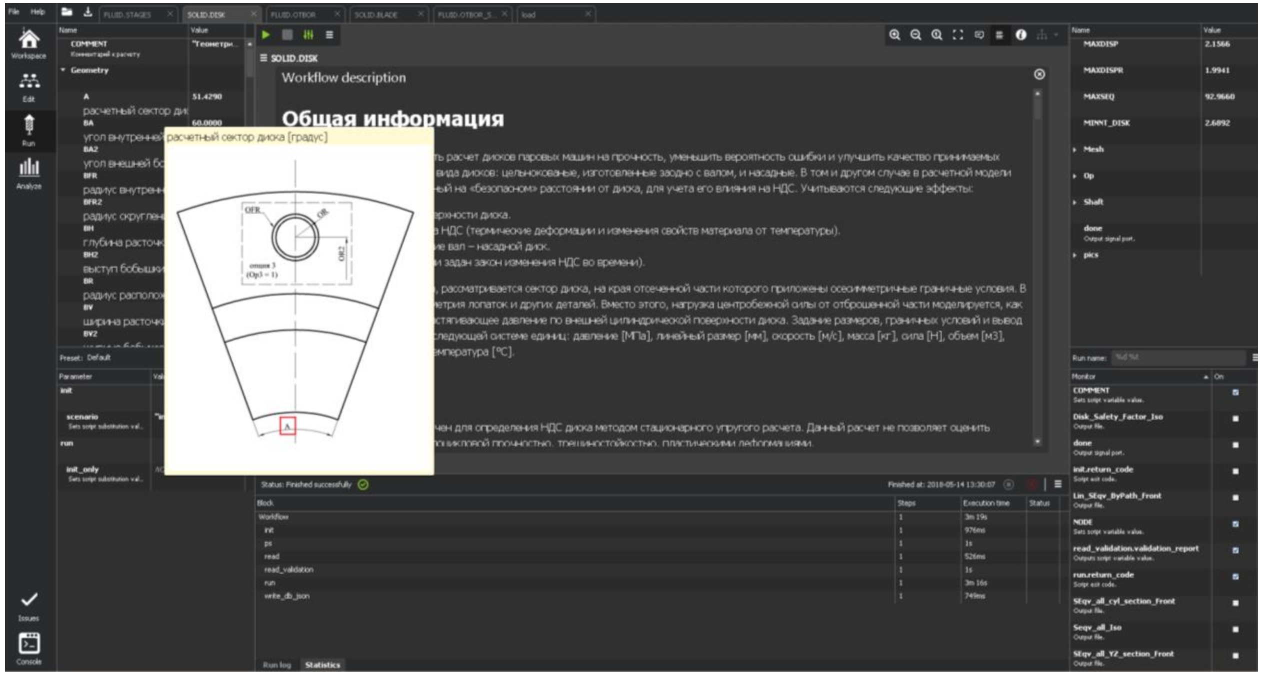
Automated Modules: Interface

All automated modules have common user interface based on pSeven platform, developed by Datadvance.

Due to web-based nature of the platform, solution can be deployed on the server and accessed via web-browser.

User can switch between simulations, enter input parameters, choose simulation statements presets and browse the results.





Parametric and optimization studies in the modules are based on pSeven Core capabilities (including adaptive DoE)

List of Modules

Project at the current stage includes the following modules:

1. Turbine disk stress analysis:
- Non-linear static stress simulation, centrifugal and steam flow loads.

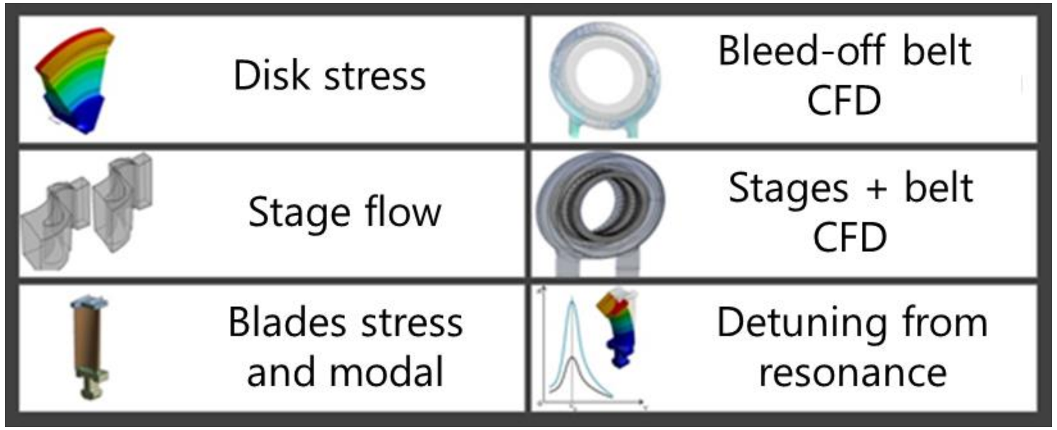
2. 3D CFD simulation of the flow channel:
- Sectoral and full-360 formulations, bandage flow-overs effects
- Stage efficiency and blade loads evaluation.

3. Vibration analysis:
- Non-linear static stress simulation, centrifugal and steam flow loads
- Modal analysis, eigenfrequencies extraction
- 12 simulation statements

4. Automated resonance detuning:
- Optimization of geometry parameters to avoid resonance behavior of the blade

5. CFD simulation of bleed-off belt:
- Evaluation of hydrodynamic losses, heat transfer coefficient

6. CDF simulation of the turbine stages in presence of bleed-off belt:
- Influence of partial flow admission on the flow pattern and blades modes



All listed modules are based on Ansys CFX and Ansys Mechanical solvers with various meshing tools involved.

They are using common API library of automation methods, developed for this project.

Components of the Project Library

Main components used by modules:

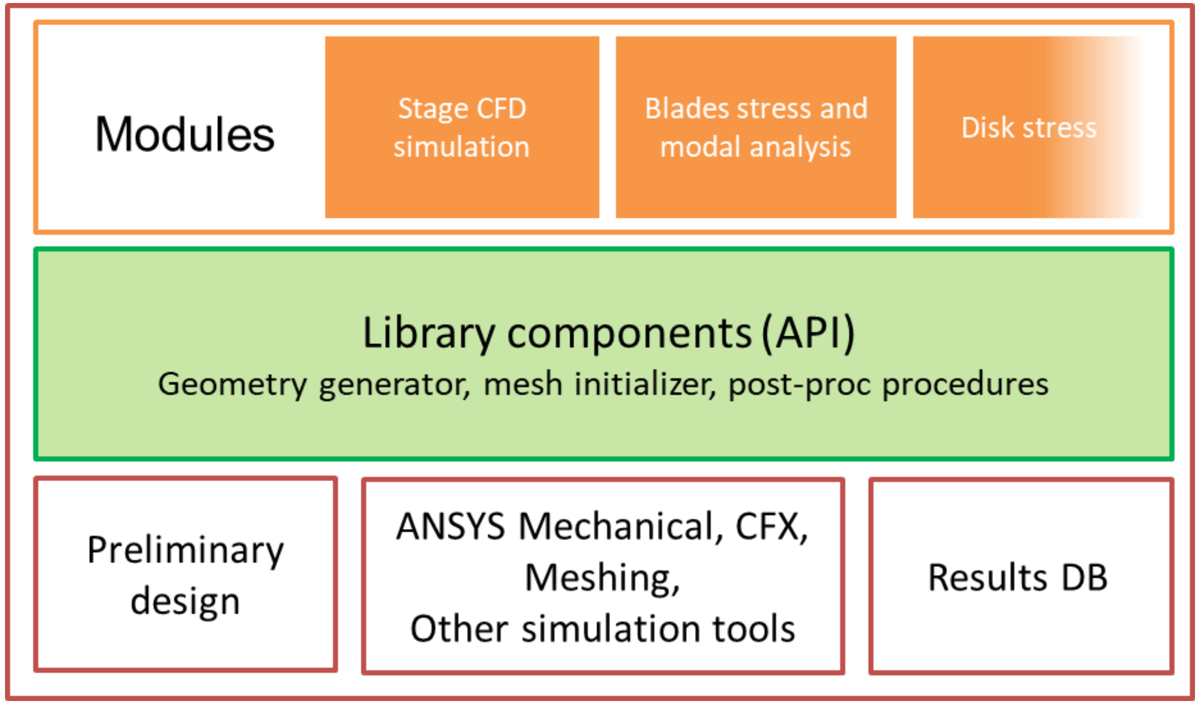
1. Geometry generator:
- Wide range of geometry templates for all units
- Validation tree for parameters combination

2. Automated meshing procedures:
- Well-developed system of semi-empirical meshing rules
- “Accuracy - speed” slider setting

3. Automated simulation setup:
- Incorporates simulation methodologies for all studies

4. Post-processing and reports presets:
- Cut plots, graphs
- Visualization tools for modal analysis

5. Interfaces (connectors):
- Between modules for boundary conditions transfer
- To preliminary design results DB
- To simulation results DB (SPDM)



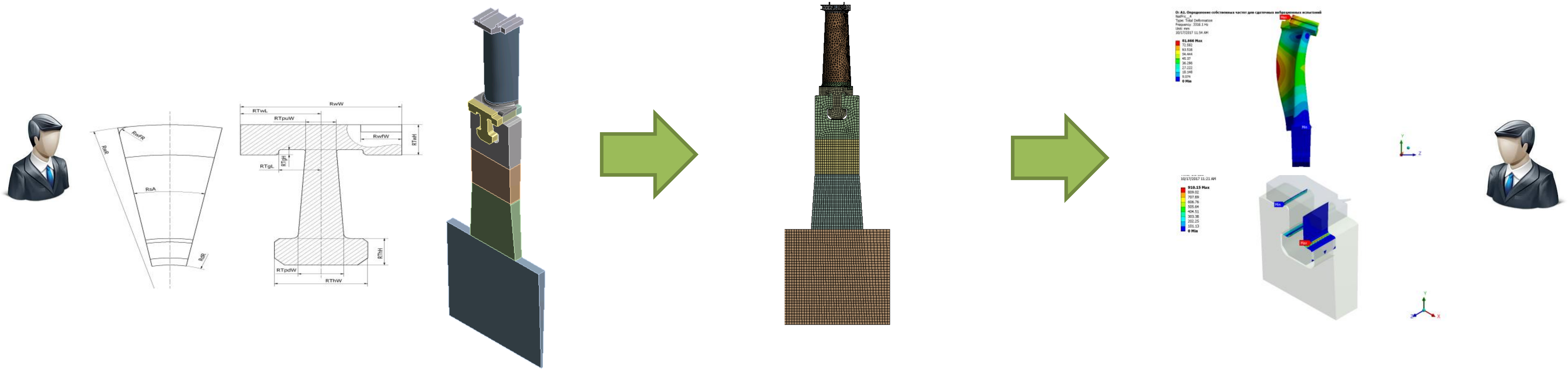
All components are packed into single library to enable new modules development, even by the customer.

Blades Stress Modal Analysis

Detuning procedure is based on the blades stress and modal analysis module.

It automates the following simulation studies:

- Nonlinear static stress of the blades in presence of centrifugal and flow loads
- Eigenfrequencies and eigenmodes evaluations
- Campbell diagram plotting
- Periodic (partial) flow effects

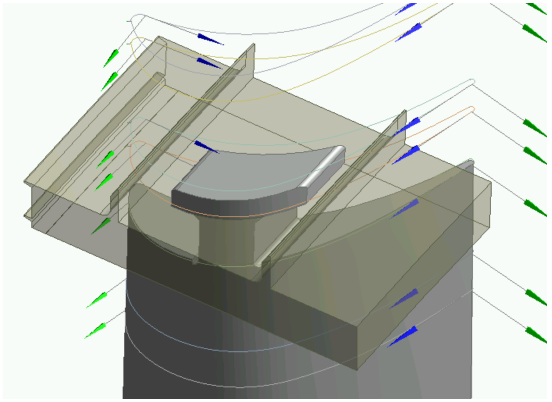


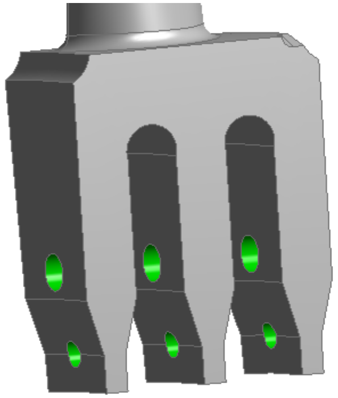
Parameters input (based on templates) Automated meshing and simulation Post-processing

Geometry Templates & Parameters

Module supports:

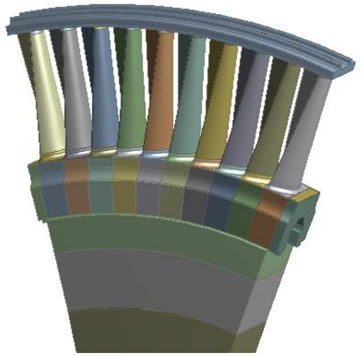
- Several types of shroud bandages
- Several types of locks
- 12 simulation cases, including full stack with disk

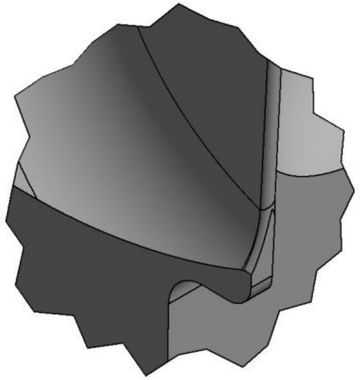




Basic geometry is complemented with detailed geometry settings:

- Fillets radiuses (may differ along blade profile)
- Shroud ring thickness
- Blade-root connection features
- Blades stacking settings





Module supports more than **400** various geometry **parameters** for 9 basic geometry templates.

Any valid combination can be used for further automated eigenfrequency detuning.

Simulation Model

Geometry models for automated detuning studies include blade (or blades stack) with disk and shroud.

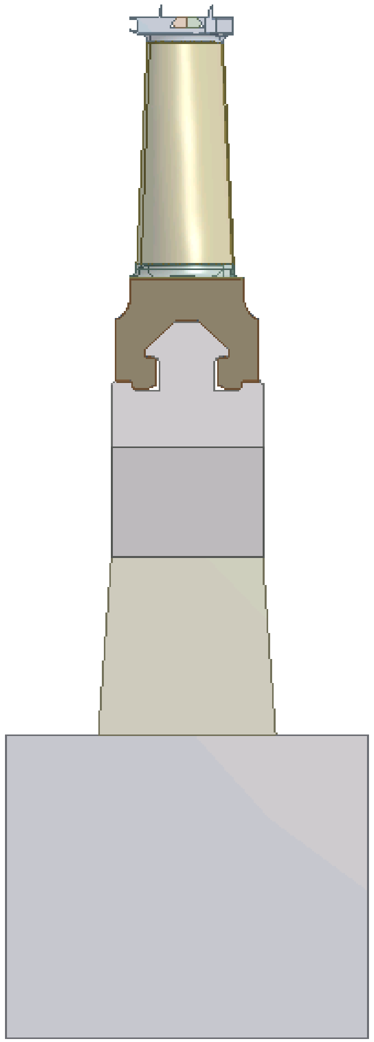
10 different simulation statements are available for modal analysis and can be used in detuning study.

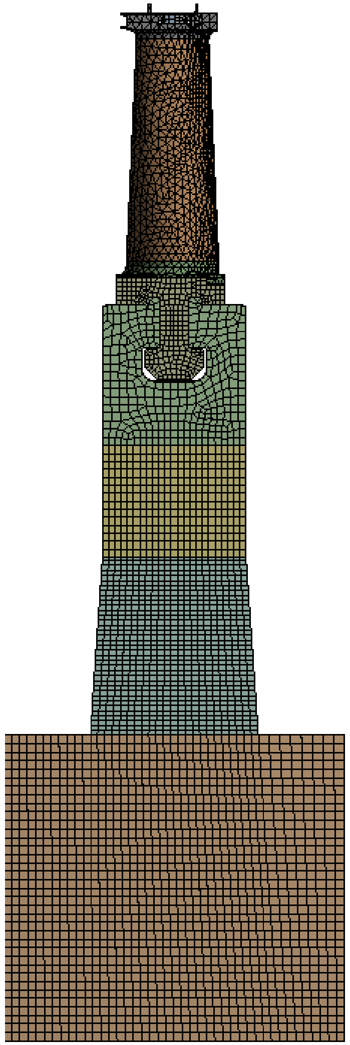
Simulation model:

- Cyclic symmetry
- Centrifugal and thermal loads
- Fixed rotation rate
- All contacts have friction
- Tension in lock
- Kinematic constraints for the shroud

Total mesh size is about 30 000 cells.

Simulation is performed in ANSYS Mechanical.





Blades Eigenfrequencies Detuning

To ensure operational safety we have to guarantee the rotor blades' eigenfrequencies under operating conditions to be away from possible resonances with the rotation frequencies.

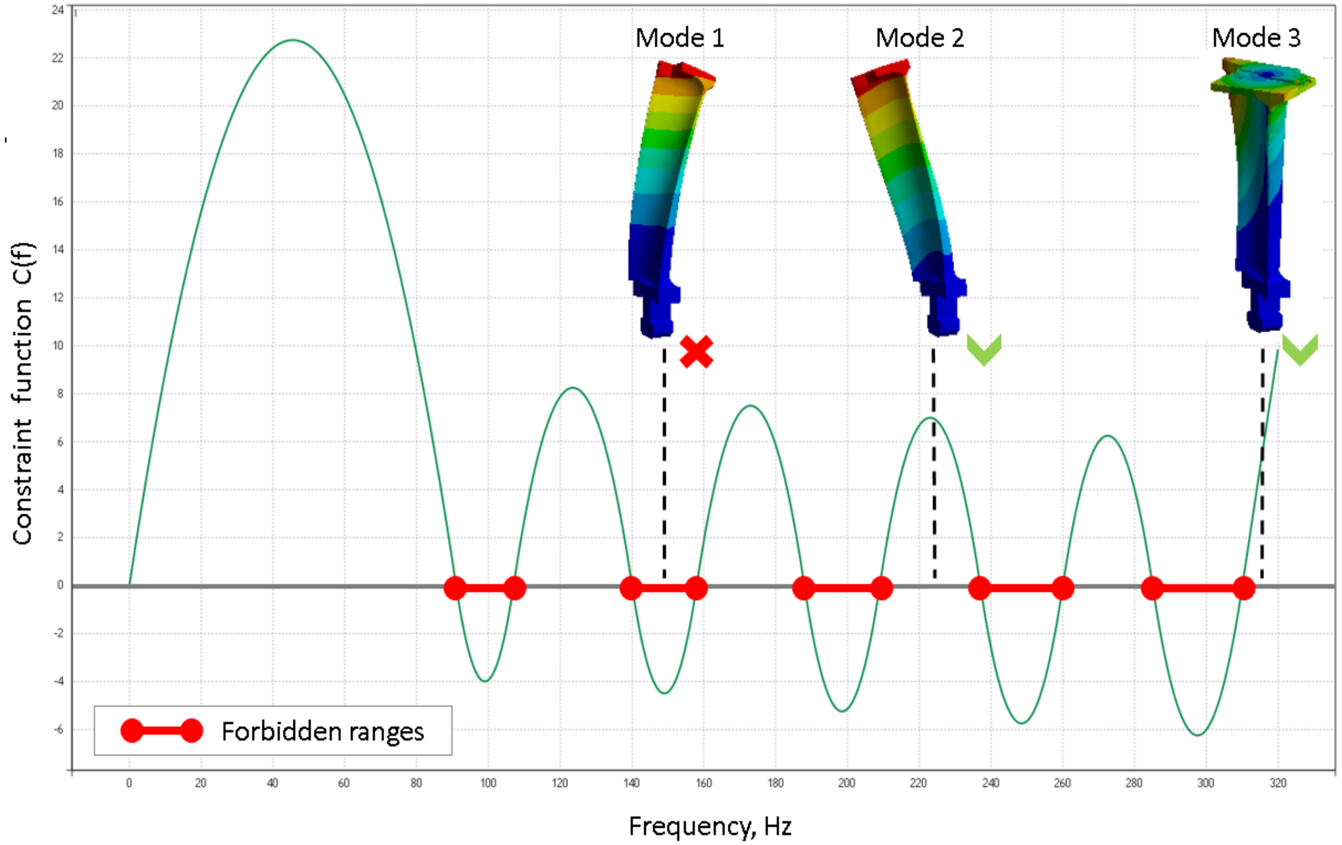
For given rotation rate all eigenfrequencies of the blades, blades stacking and blade & disk joints should lay in the allowed ranges.

Detuning problem might be formulated as:

$$C(F_i) > 0 \; \forall \; F_i,$$

where F's are the eigenfrequencies and C(F) is an artificial constraint function.

Example of such function (quadratic) is shown on the picture.



Detuning as CSP Optimization Problem

Blades eigenfrequencies can be controlled by the geometry parameters ***G*** of the blade.
It means that the following optimization problem should be considered:

$$\boldsymbol{G}_{\boldsymbol{lower}} \leq \boldsymbol{G} \leq \boldsymbol{G}_{\boldsymbol{upper}}$$
$$C(F_i(\boldsymbol{G})) > 0 \; \forall \; F_i(\boldsymbol{G}),$$

This type of optimization problem is called CSP (constraint satisfaction problem).
The goal for the optimization algorithm is such case is **to find any <u>single</u> feasible solution** thus ensuring problem feasibility.

However, in real life applications the problem usually includes the technological constraints, which are hard to formalize and therefore single (the first obtained) optimal solution may be not suitable.

So, more useful would be to look for **<u>multiple different solutions</u> in the feasible domain**.

Such problem can be solved by using Adaptive Design of Experiment technique in pSeven.

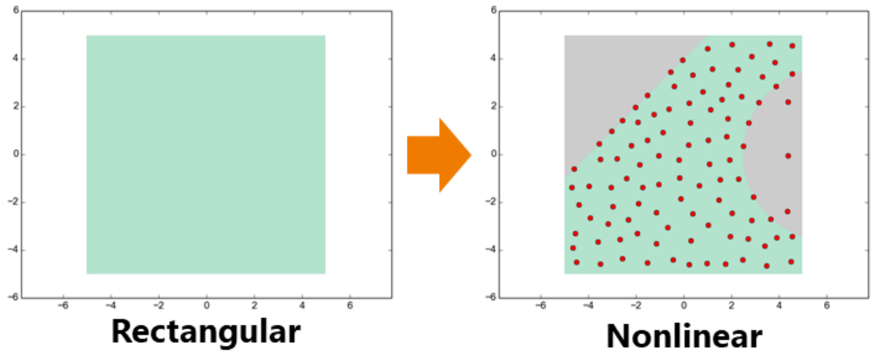
Adaptive Design in pSeven: Basics

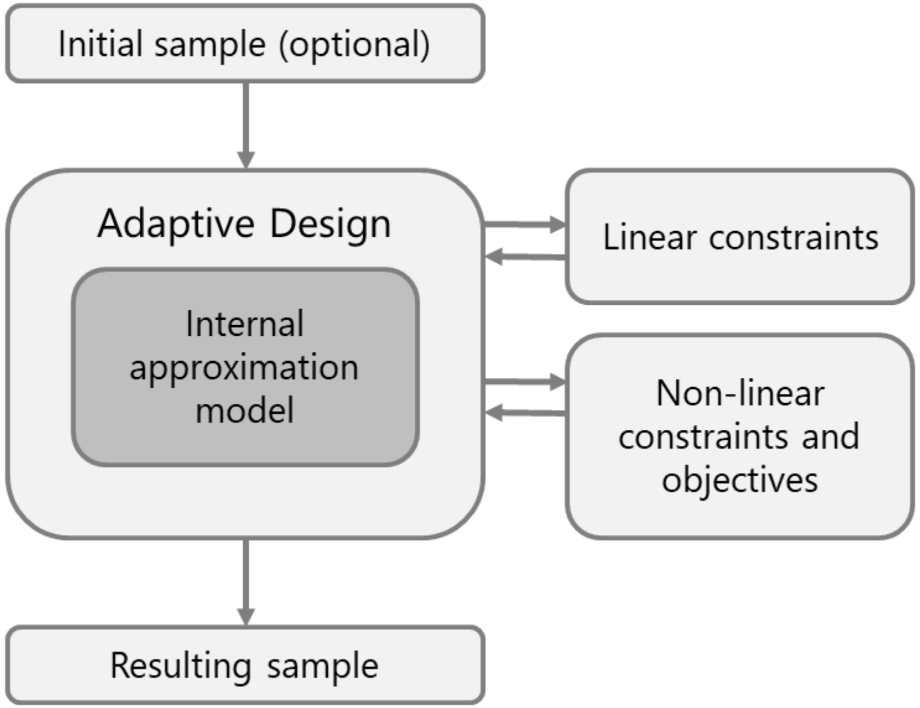
- Standard Design of Experiments (DoE) methods support only “rectangular” design space.

- How to sample “nonlinear” design space?

- Adaptive Design method:
  - Based on iteratively refining hierarchical approximation model
    - Concept adopted from Surrogate-Based optimization (SBO) techniques
  - Up to ~100 variables
  - Arbitrary number of linear constraints
  - Non-linear constraints and “objectives” defined via Blackbox

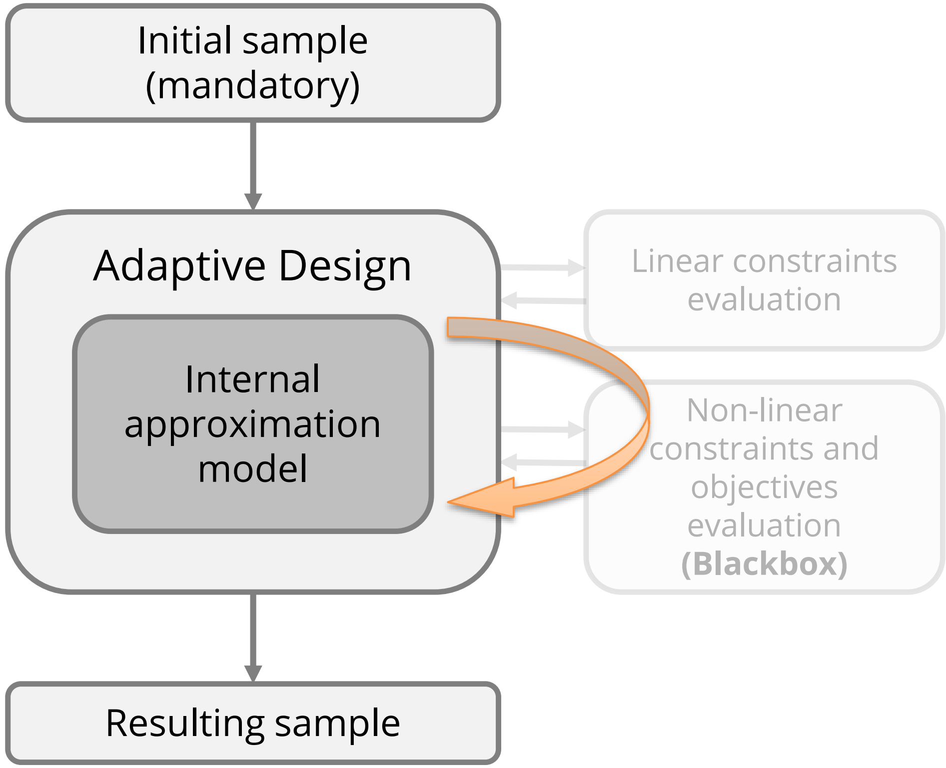
- Adaptive Design supports 3 scenarios:
  - <u>Feasible domain sampling</u>
  - Approximation model improvement
  - Search for designs with given function value (level set)





Sample-Based Adaptive DoE

It is possible to use the ADoE even without simulation blackbox (despite the iterative nature of the method).



Idea is to **rely only on internal approximation model** when generating new points.

Initial sample in this case is **mandatory**.

New points will be generated without responses values
They can be used in lab tests, added to initial sample and the whole study can be repeated.

The goal is typically to **reduce the number of measurements in the unfeasible points.**

Adaptive Design: Features

1. Initial designs supported:
    - “Initial guess” sample – points to evaluate
    - “Existing data” – samples with previously obtained responses
2. Linear constraints are restored in the first place and never violated after
3. Efficient handling of non-linear expensive constraints and objectives:
    - Internal approximation model improves each time new points is received
    - Search intensity parameter to control speed-quality balance
    - NaN support
4. Noise stable
5. Batch mode support (several points at a step)

Adaptive Design vs LHS

Demo problem:

Variables: $\vec{x} \in [0,1] \times [0,1]$

Constraint: $f(\vec{x}) = 2 + 2.5(x_2 - 5x_1^2)^2 + (1 - 5x_1)^2 + 2(2 - 5x_2)^2 + 7\sin(2.5x_1)\sin(17.5x_1x_2) > 7$

For **LHS** technique *budget* does not mean the sample size, since it generates points in variable space and the constraints are checked after evaluation.

Budget	Feasible Points	%
10	7	**70**
30	21	**70**
50	33	**66**
70	48	**69**
90	64	**71**
110	80	**73**
130	86	**66**
150	103	**69**
170	122	**72**

ADoE restores response behavior using internal surrogate model and generates points uniformly only in feasible domain. For this technique *budget* ~ sample size.

Budget	Feasible Points	%
10	9	**90**
30	27	**90**
50	46	**92**
70	66	**94**
90	86	**96**
110	106	**96**
130	126	**97**
150	146	**97**
170	166	**98**

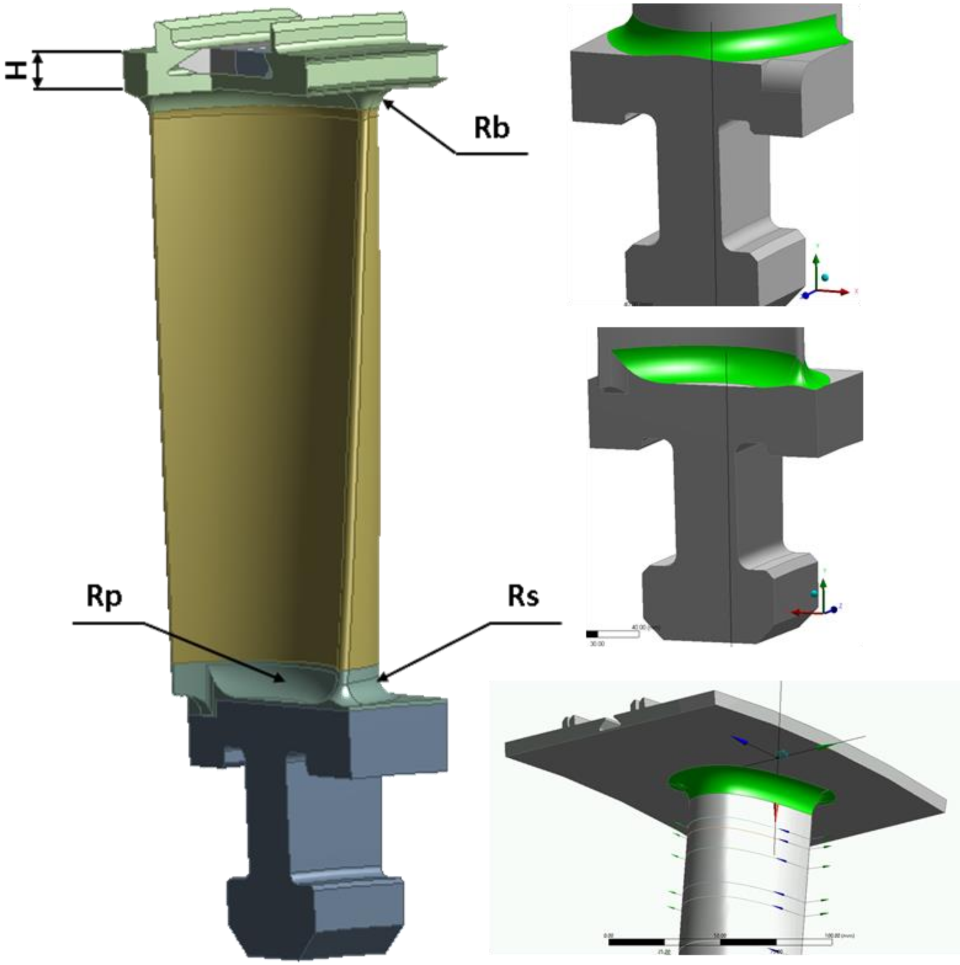
Adaptive DoE for Detuning: Parameters

- For demo purposes we used only 4 geometry parameters of the blade:

Parameter	Description	Lower bound	Upper bound
Rp, mm	Fillet radius (low, inside)	5	10
Rs, mm	Fillet radius (low, outside)	5	10
Rb, mm	Fillet radius (up)	5	10
H, mm	Shroud ring rim	3	15

- Problem statement can be extended to include any other parameters affecting the eigenfrequencies spectrum.

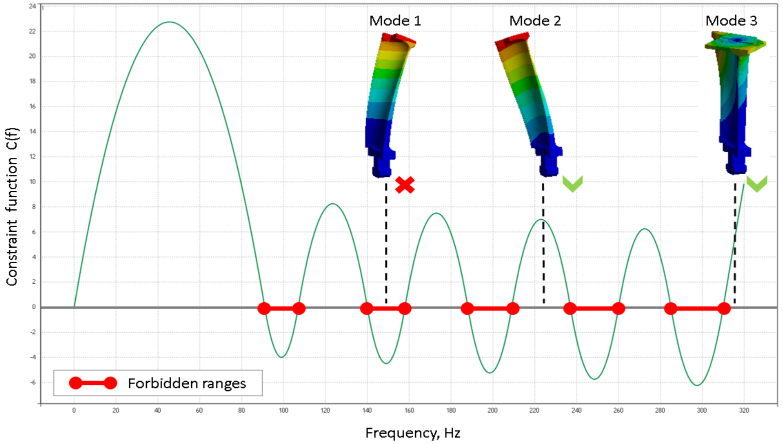
- Method supports arbitrary number of variables, however the speed may decrease at dimensionality more than ~50.



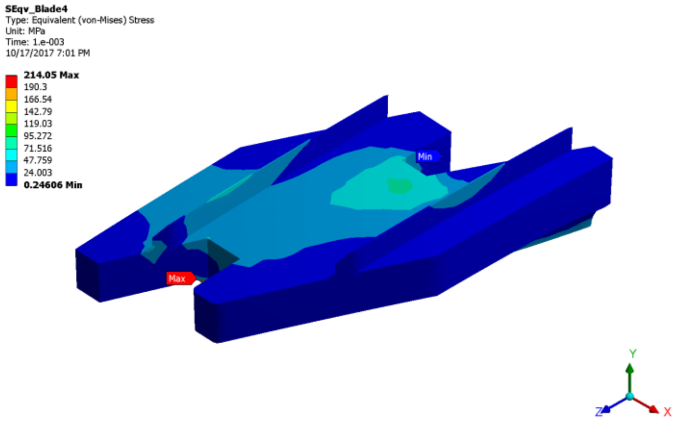
Adaptive DoE for Detuning: Constraints

- Resonance criterion is represented by artificial constraint function C
- Problem statement may also include constraints for maximum stress in different parts of the blade.
- For demo purposes we will focus only on first flexural mode.

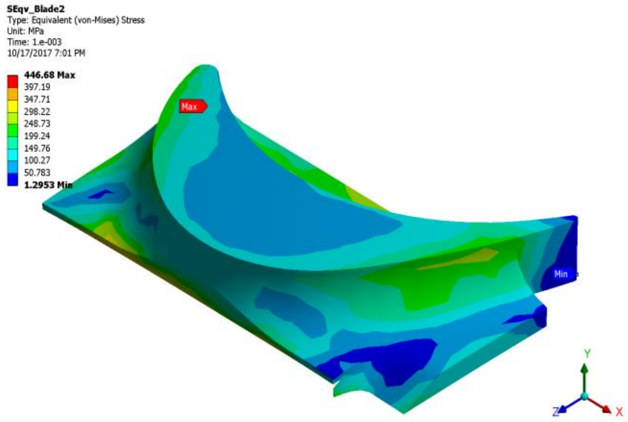
Constraint	Description	Bounds
C	Artificial function based on allowed frequency regions	>0
stressT, MPa	Max stress in shroud rim	<320 MPa
stress, MPa	Max stress in blade root	<320 MPa



C function (piecewise-quadratic)



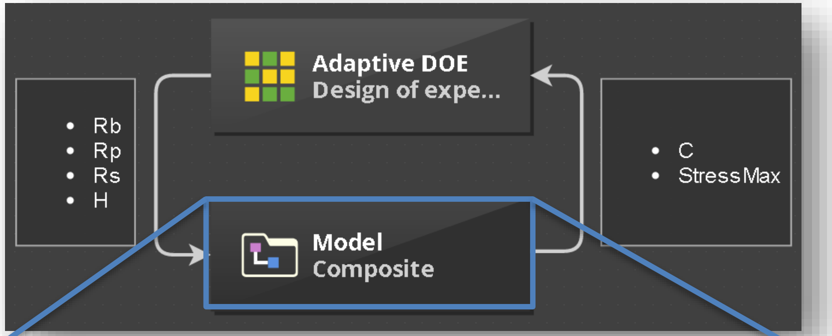
Stress in shroud (von-Mises)



Stress in root (von-Mises)

Adaptive DoE for Detuning: Automated Module

Detuning of selected eigenfrequencies away from resonance regions (set as a set of forbidden frequencies ranges).

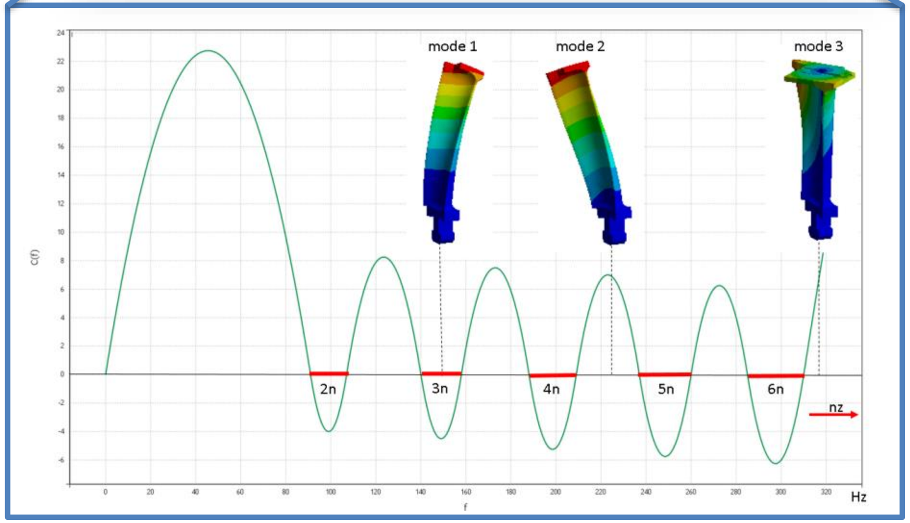


Input parameters:

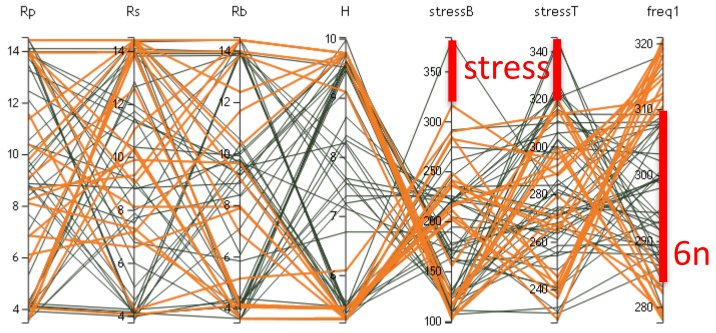
- Eigenfrequencies numbers for analysis
- Stress constraints values
- Variables in consideration and bounds

Optional settings:

- Custom forbidden ranges boundaries



Automated generation of the workflow and constraint function

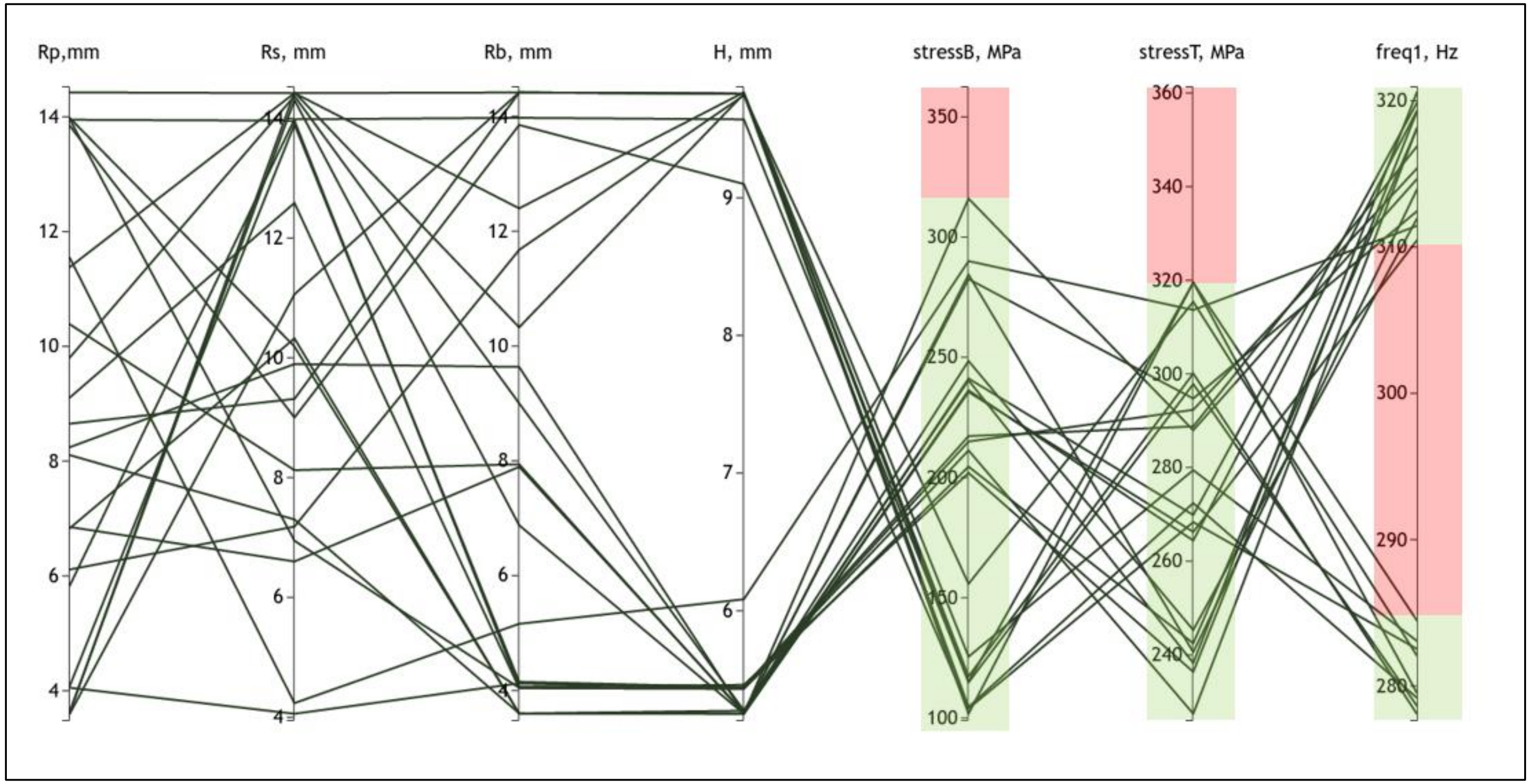


Results visualization

Adaptive DoE for Detuning: Results

Feasible geometry parameters and corresponding constraint values are presented on parallel coordinates plot.

- Designs are distributed almost uniformly and describe various geometries
- Adaptive DoE found **21 feasible** geometries from 80 simulation runs.
- For comparison, uniform DoE sample contained only **9 feasible** points.
- This advantage will only grow with extension of total simulation budget.



Feasible

Infeasible

Conclusions

- The automated module for rotor blades' eigenfrequencies detuning is introduced as a part of solution for simulation automation.

- Optimization problem statement was formulated for detuning routine and then solved using a novel effective adaptive DoE algorithm. Based on SBO methodology, it allows obtaining a variety of blades geometries away from resonance areas within limited evaluations budget.

- Problem statement can be easily extended for additional parameters and constraints. Together with full automation of the simulation for wide range of geometries and load cases, it makes the presented automated module a useful tool for simulation-based steam turbine design.