Ansys Turbomachinery modelling with Aeromechanics focus

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Ansys

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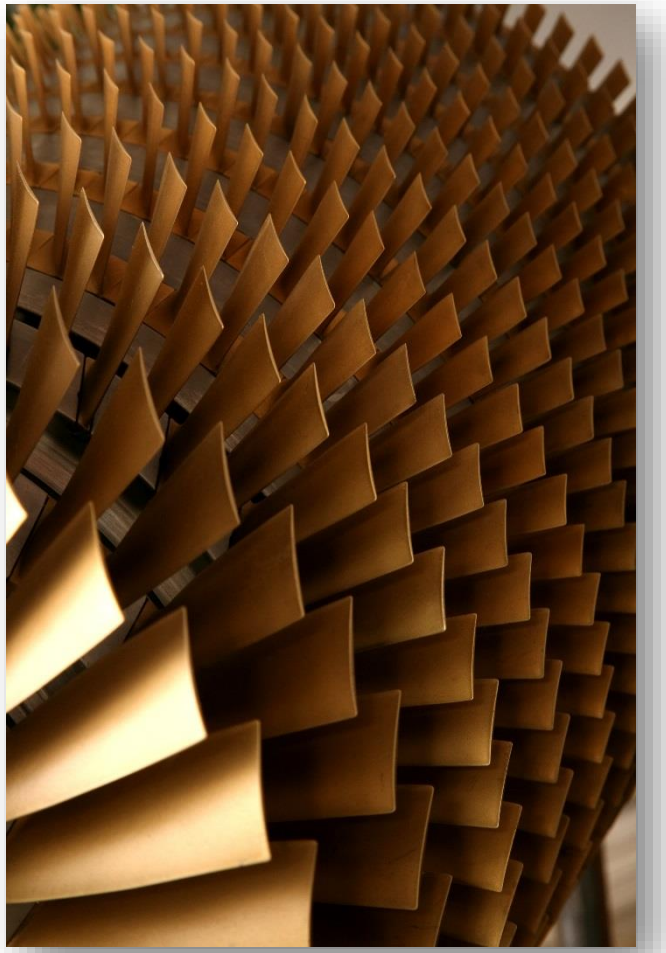
Agenda

- Overview, Challenges & Trends
- ANSYS Turbo Systems & Workflow
- Rotor/Stator Coupling
  - Steady State Models
  - Transient Models
- Aeromechanics
  - Flutter
  - Forced Response
  - Thermal, Static, Modal,…
- Automatization & Optimization

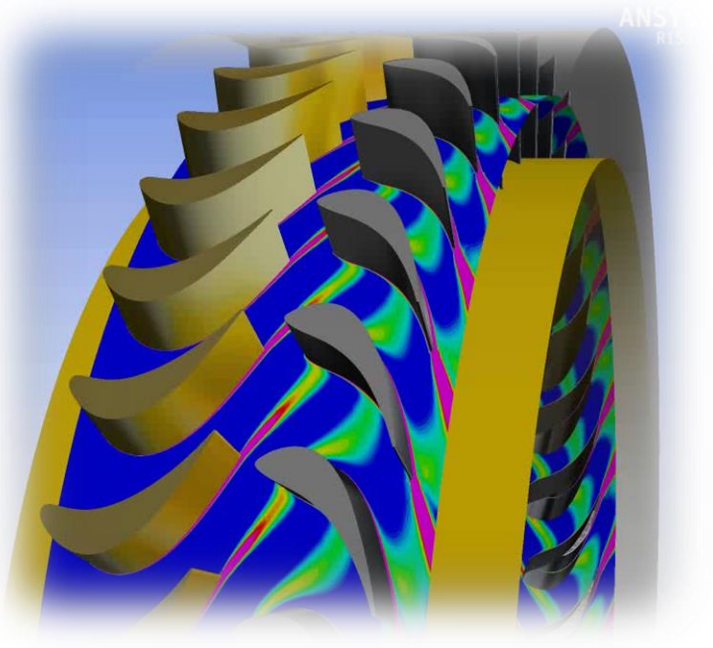


Overview, Challenges & Trends

Ansys

Turbomachinery Simulations Trends

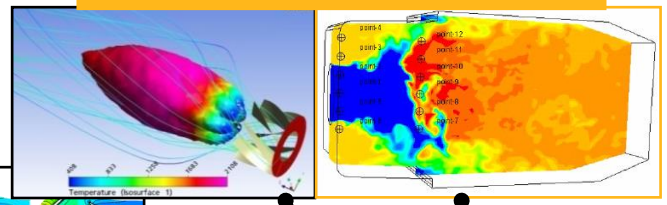
- Complex geometries
- Unsteady simulation
  - Rotor/stator interaction
  - Off design performance
  - Inlet distortion
  - Acoustics
- Multidisciplinary
  - Conjugate heat transfer
  - Aeromechanics



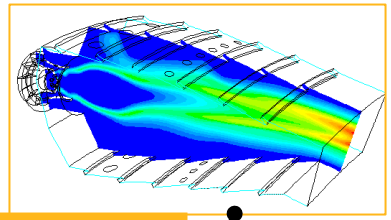
- Optimization & robust design
- Complete system simulation

Multidisciplinary Application

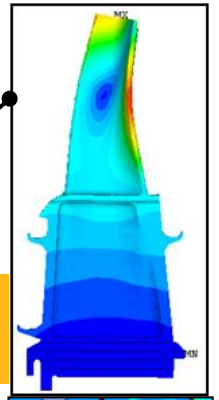
Combustion



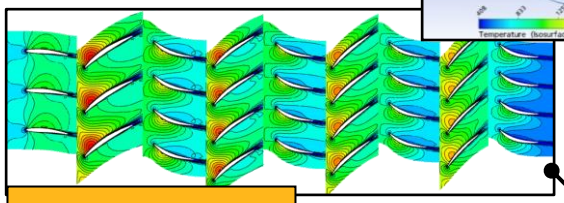
Emissions

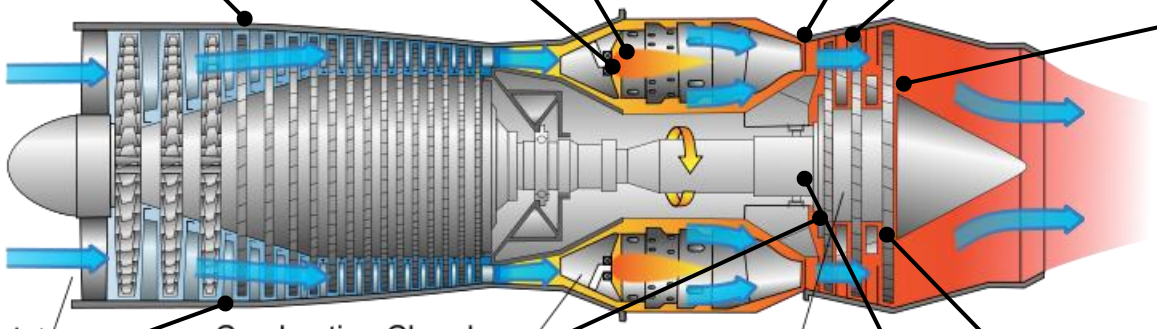


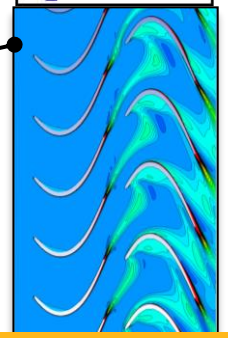
Modal Analysis



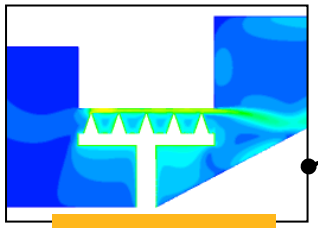
Compressor Aerodynamics



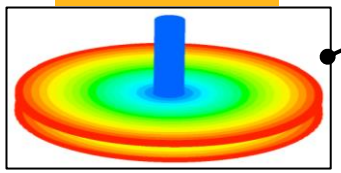




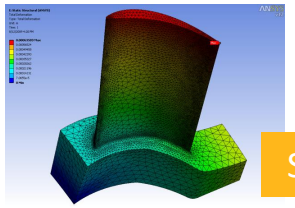
Turbine Aerodynamics

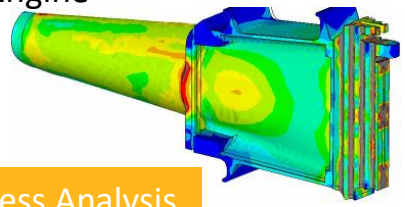


Disk & Seal Analysis

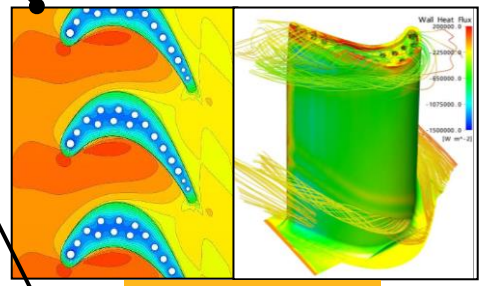


(CC) Rolls Royce plc: "The Jet Engine"



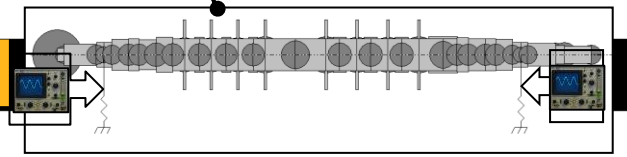


Stress Analysis



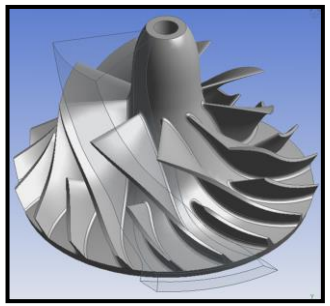
Heat Transfer

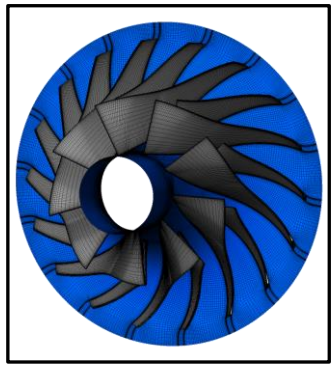
Rotordynamics

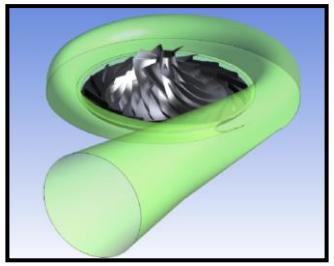


ANSYS Turbo Systems & Workflow

Design Workflow for a Centrifugal Compressor







Preliminary design with 1D tools or existing design

Impeller/rotor geometry

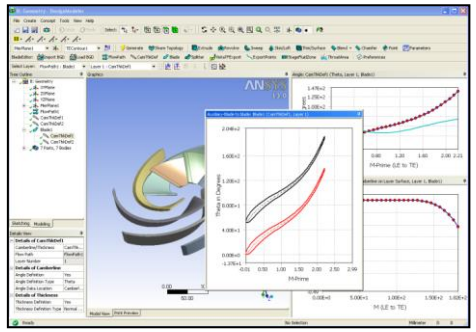
2D Throughflow analysis

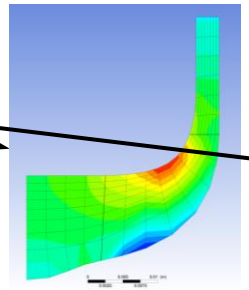
3D Grid generation

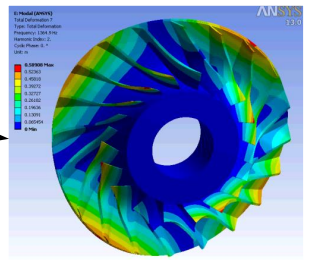
3D Stage CFD

Volute geometry + mesh

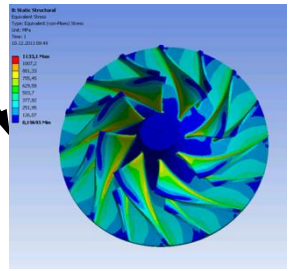
3D Stage + volute CFD





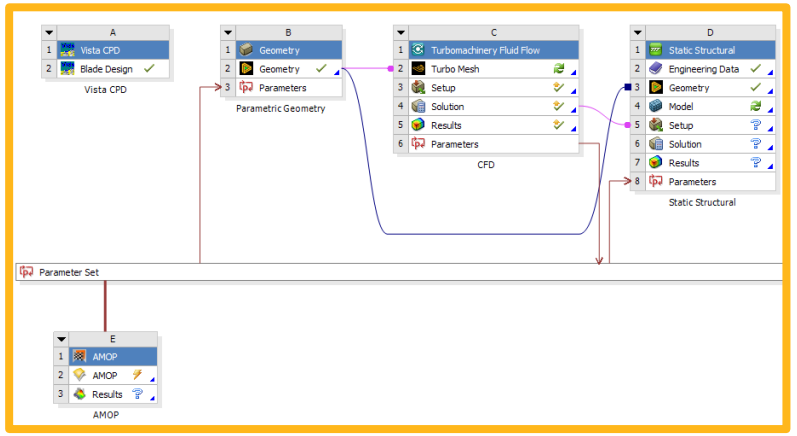


Modal analysis



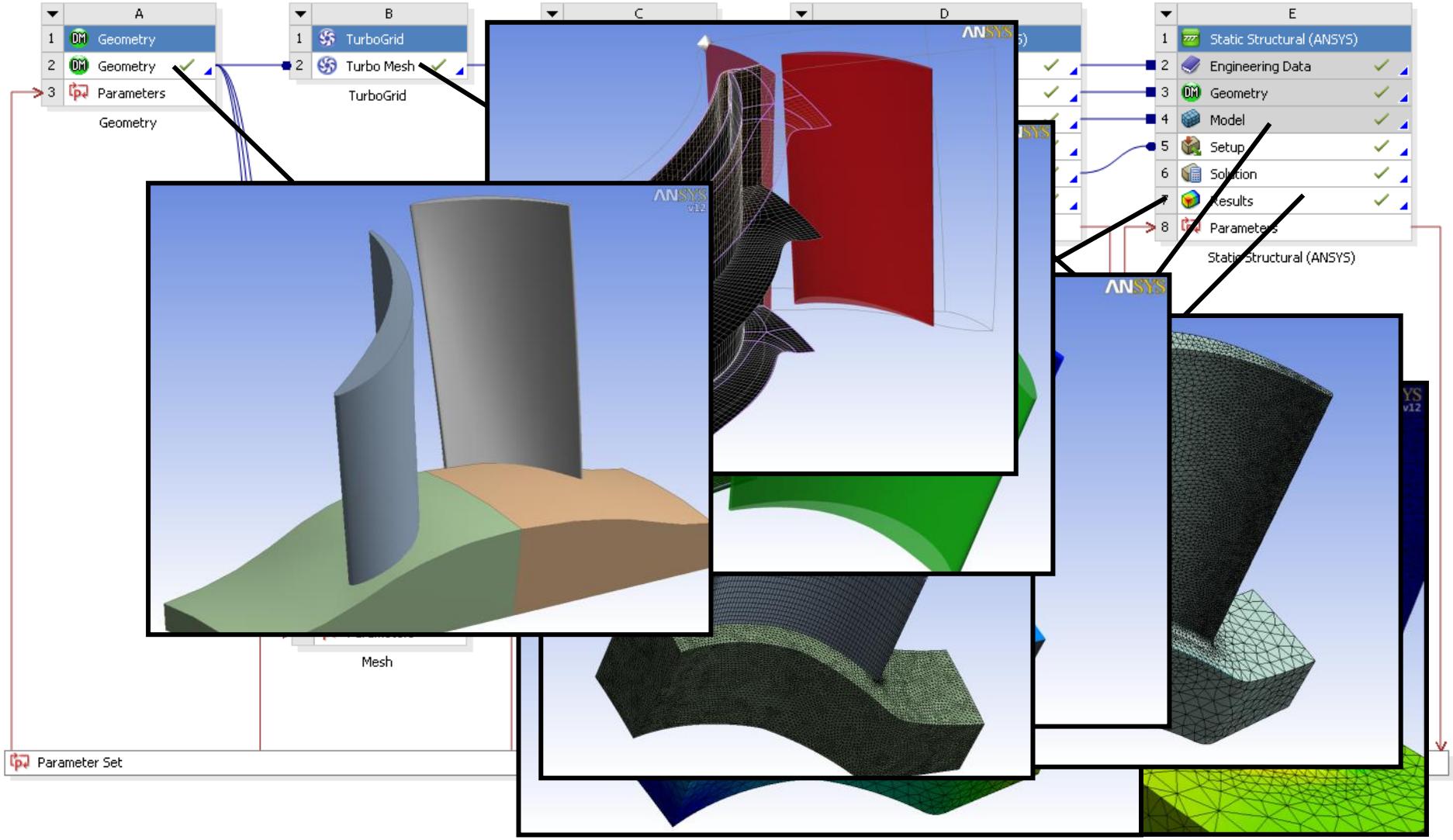
Stress analysis

Post-process results (quantitative & qualitative)



Ansys Workbench workflow for Compressor/Pump/Turbine Analysis

ANSYS Workbench – Parametric Workflow



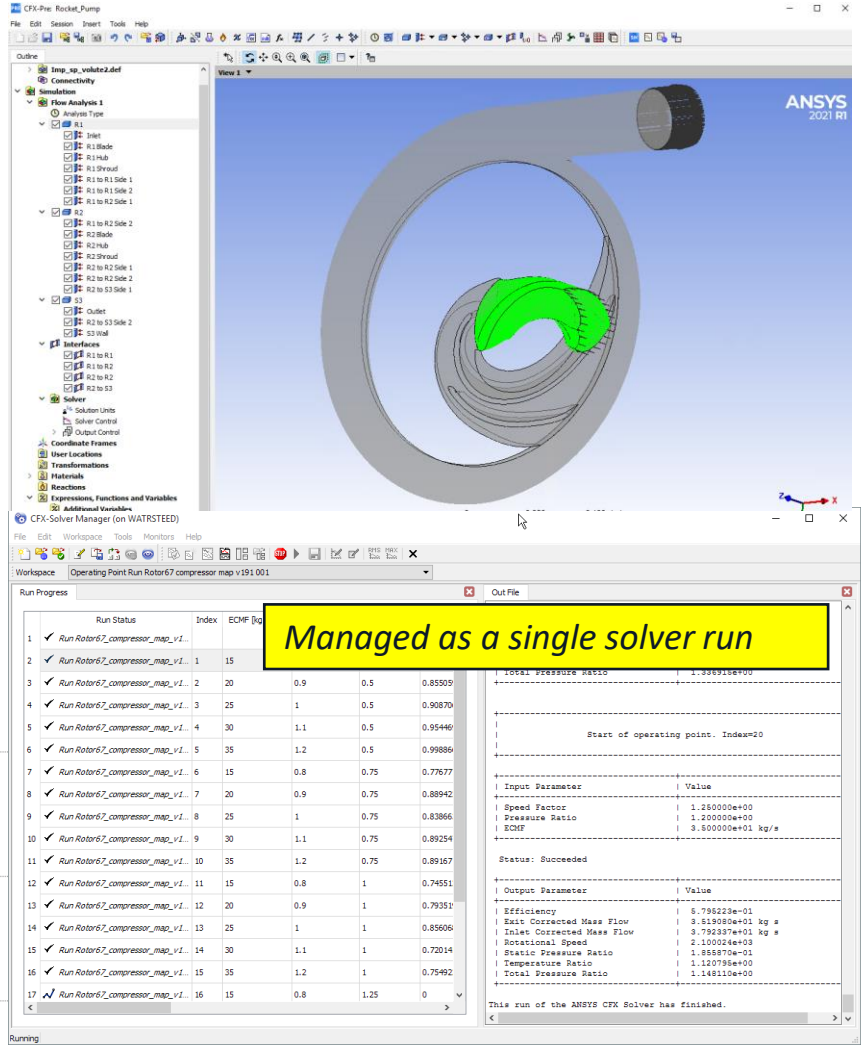
Automated Machine Performance prediction

Input data
(Geometry, Operating conditions)

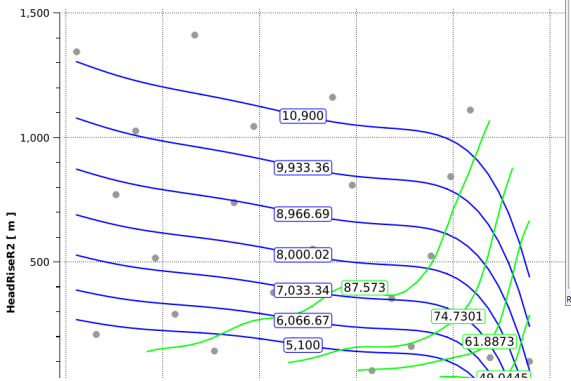
Generate **Mesh**es, Build **CFD Setup**

Run **Parallel CFD** Simulations

Performance map plot + Additional post-processing

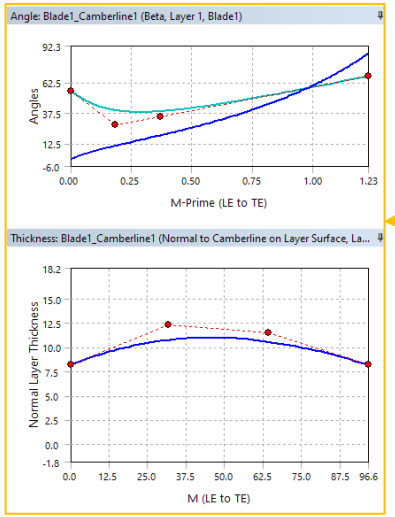


Managed as a single solver run

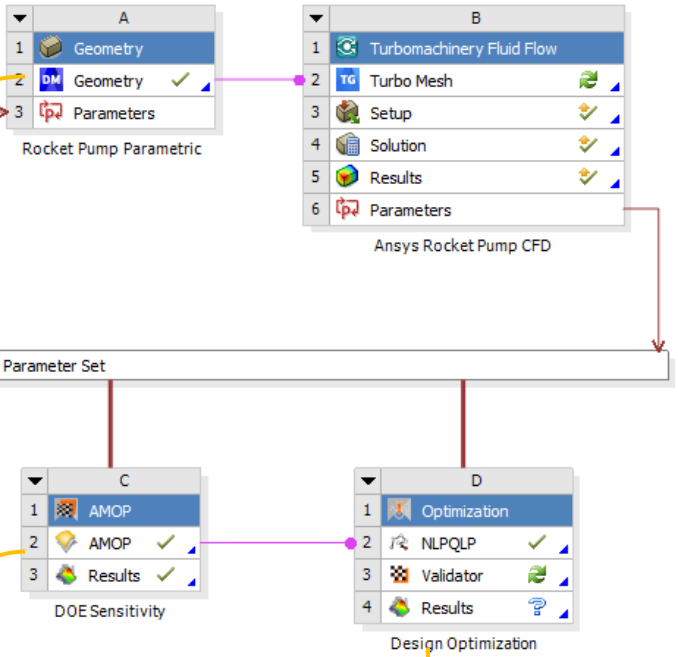


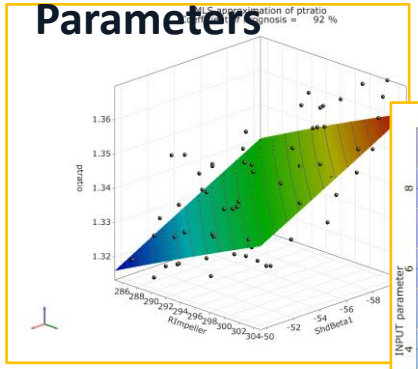
Accurate performance map generation in les than 30 minutes

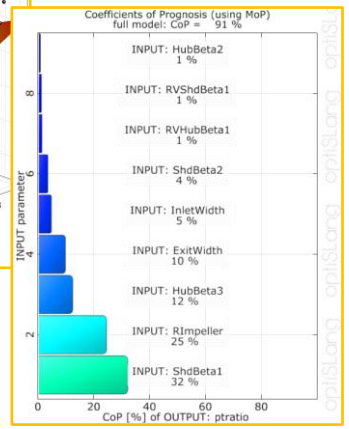
Aero-Mechanical Design Optimization



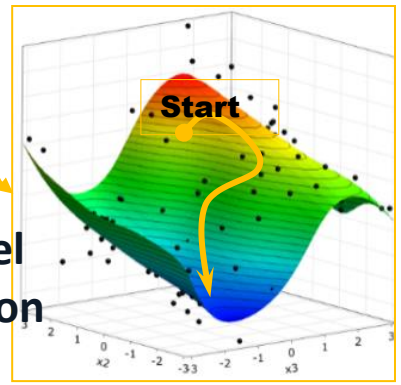
Design Parameters







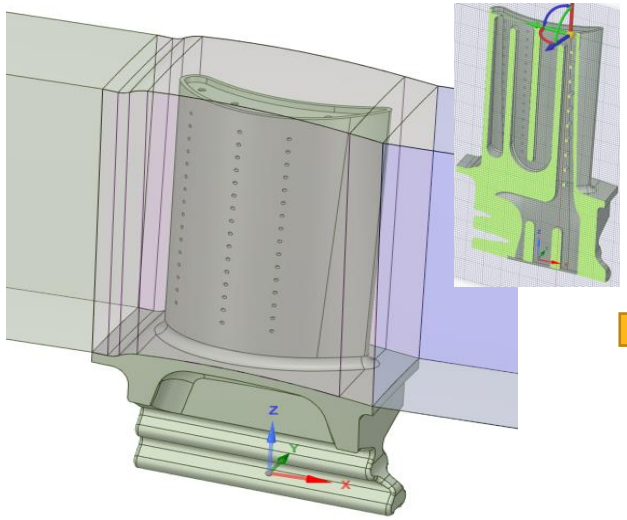
Important Design Parameters



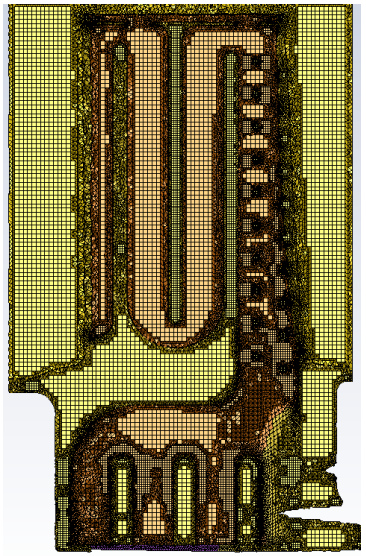
Metamodel optimization

Optimized Inducer & Impeller of a Rocket Pump (200 Design Points, run concurrently for 3 hour total wall clock time to get optimized design)

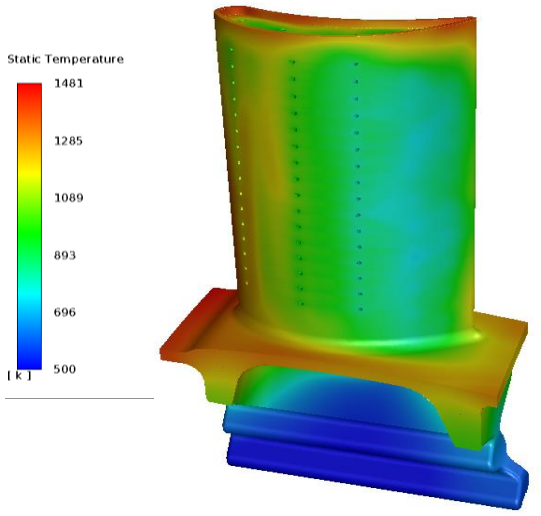
Conjugate Heat Transfer



Automated Geometry Clean-up and Volume Extraction

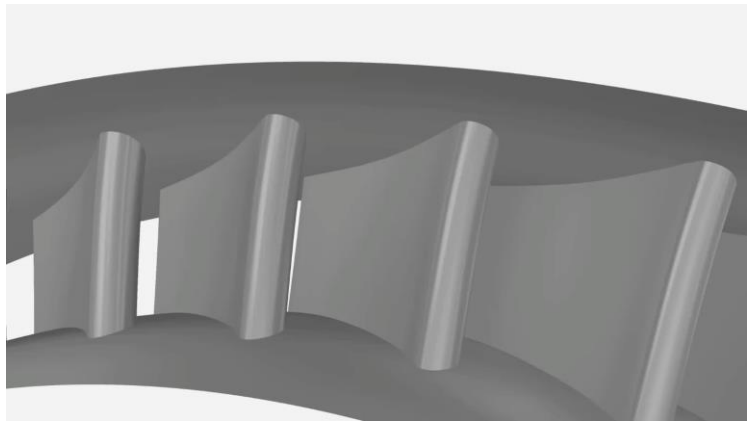


High Quality mesh in 5 minutes



CHT Results

- CHT with fast transient statistics
- Cooled blades and combustor liner durability
- Blade film cooling



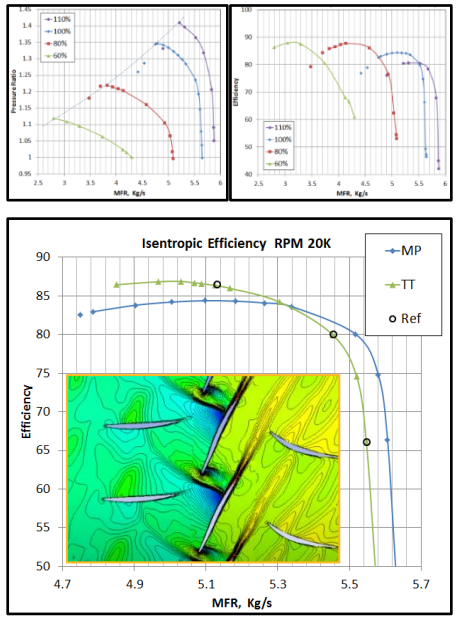
Blade Film Cooling

Rotor/Stator Coupling

Ansys

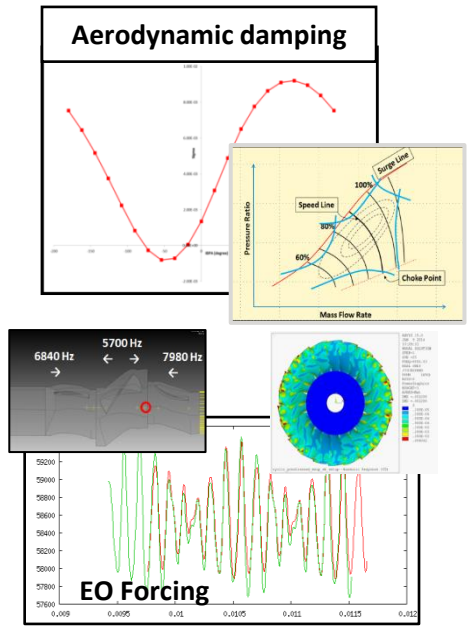
Turbomachinery Aero-Mechanical-Thermal Analysis

Aerodynamic Analysis

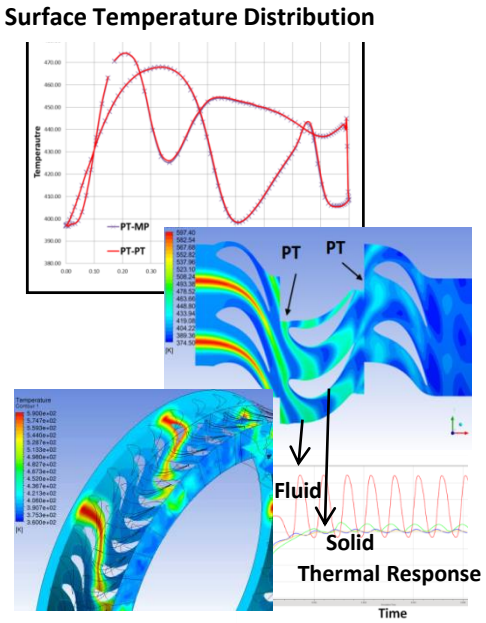


Steady & Transient

Aeromechanical Analysis



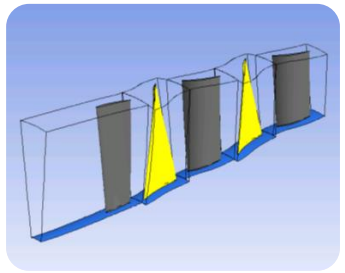
Aerothermodynamic Analysis



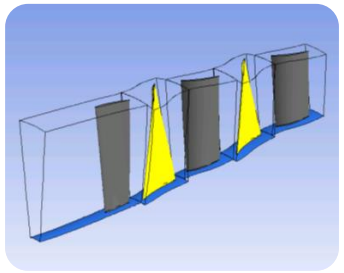
Transient

Steady State Rotor Stator Interfaces

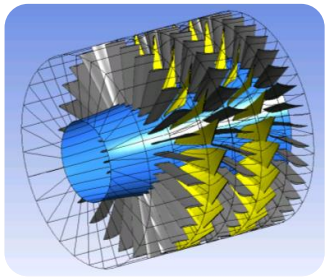
Steady pitch change



Transient pitch change



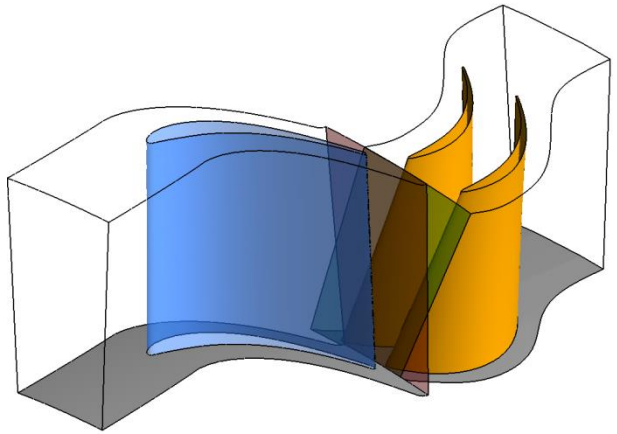
Transient full-annulus



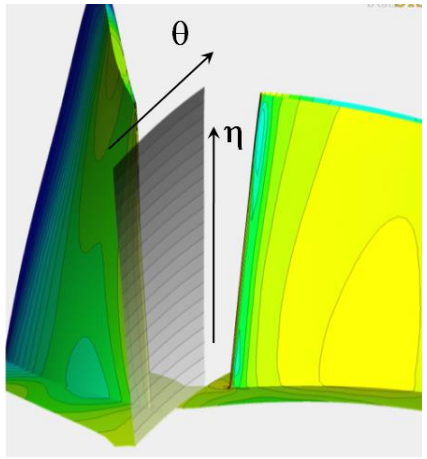
- Stage interface (mixing plane)
- Frozen rotor interface

Steady State – Stage Interface (Mixing Plane)

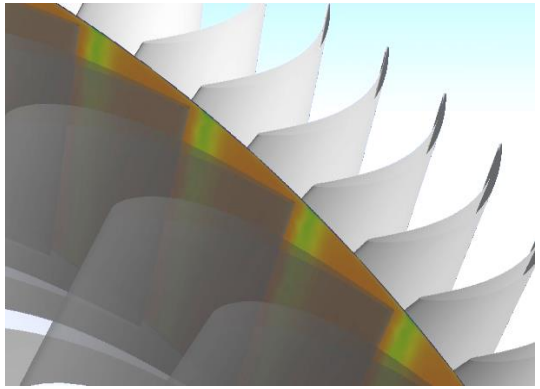
- Industry standard for steady state prediction of aerodynamic performance
- Blade pitch change via conservative “mixing” process in circumferential direction



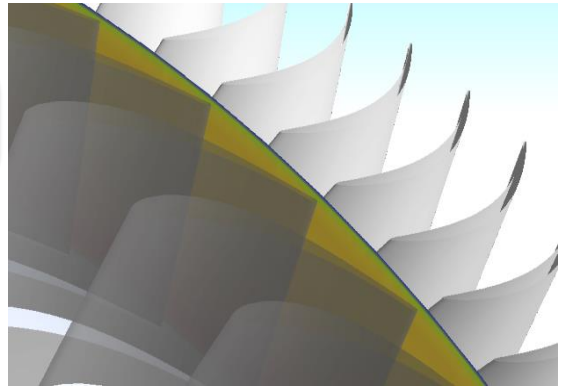
Upstream interface side



Downstream interface side

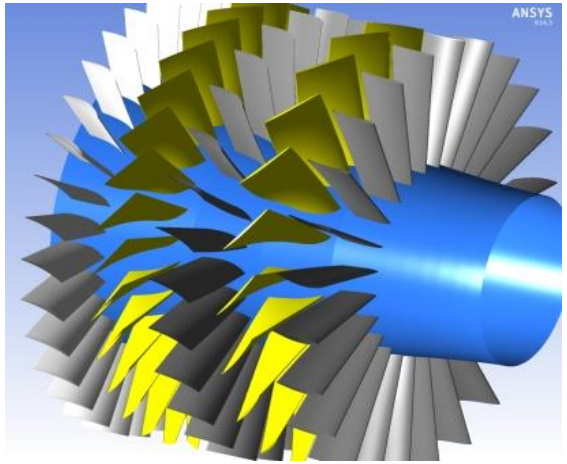


Mixing



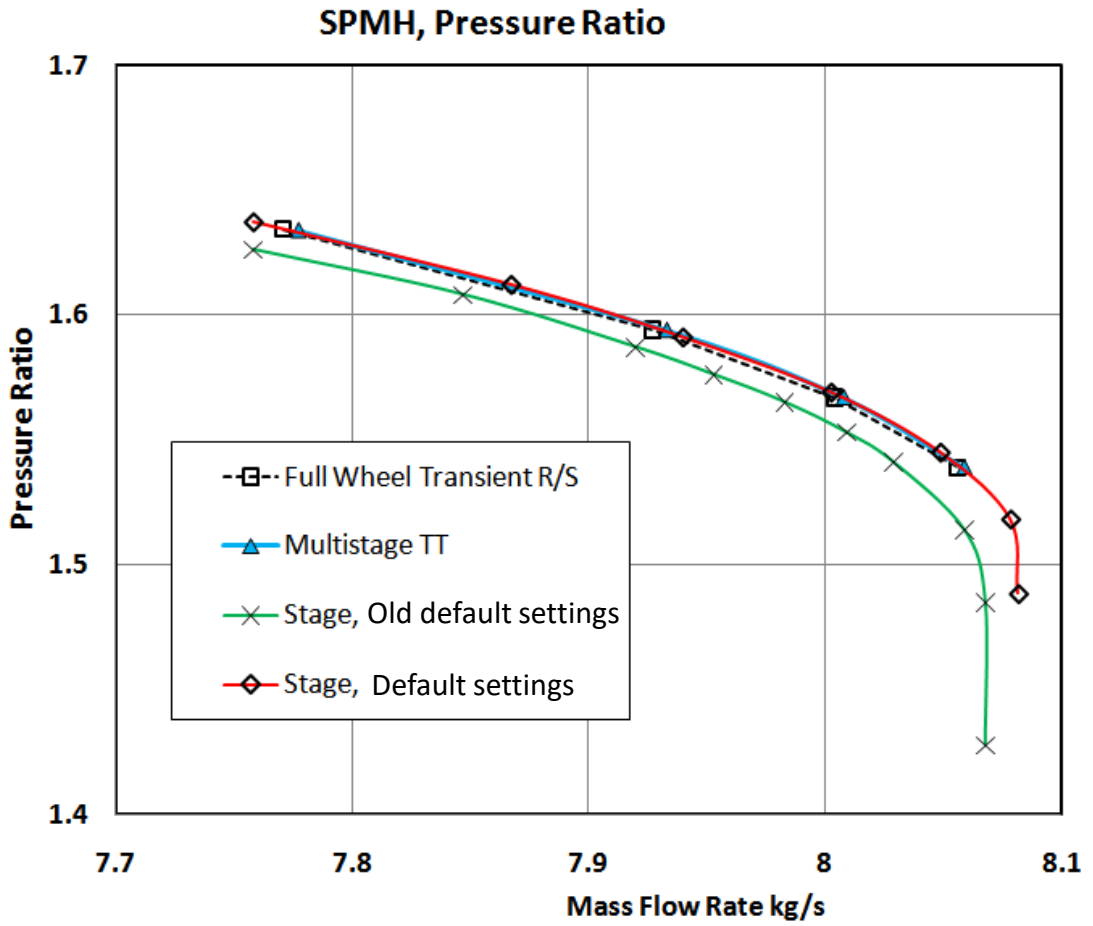
Example – 2.5 Stage Axial Compressor

Hannover compressor with modified blade counts



Design rotational speed	17100 rpm
Mass flow rate	7.82 kg/s
Total pressure ratio	2.7
Isentropic efficiency	89.8%
Inlet total pressure	60 kPa
Inlet Mach number	0.5

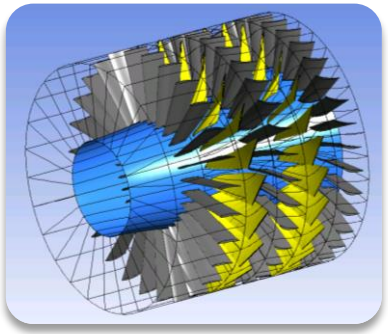
Ref. 1/3 wheel	11.6 mil nodes
TT, PT, mixing-plane	1.3 mil nodes



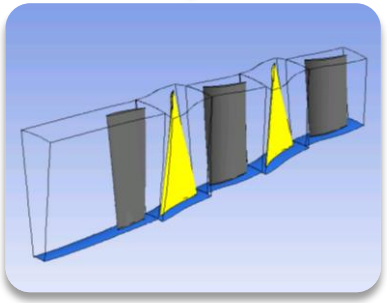
Transient Blade Row Simulations

Solve on Reduced Geometry

Full-wheel Model

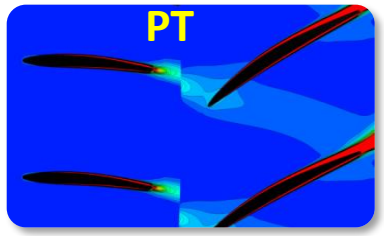


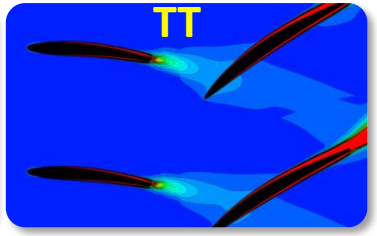
Reduced Model

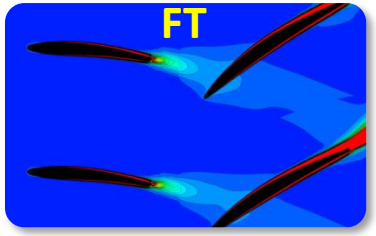


ANSYS CFX transient pitch-change models

Profile Transformation (PT)	Time Transformation (TT)	Fourier Transformation (FT)
Small/Moderate Pitch	Small/Moderate Pitch	Large Pitch
• Single Stage • Multistage	• Frozen gust • Single Stage • Multistage	• Frozen gust • Single Stage • Multistage • Blade Flutter





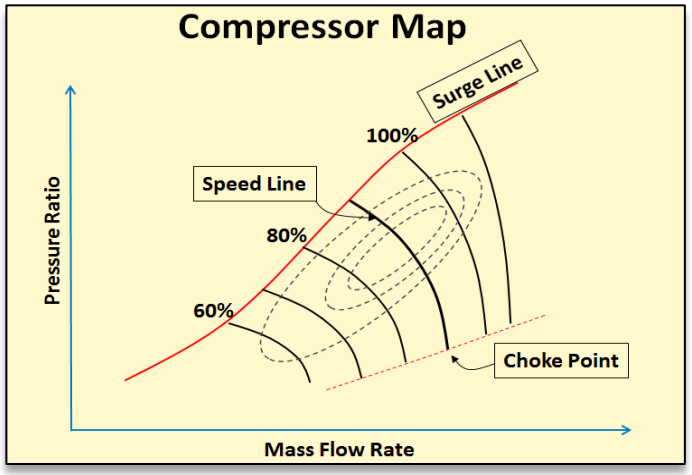


Transient interaction

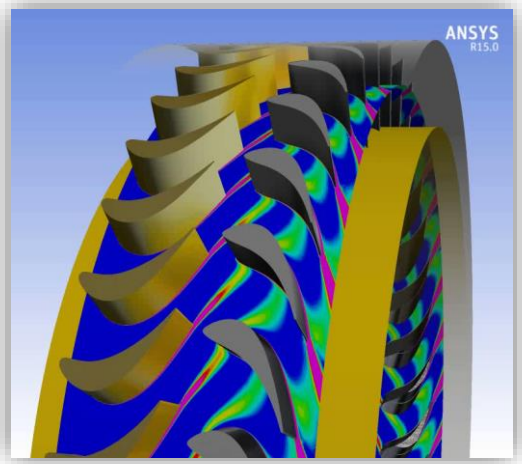
Transient interaction + Correct blade passing frequencies

Transient Applications

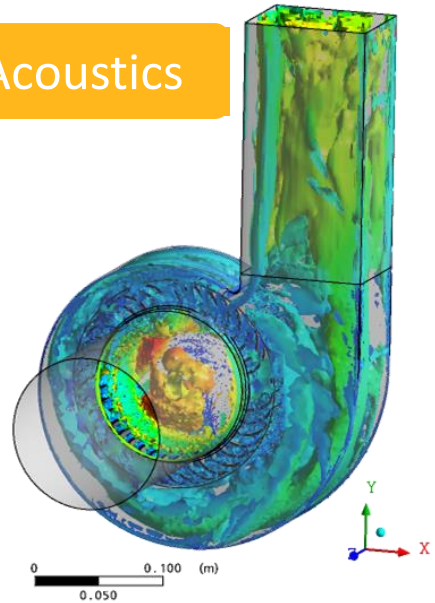
Better performance prediction



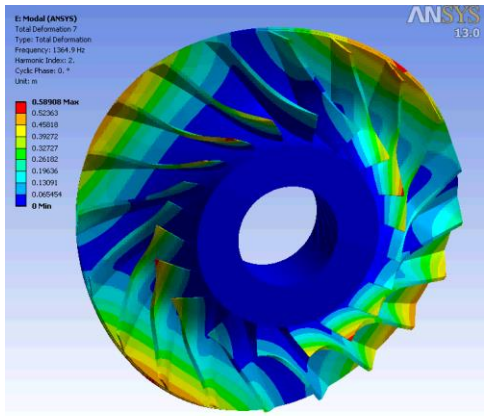
Unsteady interactions



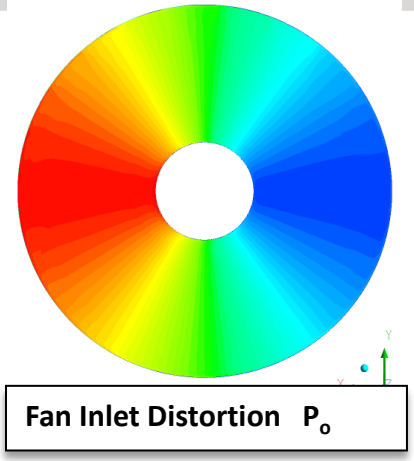
Acoustics



Aeromechanics

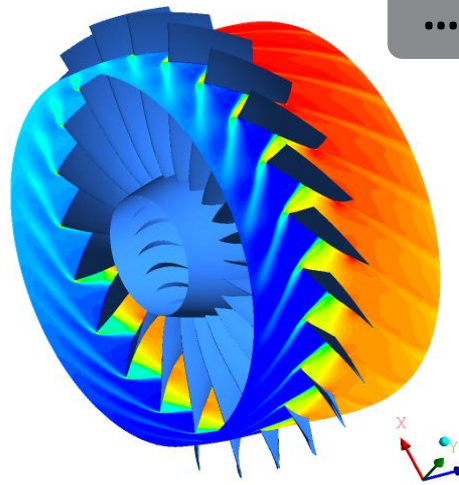


Asymmetric geometr



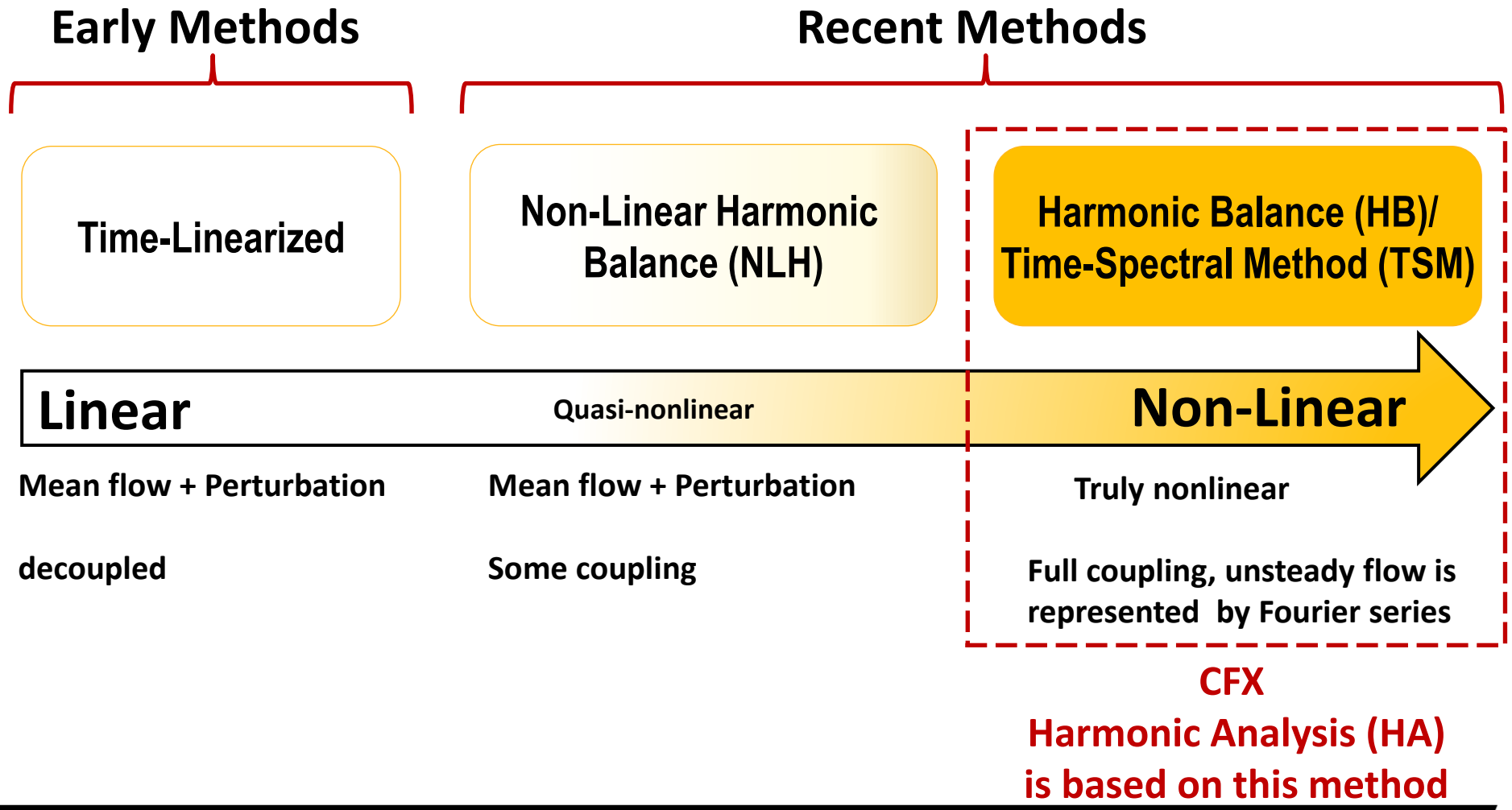
Fan Inlet Distortion P_o

...



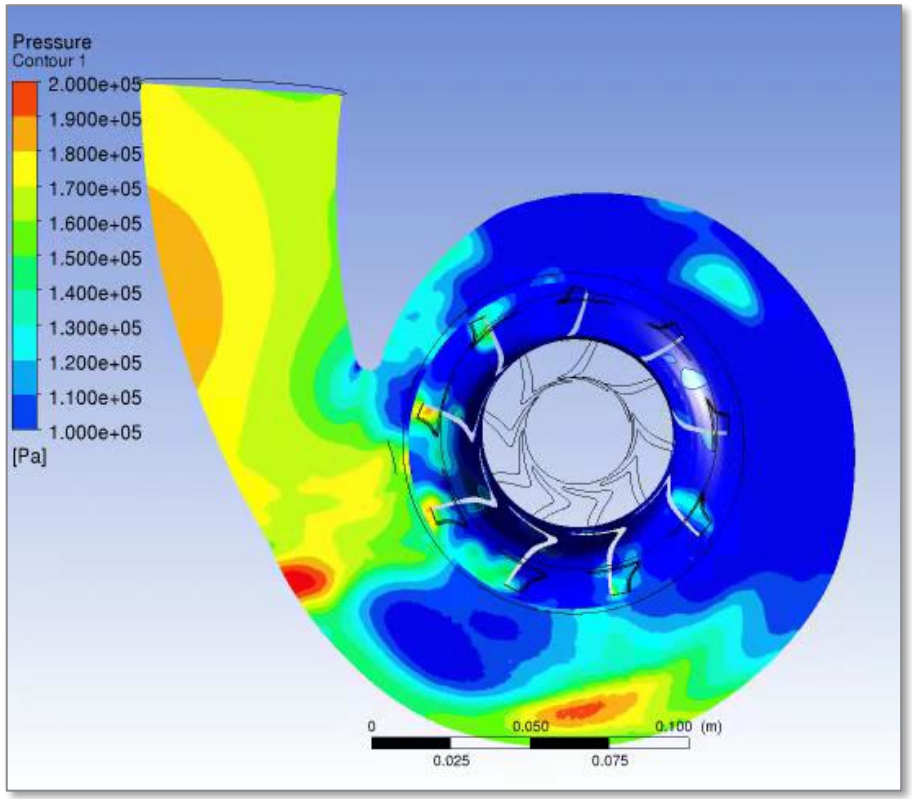
Transient Blade Row Simulations

Frequency Based Methods in CFD Codes

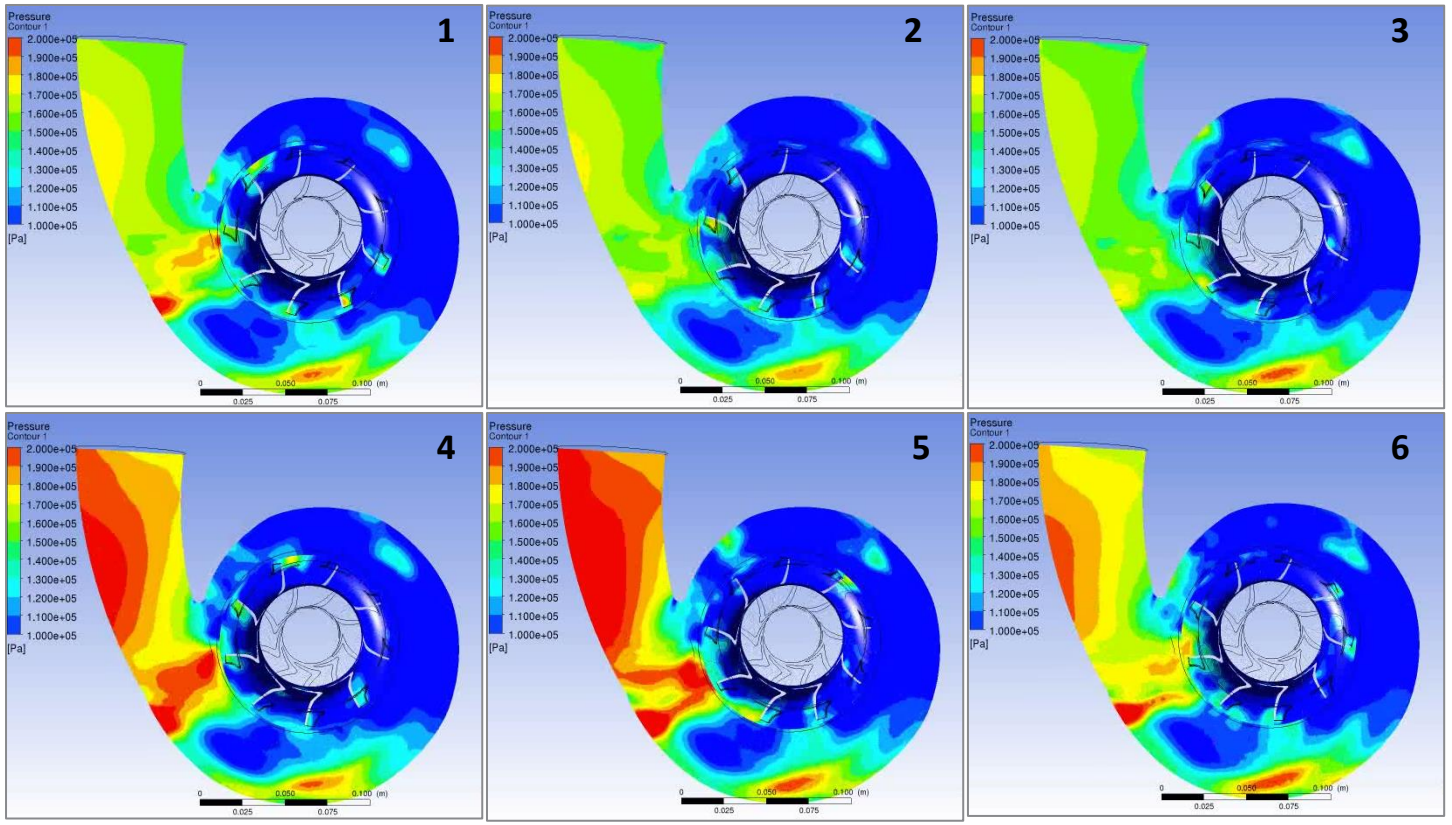


Harmonic Balance accelerates transient analysis

Harmonic Analysis captures transient behavior for turbocharger turbines and 100X faster



Animation of inlet pulse captured with Harmonic Analysis



Evolution of pressure during inlet pulse cycle

Geometry courtesy of PCA Engineering

Aeromechanics

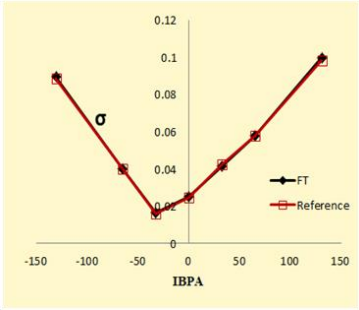
Ansys

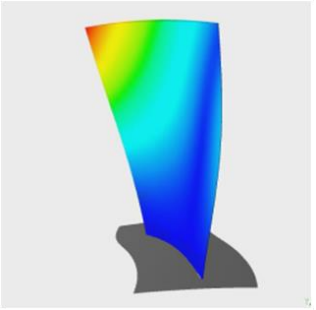
Aeromechanical Analysis

- Fatigue and fracture of rotating components is a challenge for industry
  - High temperature environment
  - Highly stressed
  - Low damping
  - Many vibration cycles
- Industry trends point towards light weighting
  - More integrally bladed rotors
  - Wear or damage can demand complete replacement
    - Maintenance/downtime costs can be very high
  - Slender blades can be more susceptible to failure
- Advanced aeromechanical simulation is becoming standard practice
  - Demands a standard commercial tool that is easy to use for design engineers

Severe damage to bladed disk (*Zielinski, 2005*)

Aeromechanical Simulations





Fluid Structure Interaction (FSI)

CFD ⇄ **FEM**

Expensive

Alternate more practical 1-way FSI models

Blade Flutter Analysis (Aerodynamic Damping)

- Blade oscillation is specified (Modal analysis)
- Compute Aero-damping based on work done on the blade by the fluid (CFD)

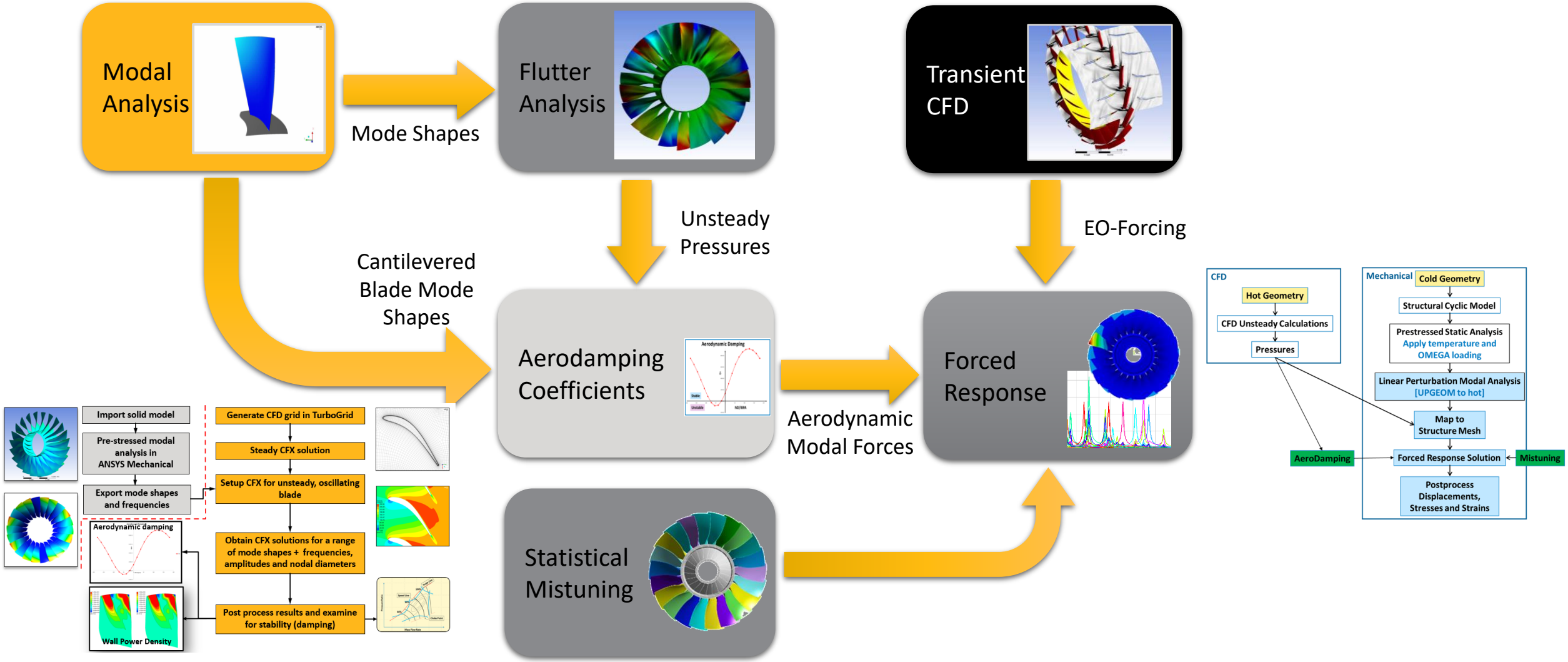
Can predict if blade <u>will</u> or <u>will not</u> flutter

Forced Response Analysis

- Excitation forces obtained from blade row (CFD)
- Compute blade response such as motion and stress level when subjected to these excitations (MSUP Harmonics).

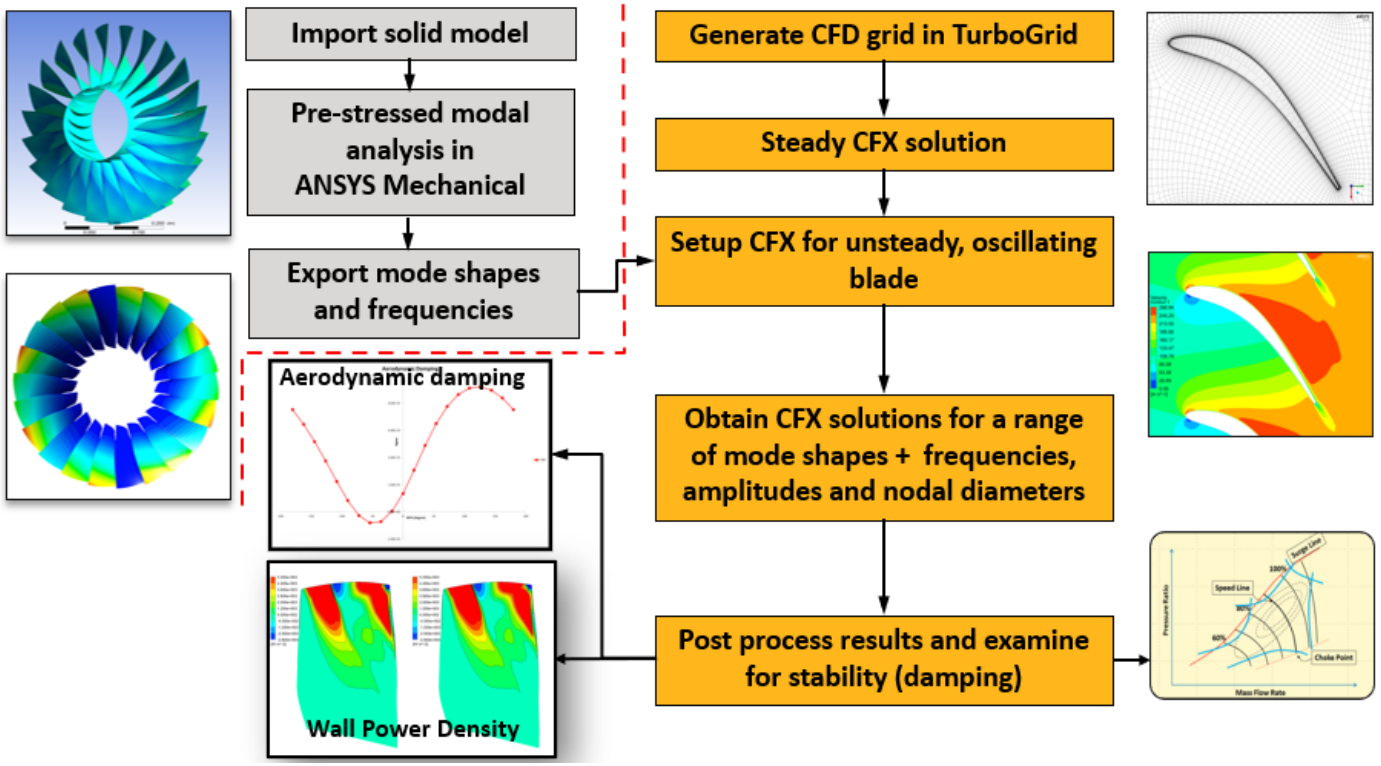
Can predict blade motion & when structure will fail

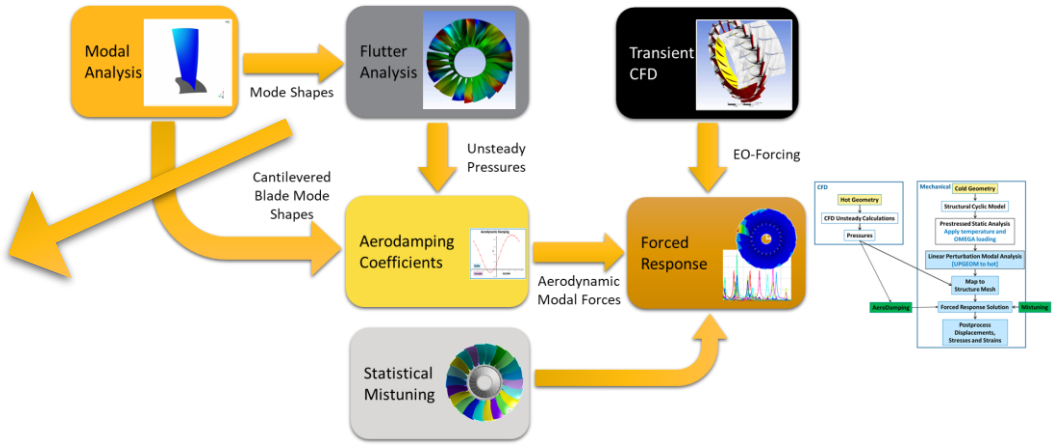
Aeromechanics Workflow



Seamless, streamlined, validated, Flutter and Forced Response Workflows

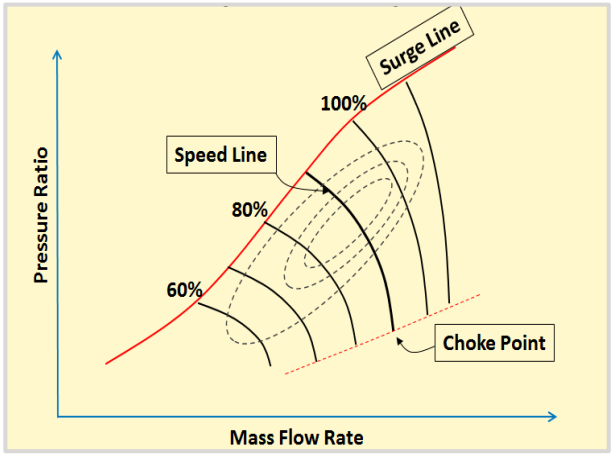
Aeromechanics Workflow – “Aero” side



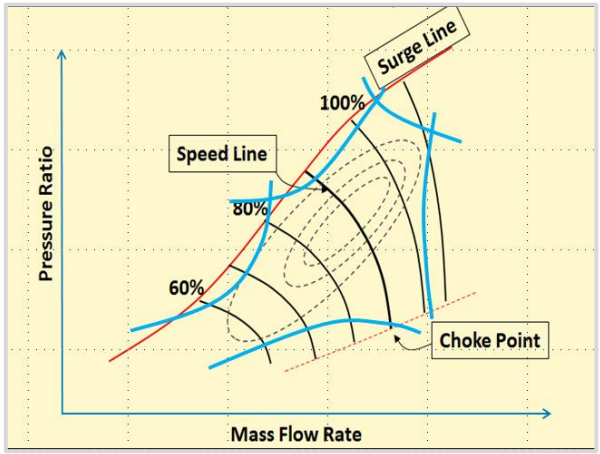


Blade Flutter & Aerodynamic Damping Calculations

Blade Flutter Analysis:
Determine if the aero loads will damp out blade vibration at natural frequencies



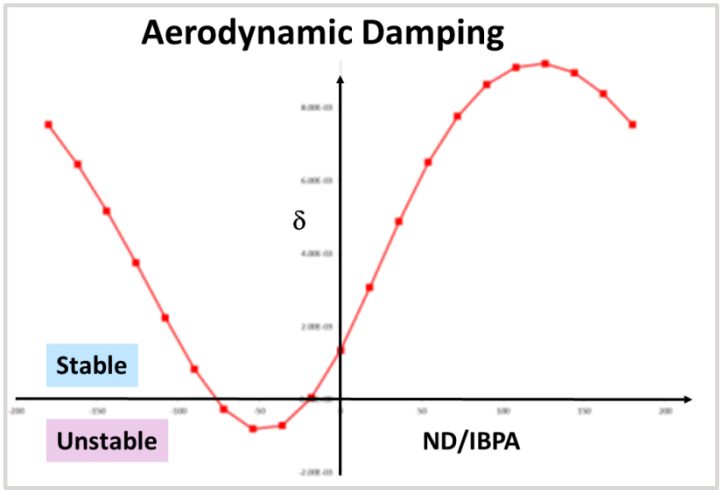
Performance map based on aerodynamic analysis

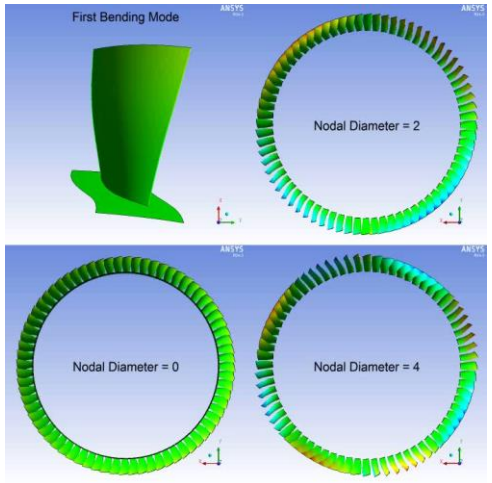


Performance map based on Aeromechanical analysis

Flutter Margin

Aerodamping in Forced Response analysis

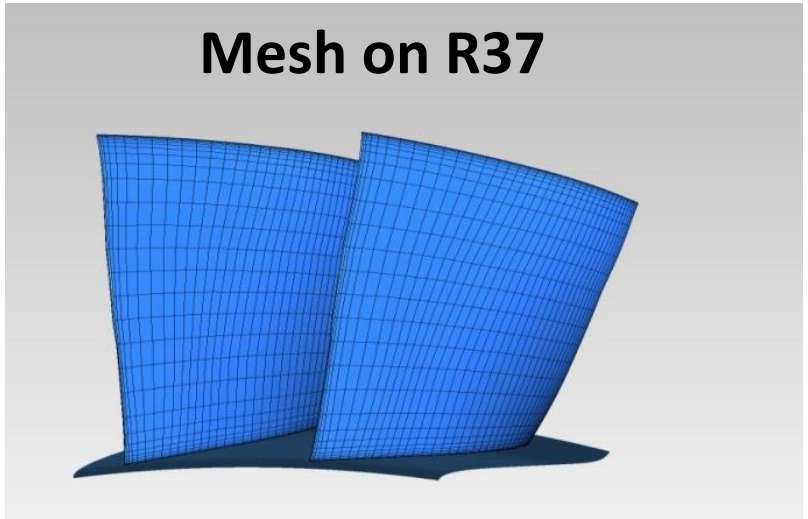


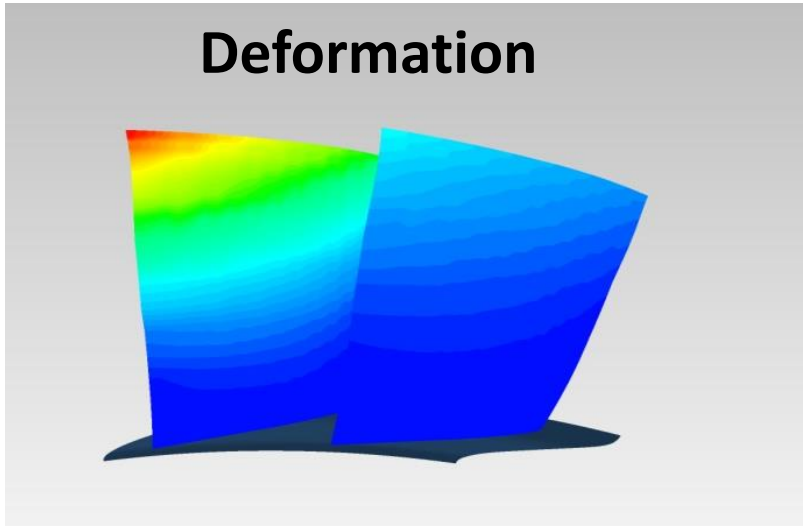


Harmonic Analysis (FT Pitch-Change) Blade Flutter/ Aero-damping

- Rotor 37 axial compressor
- 36 rotor blades
- Rotation= 1800 rad/s
- Blade vibration:
  - From ANSYS Mechanical Modal analysis
  - 1st Bending, frequency=1152.13 Hz
  - Max displacements = 0.00129 m

Test objective is to compare HA-FT to Transient-FT solution
- Aero-damping values
- Computation efficiency

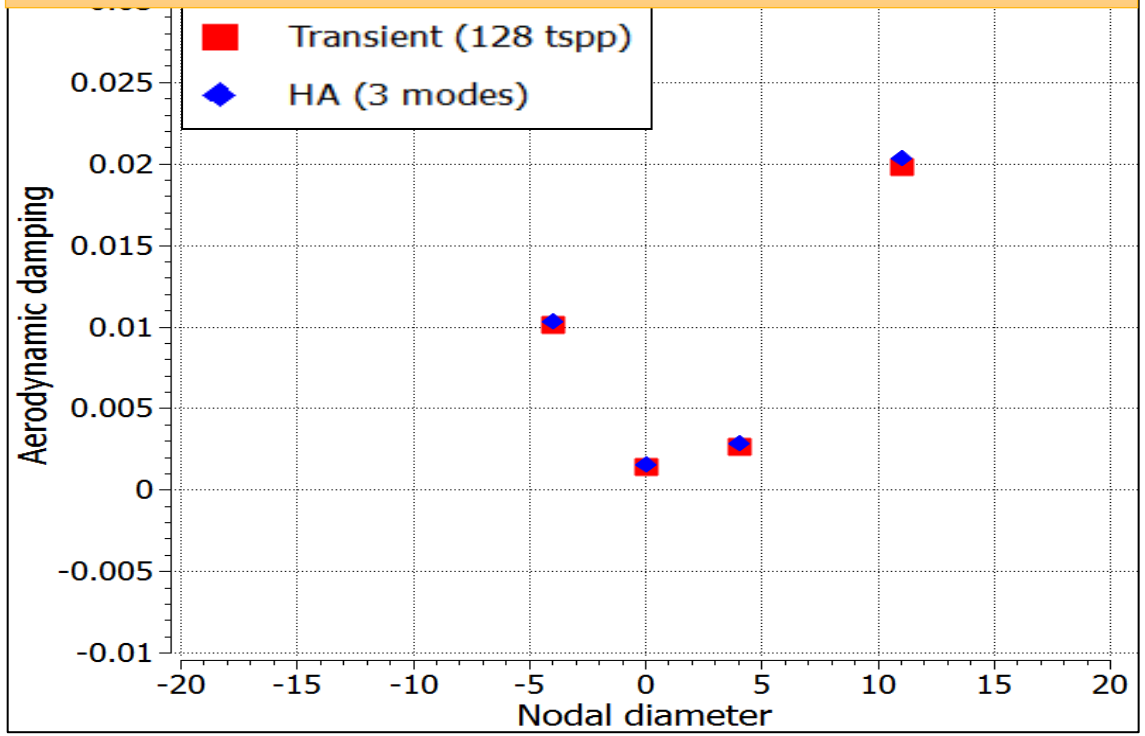




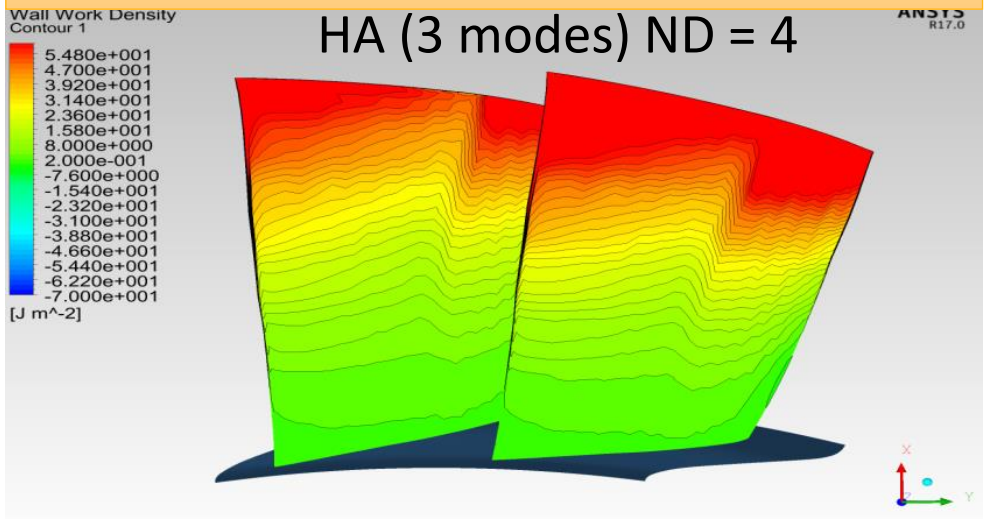
Harmonic Analysis (FT Pitch-Change) Blade Flutter/ Aero-damping

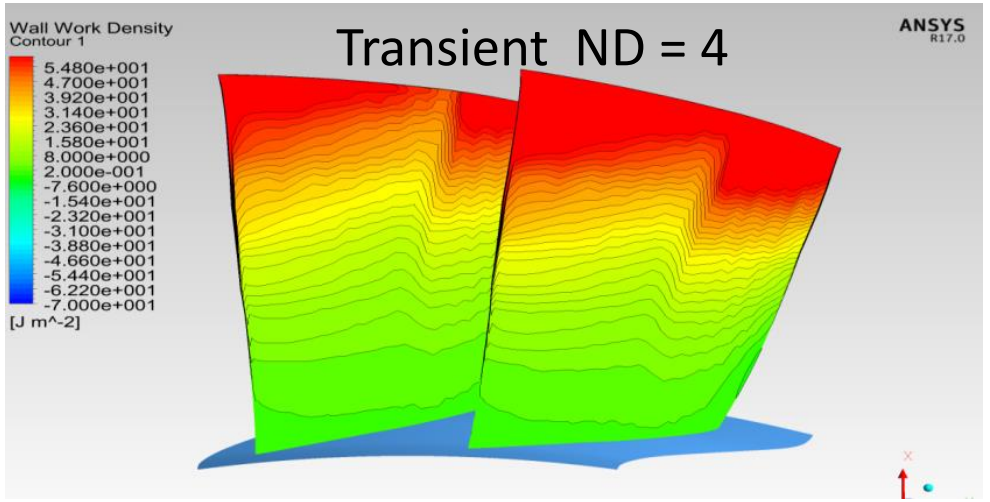
Aero-damping comparison

Aero-damping HA-FT vs Transient -FT

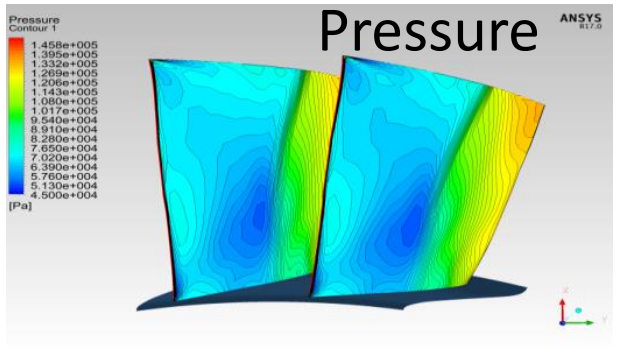


Work Wall Density



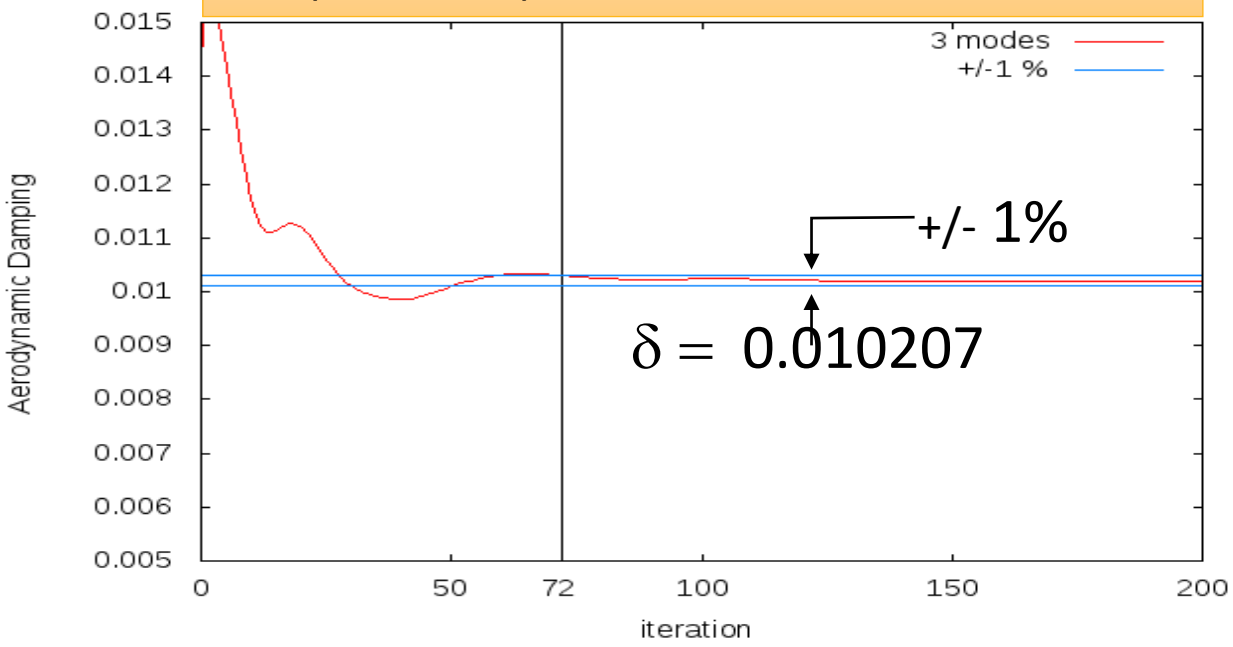


Harmonic Analysis (FT Pitch-Change) Blade Flutter/ Aero-damping

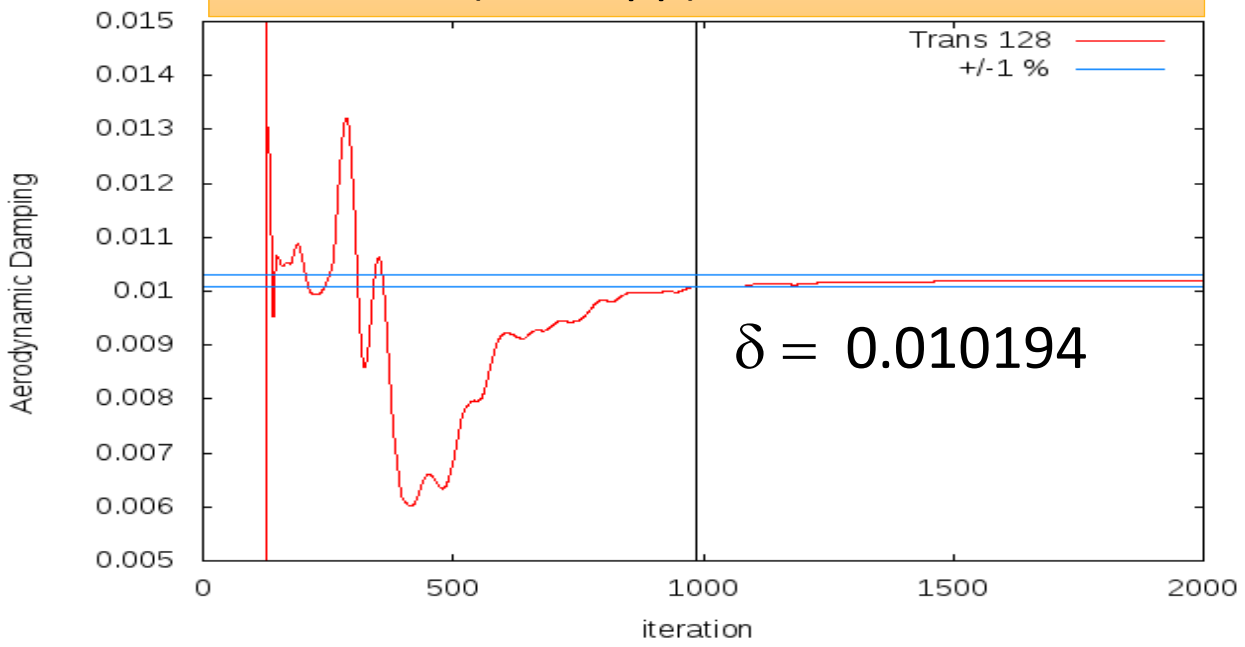


Convergence comparison

HA (3 modes) ND = -4

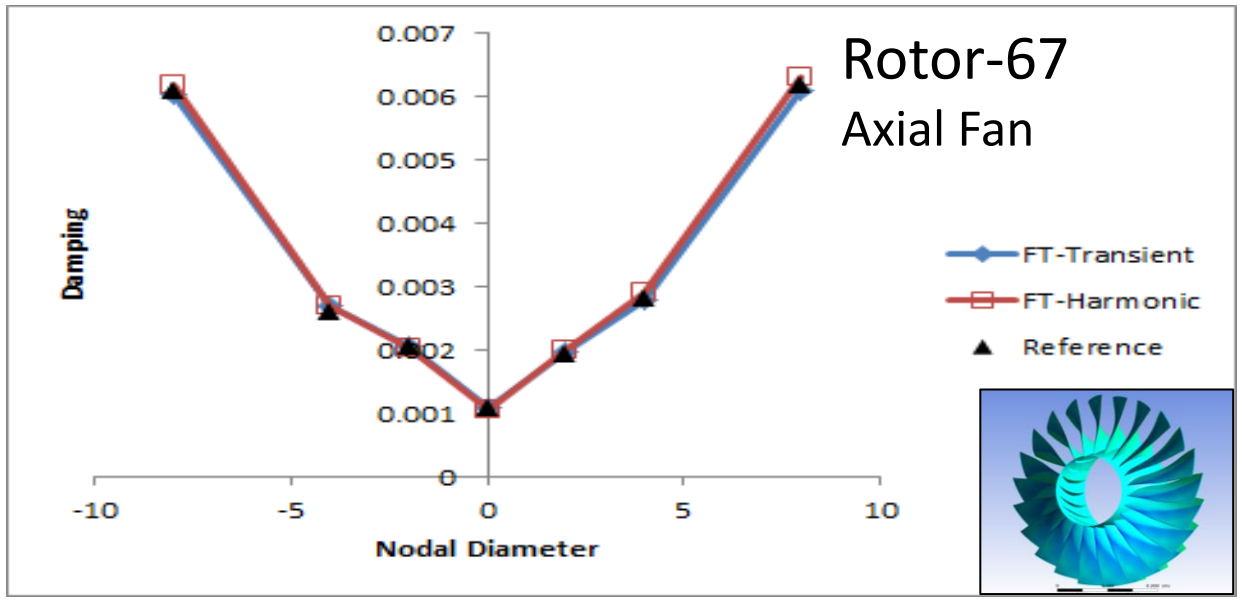


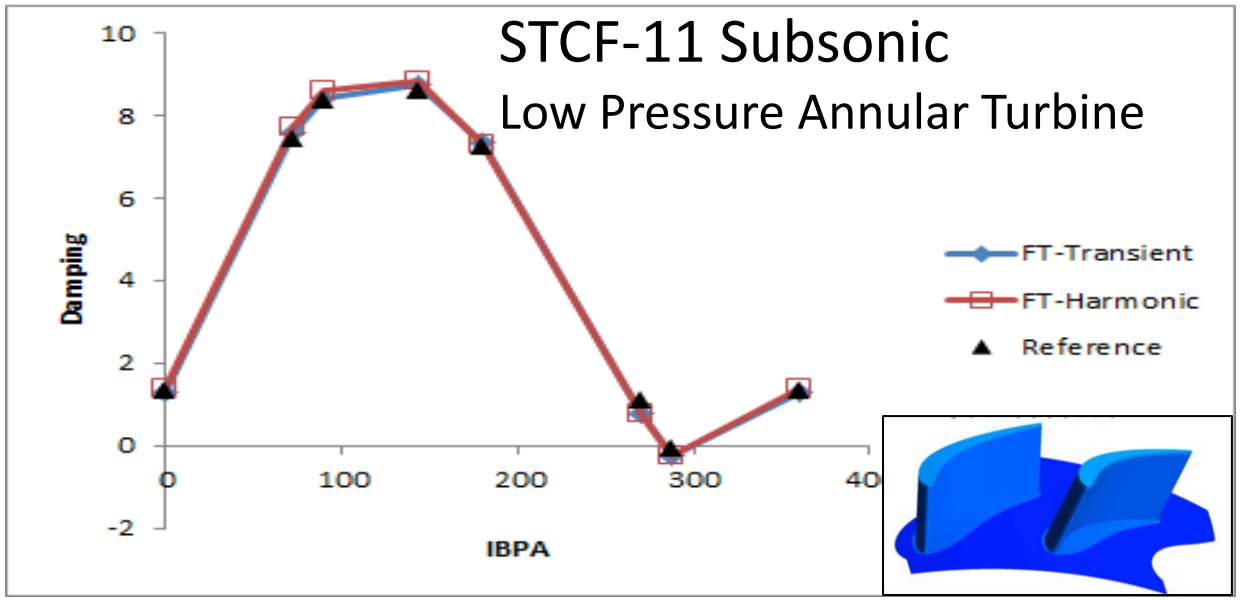
Transient (128 tspp) ND = -4



FT-HA (3 modes) 16X faster than FT-Transient

Harmonic Analysis (FT Pitch-Change) Blade Flutter/ Aero-damping

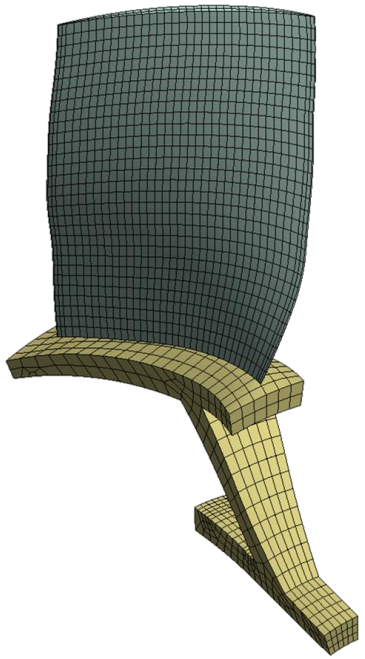




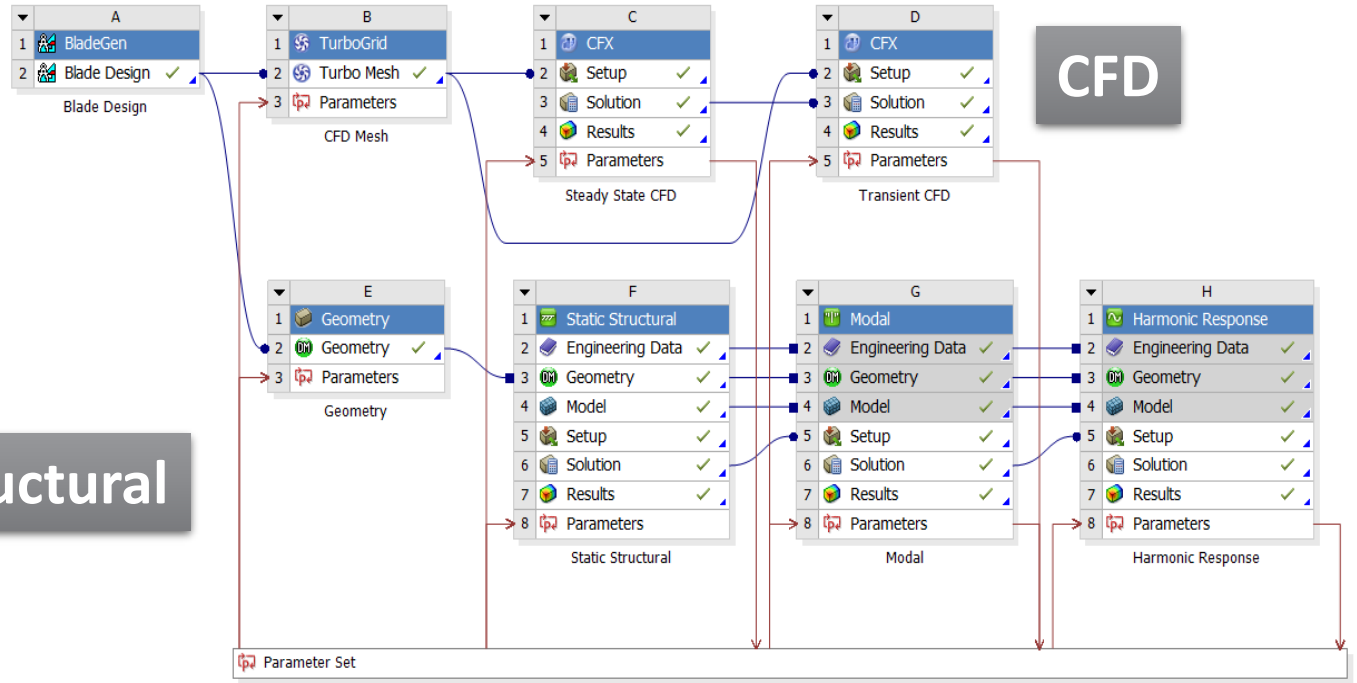
- All Calculations done with 1 mode , 15 pseudo-time-step per oscillation cycle
- starting from steady-state solution
- FT-HA (1 mode) about 20x to 30x Faster than FT-Transient (based +100 tspp)
- FT-Transient about 5x to 7x faster than Full-wheel solution

10-to-100X faster

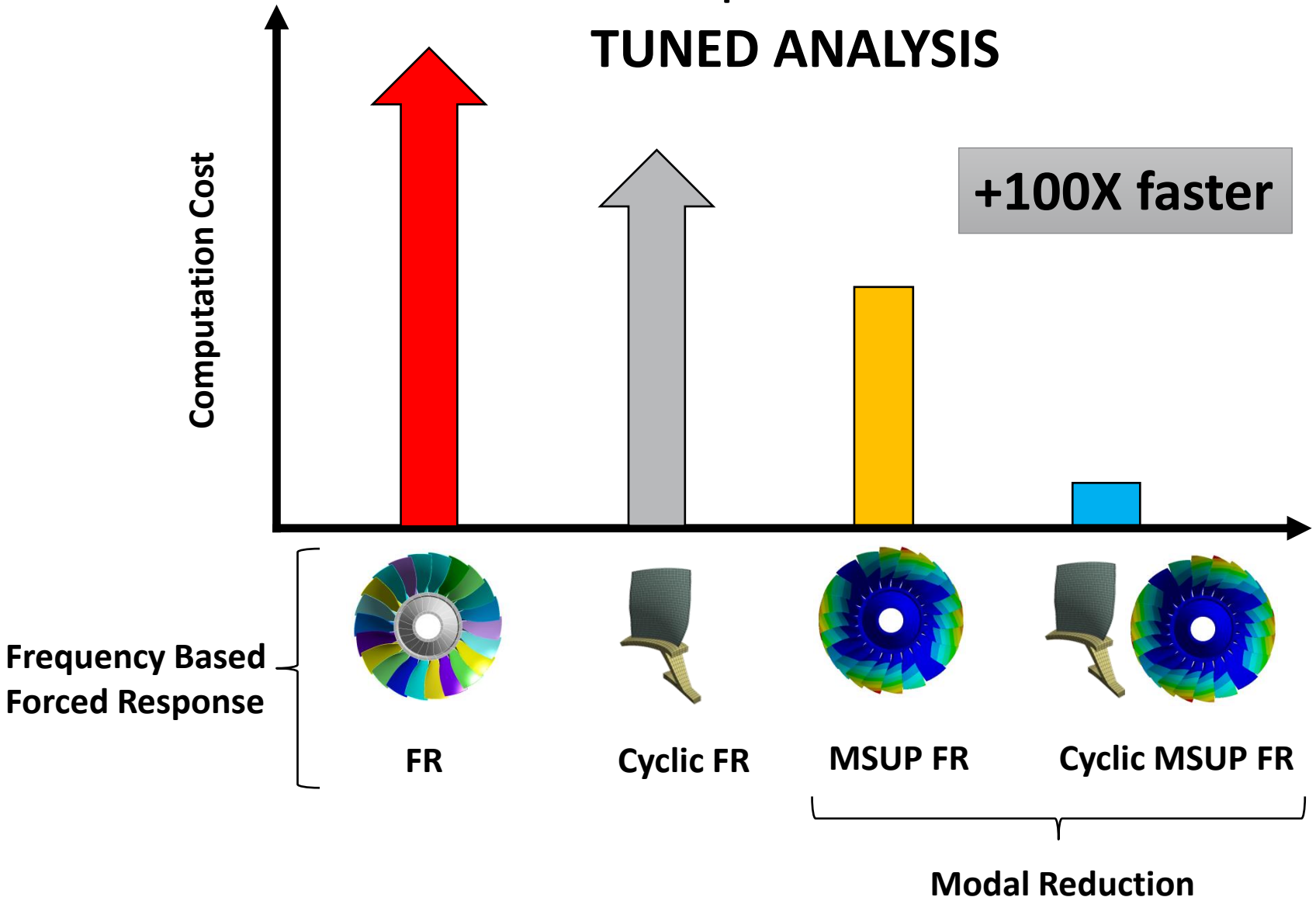
Forced Response Analysis - Workflow



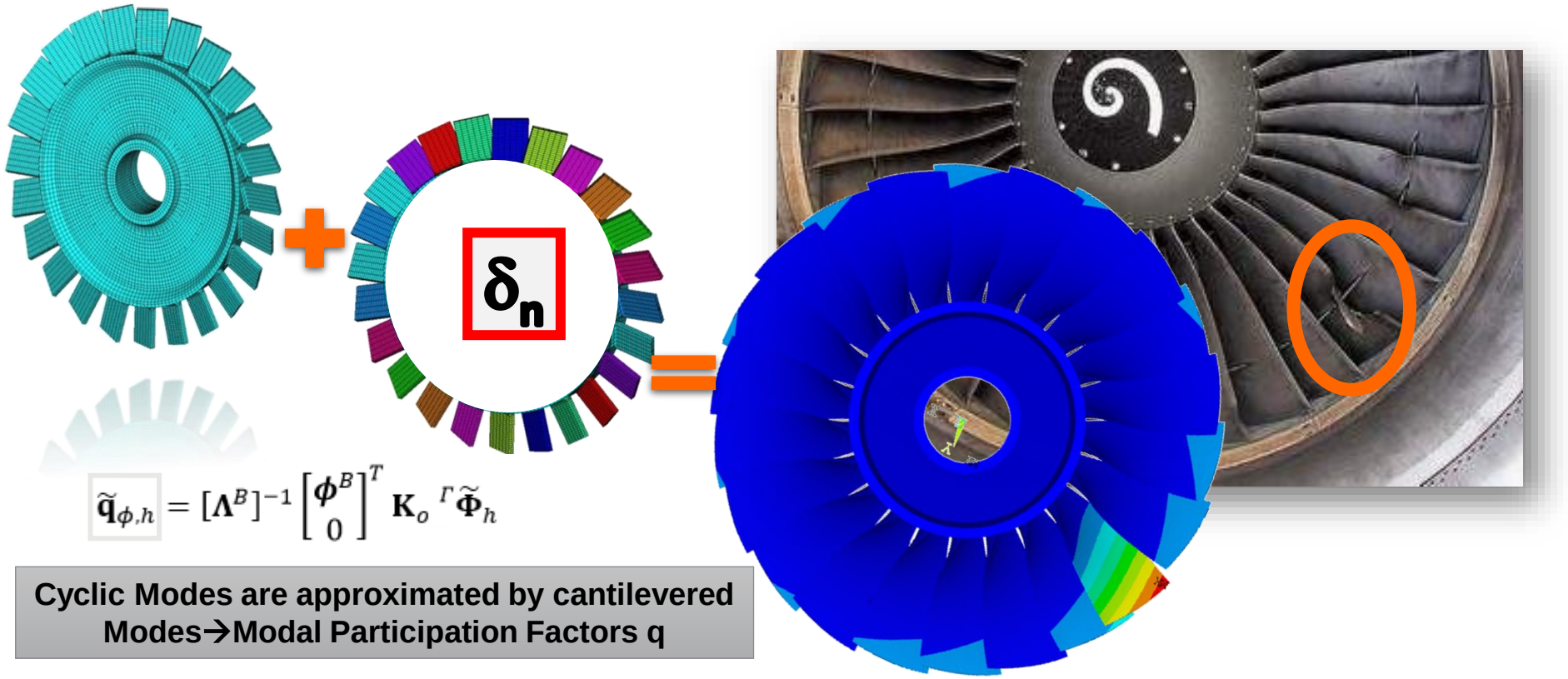
- Small industrial sized example
  - Number of sectors: 22
  - Number of elements: 3141 per sector
  - Number of nodes: 18133 per sector



Fast and Efficient Forced Response Method



Aeromechanics – Mistuning



$$\tilde{\mathbf{q}}_{\phi,h} = [\mathbf{\Lambda}^B]^{-1} \begin{bmatrix} \boldsymbol{\phi}^B \\ 0 \end{bmatrix}^T \mathbf{K}_o {}^{\Gamma}\tilde{\mathbf{\Phi}}_h$$

Cyclic Modes are approximated by cantilevered Modes→Modal Participation Factors q

$$\left\{ -\Omega^2 \mathbf{I} + i\Omega \left[\left(\beta + \frac{1}{\Omega} g \right) \mathbf{\Lambda}^s + \alpha \mathbf{I} \right] + \mathbf{\Lambda}^s + \sum_n \mathbf{q_n}^T \delta_n \mathbf{K_c} \mathbf{q_n} + \mathbf{K_a} \right\} \mathbf{a} e^{i\omega t} = \left\{ \sum_n F_{n,EO}^T \tilde{\Phi}_h^T \mathbf{F} e^{i\phi(n-1)} \right\} e^{i\omega t}$$

- Excitation frequency
- Reduced mass
- Reduced damping
- Reduced stiffness
- Mistuning terms
- Aero stiffness
- Projection to modal space and expansion from cyclic domain
- Single sector engine order forcing


Ansys