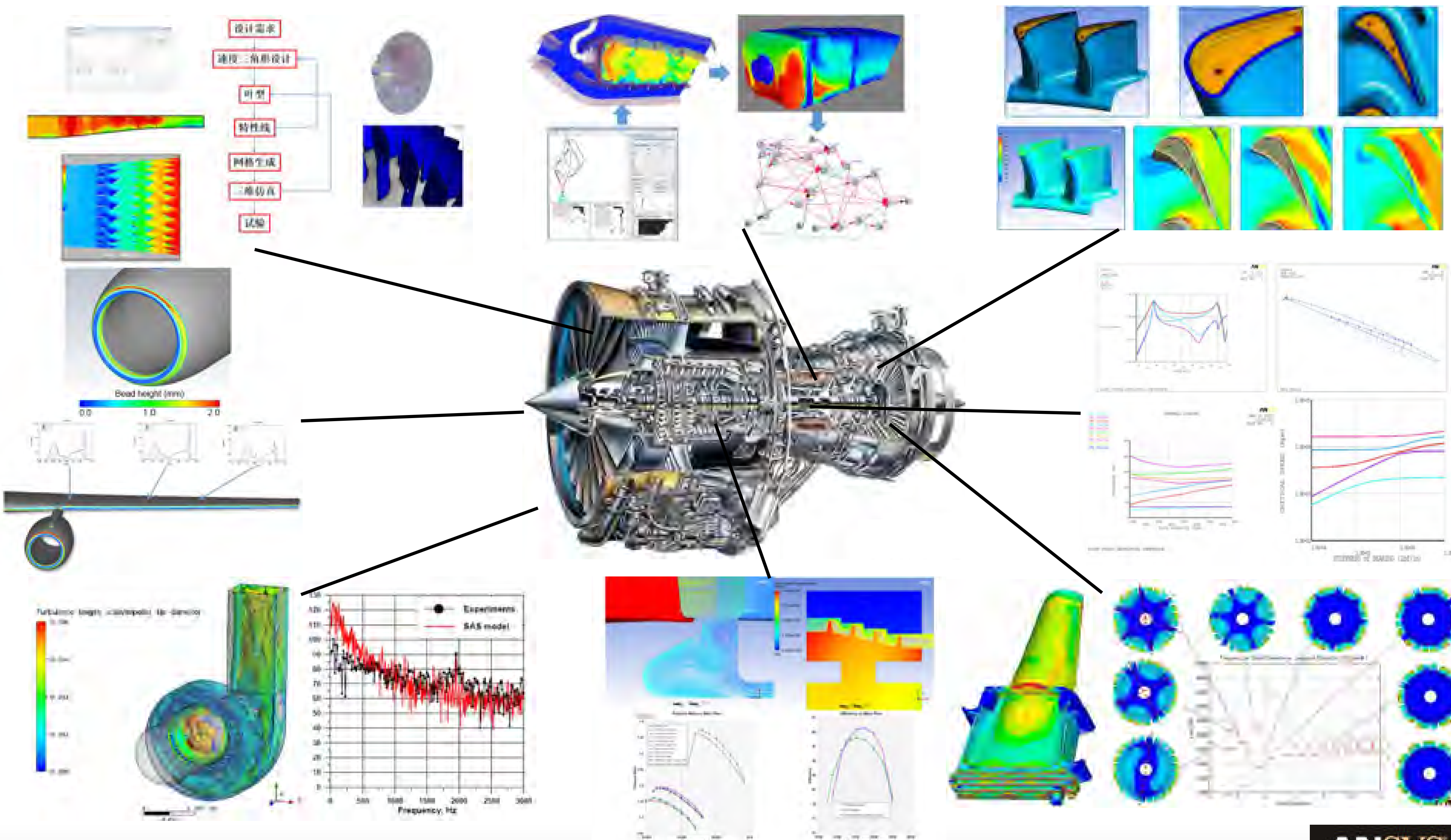
航空发动机的关键结构与流体问题及其仿真方法

杨帆 / 工程师

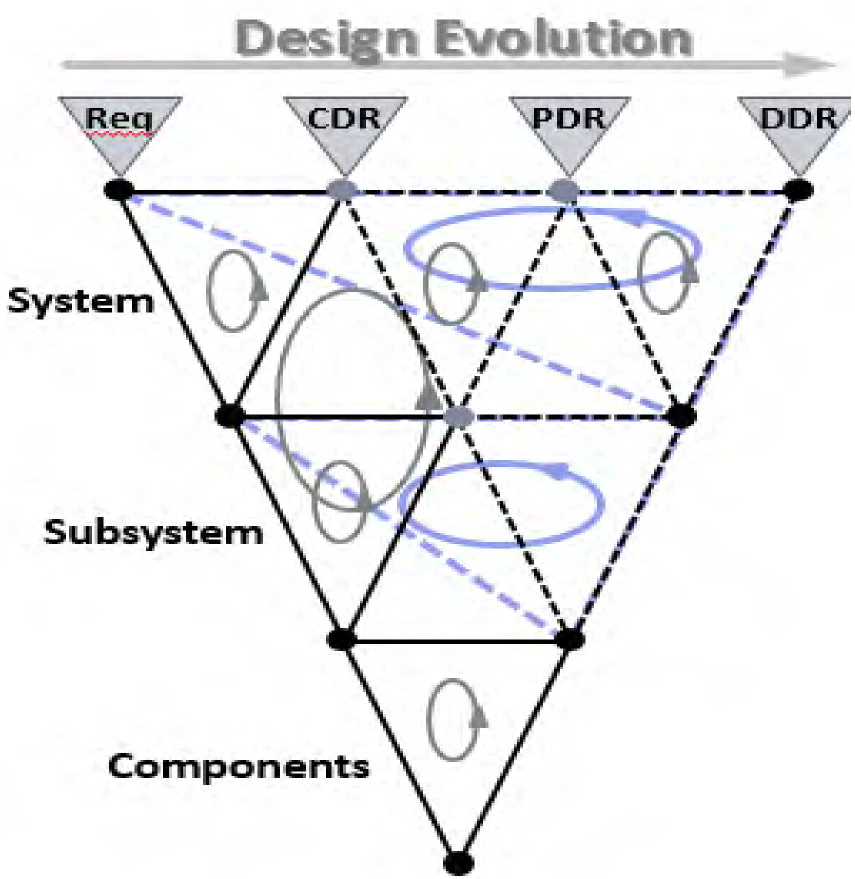
ANSYS

ANSYS仿真在航空发动机中的应用



系统

设计流程

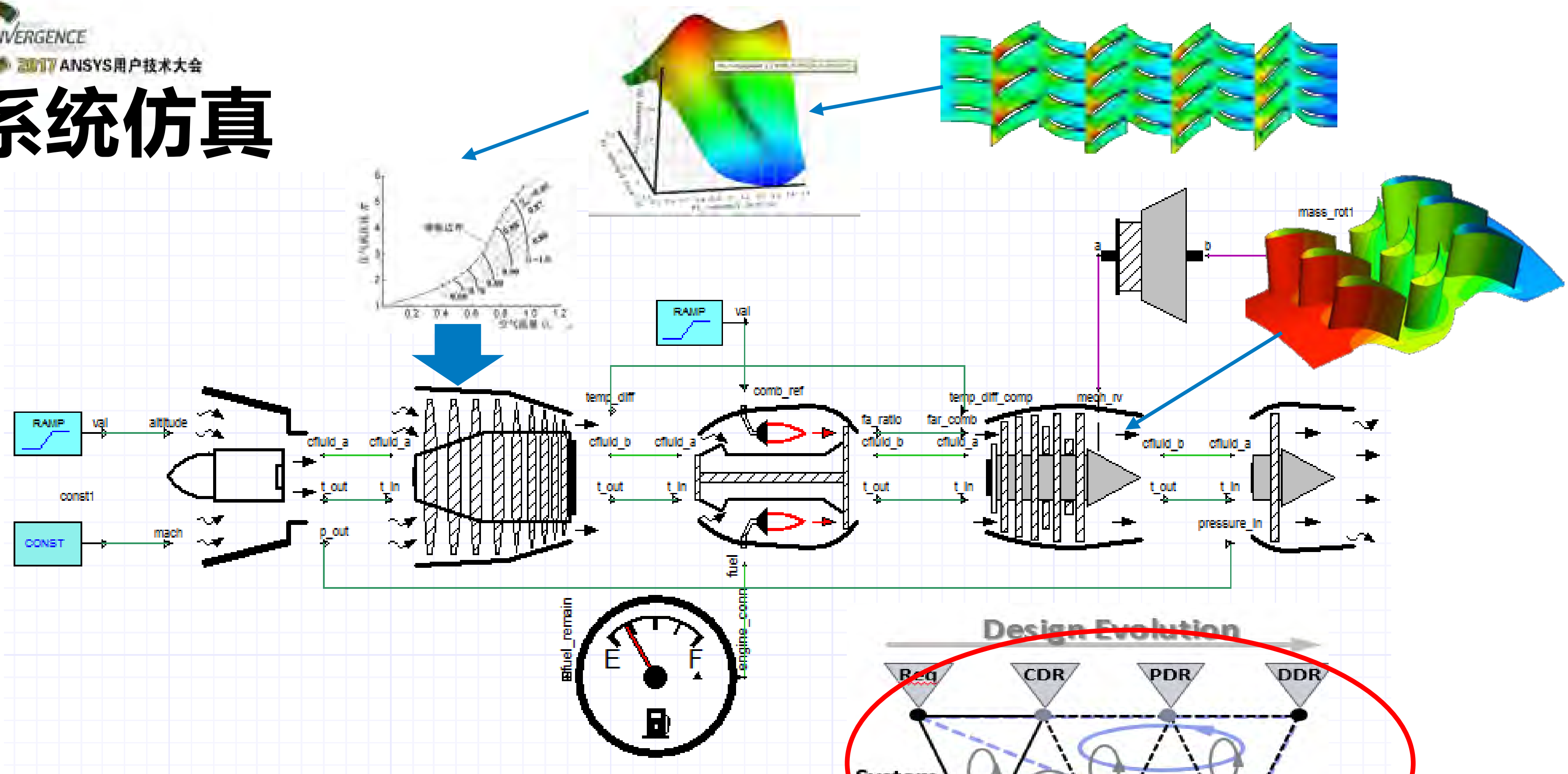


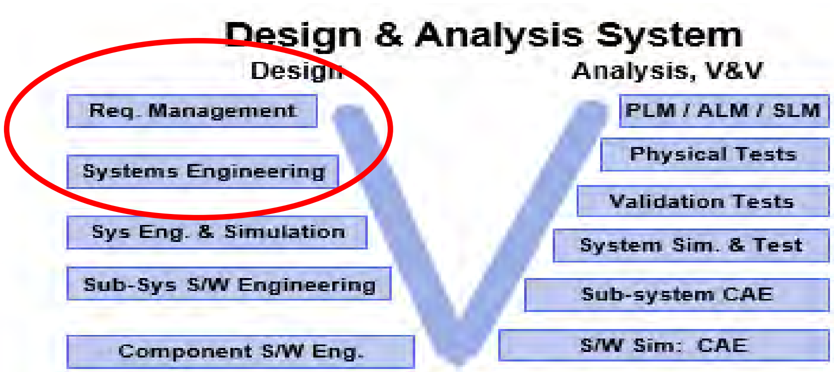
产品研发流程:
需求（Requirements）概念设计（ＣＤＲ）
初步设计（ＰＤＲ）详细设计（ＤＤＲ）

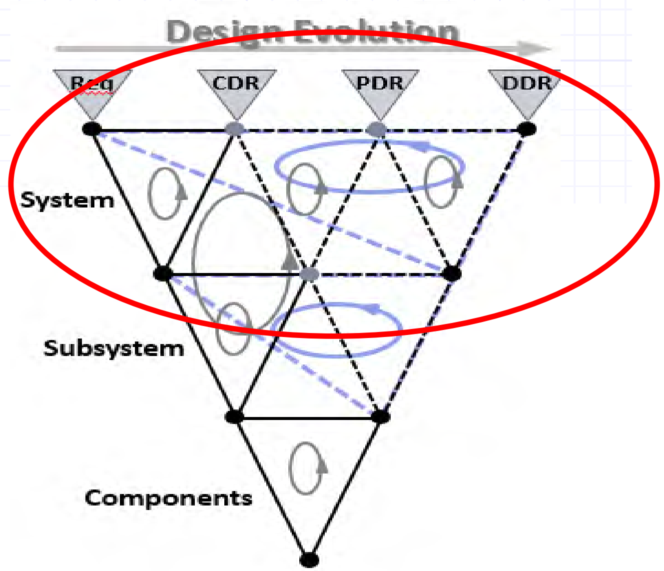
CDR：系统，1d，2d，传递函数等
PDR：系统，1d，2d/3d
DDR：零部件级1，2d，3d

1D：大体尺寸，性能
2D：精确的性能分析，形状
3D：更精确的性能分析，三维形状

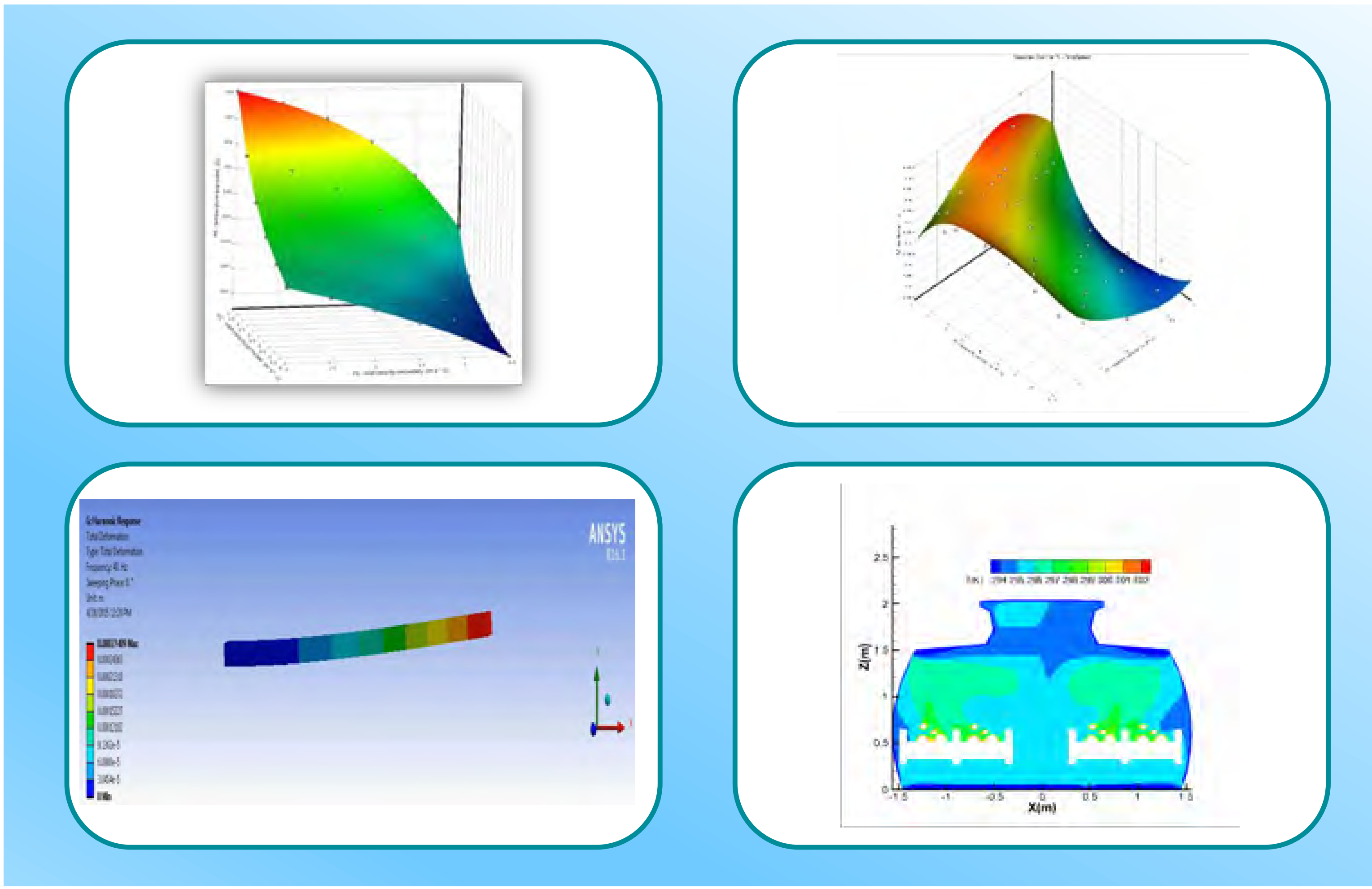
系统仿真


RAMP
val
altitude
const1
CONST
mach
cfluid_a
t_out
t_in
p_out
temp_diff
cfluid_b
comb_ref
fa_ratio
far_comb
temp_diff_comp
mech_rv
pressure_in
mass_rot1
fuel
fuel_remain
engine_cons
E
F

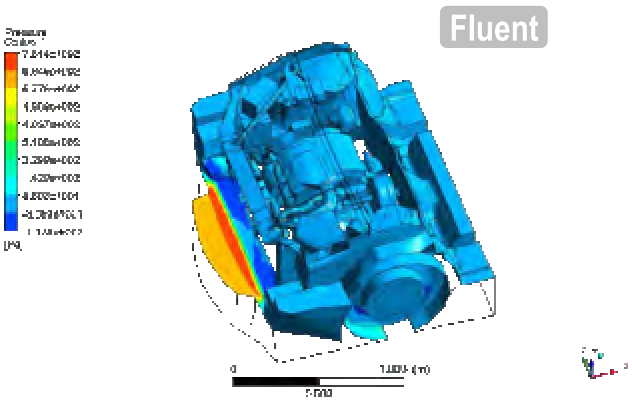

Design & Analysis System
Design
Analysis, V&V
Req. Management
Systems Engineering
Sys Eng. & Simulation
Sub-Sys S/W Engineering
Component S/W Eng.
PLM / ALM / SLM
Physical Tests
Validation Tests
System Sim. & Test
Sub-system CAE
S/W Sim: CAE


Design Evolution
Req
CDR
PDR
DDR
System
Subsystem
Components

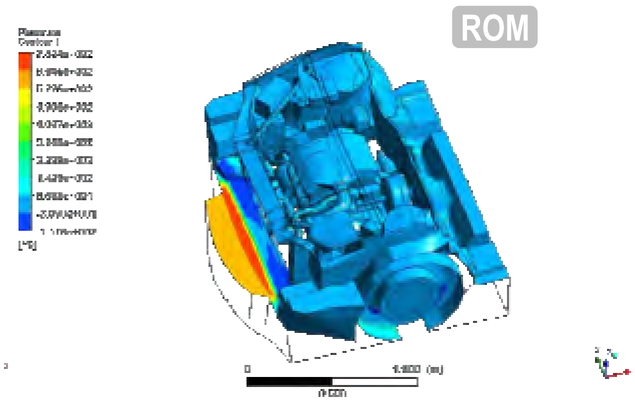
降阶模型



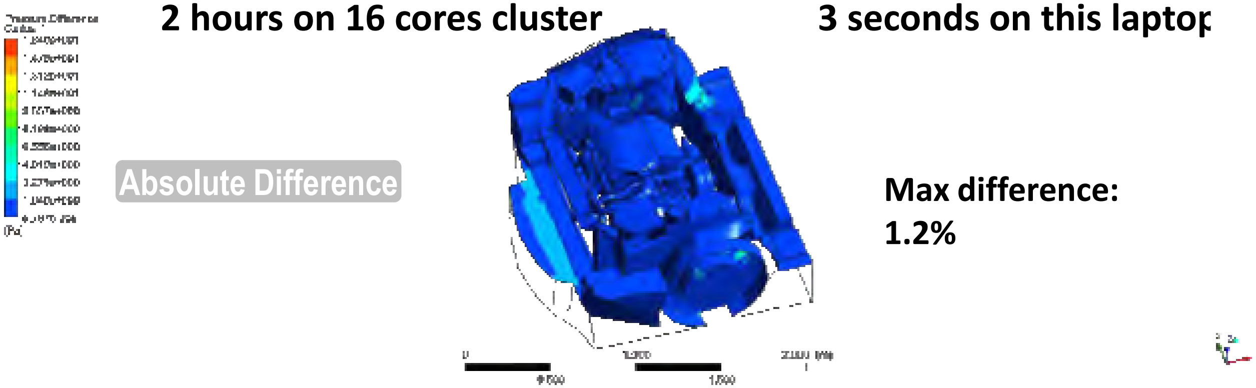
对比



2 hours on 16 cores cluster



3 seconds on this laptop

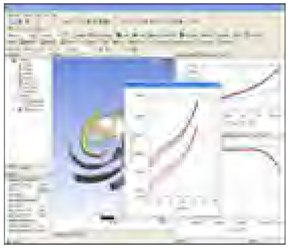


Max difference: 1.2%

叶轮机通流设计

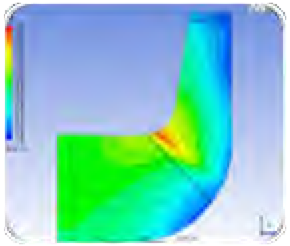
ANSYS通流设计套装

Design



BladeModeler

Screen



Vista TF

Mesh

ANSYS Meshing

Analyze

CFX

CFD Post

BladeModeler: 3D Blade Geometry

Design

Geometry creation tailored to turbomachinery

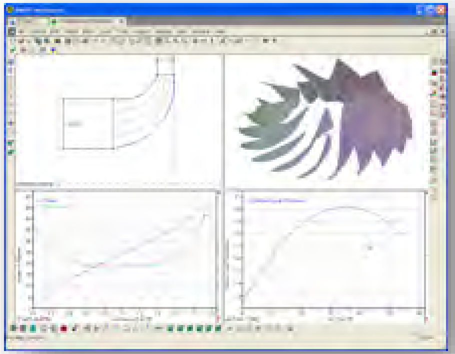
- Intuitive interaction in 2D planes
  - Meridional flow path
  - Specification of blade shape variation over span
- Radial, mixed-flow & axial components
- BladeGen and BladeEditor

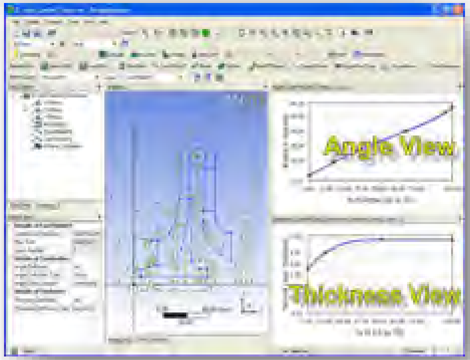
BladeGen

- Original specialized blade geometry creation tool

BladeEditor

- Add-in to ANSYS DesignModeler
  - Complete general geometry capabilities
- Full parameterization using ANSYS Workbench

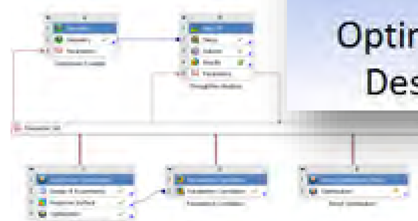




BladeModeler: Add’l BladeEditor Capabilities

Design

- **Include full geometry details**
  - Hub, shroud, fillets, …
- **Combine with other CAD parts**
- **Prepare for meshing**
  - Export for TurboGrid
  - Create periodic fluid volumes
- **Incorporate in design studies and optimization**



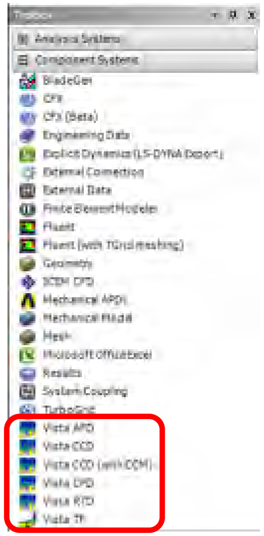
BladeModeler: Meanline (1D) Design

Design

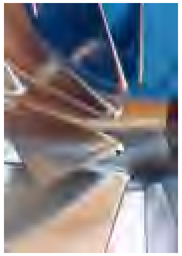
- **Vista CCD:**
  - Centrifugal compressor design
- **Vista RTD:**
  - Radial turbine design
- **Vista CPD:**
  - Centrifugal pump design
- **Vista AFD:**
  - Axial fan design

→ **Generate initial 3-D geometry model**

→ All as native Workbench applications

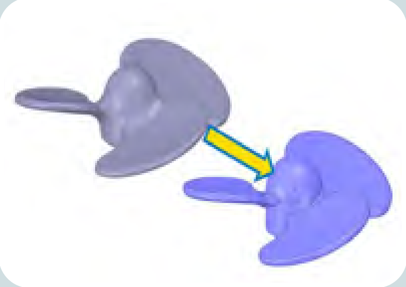


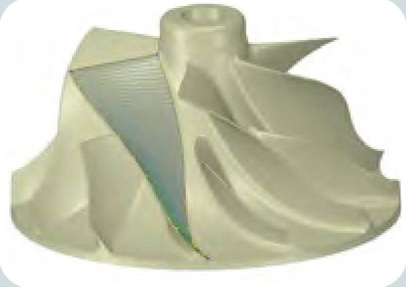
PCA ENGINEERS

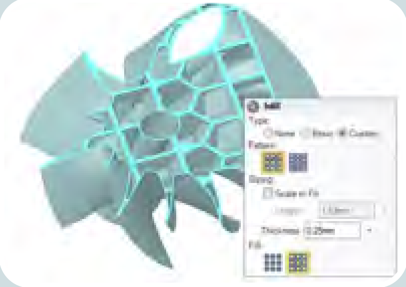


ANSYS

Geometry Handling – ANSYS SpaceClaim







Reverse Engineering:

- Fit faceted data (scans, MRI, legacy CAD, simulation meshes)
- Reference Modeling

ANSYS 17: Skin Surface tool

- Interactive fitting of surfaces to facetted models from scanned data

Prepare Additive Manufacturing:

- Clean & repair before printing
- Model prepare (shells & infill)
- Analyze printability

Vista TF

Screen

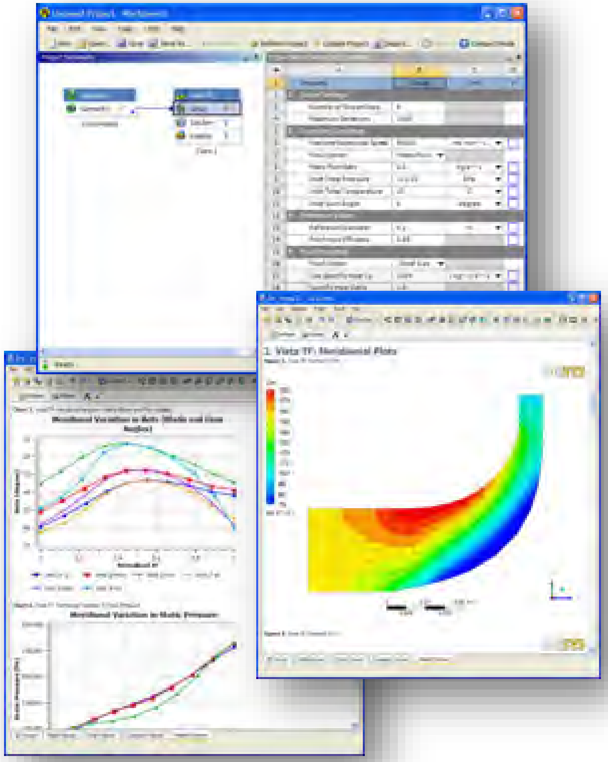
Enhances designer productivity and enables faster development of high performance designs

Initial, fast design screening based on simplified (2D) solution of flow in rotating machinery

- Capture primary flow features
- Identify trends and screen design
- Assist with design decisions
- Use with parametric optimization

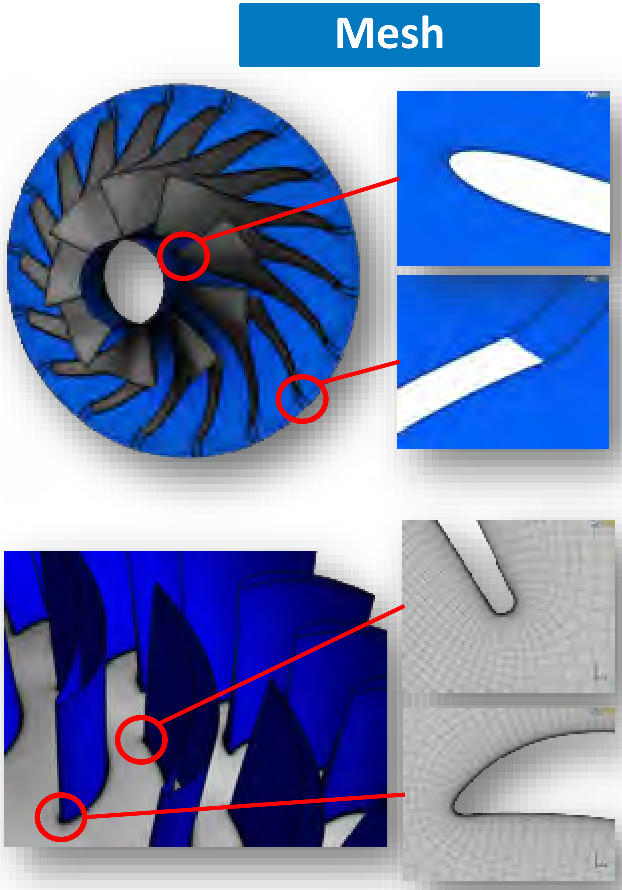
Developed together with PCA Engineers, UK

- Turbomachinery design and analysis specialists



ANSYS Meshing: TurboGrid

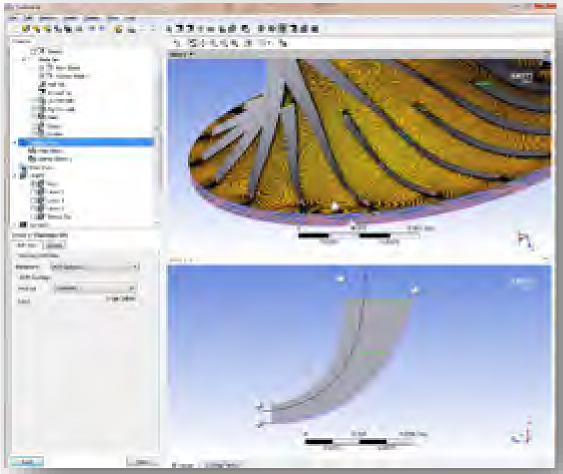
- **TurboGrid included full CFD solution bundles**
- **Blade passage-specific meshing for rotating machinery**
  - Automated
    - High quality hexahedral grid
  - Repeatable
    - Minimize mesh influence in design comparison
  - Scalable
    - Maintain mesh quality with refinement

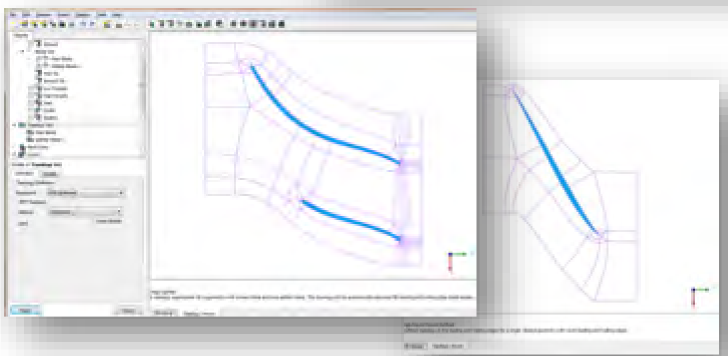


TurboGrid: Key Technology

- **Automated Topology and Mesh (ATM) method to produce high quality, anisotropic hexahedral meshes**
  - Focused on and tailored to CFD meshing of standard blade designs
- **Simplicity in use**
  - User need only adjust overall mesh size
  - User can fine tune mesh dimensions
- **Numerous templates provided**
  - Automatic and manual selection

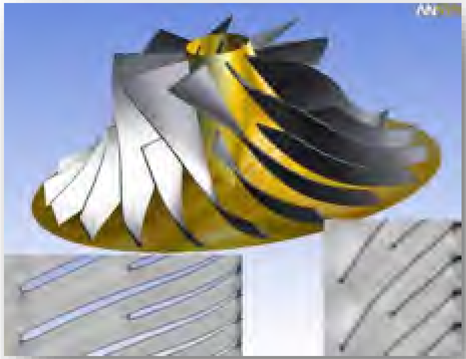
Mesh





TurboGrid: Example Applications

Mesh

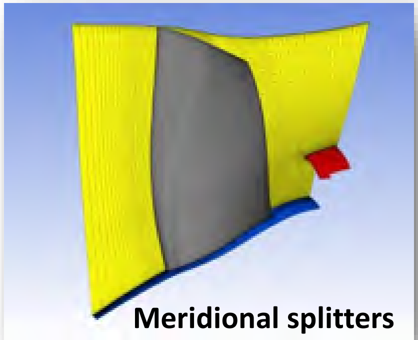


Centrifugal compressors, splitters

Tandem vanes

Mixed flow pumps

Axial fans



Meridional splitters

Looking Ahead: Expanded Automation of Hybrid Meshing

- E.g. cooled turbine blades

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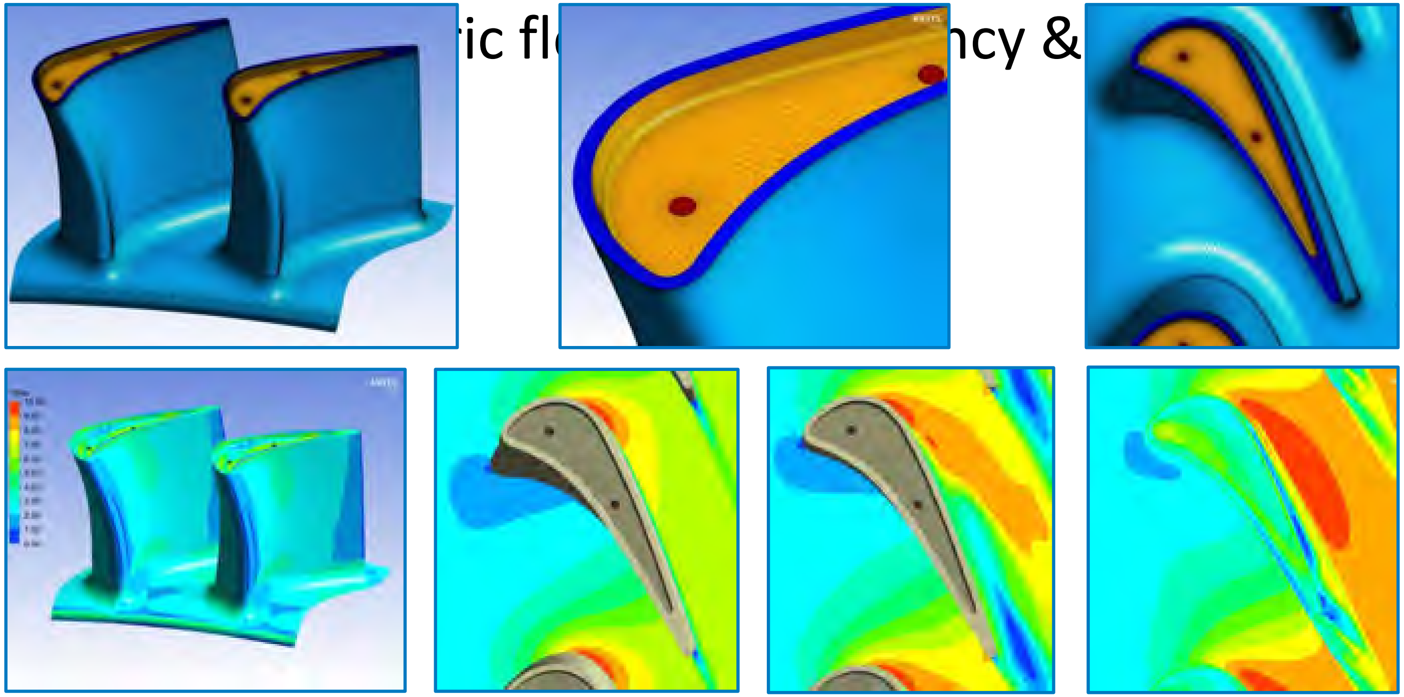

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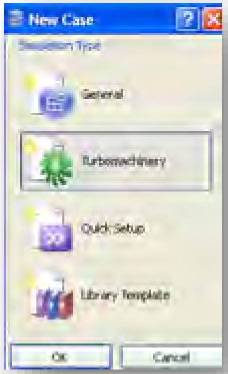
Streamlined Turbo CFD Set-Up

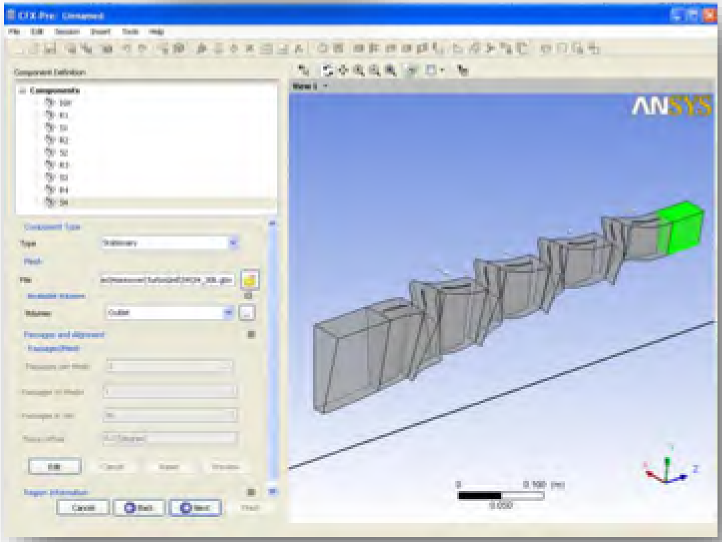


Analyze

CFX-Pre TurboMode

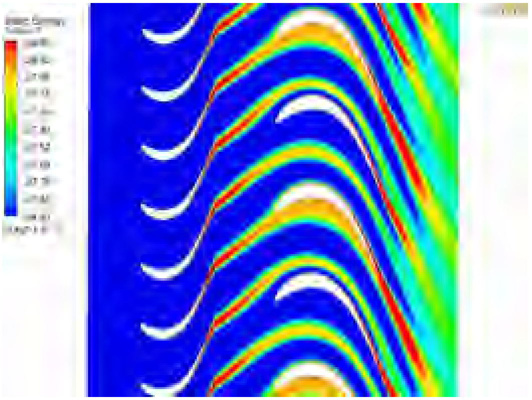
- Multiple components
- Multiple passages
- Interfaces
  - Periodic, rotor-stator
- Physics
- Boundary conditions
- Solver settings

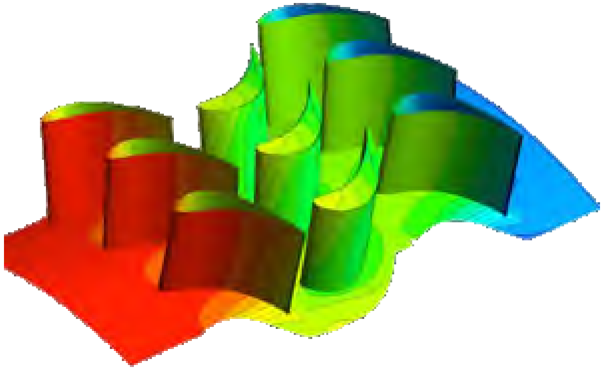
- **Return to general mode any time**



ANSYS CFD Solution

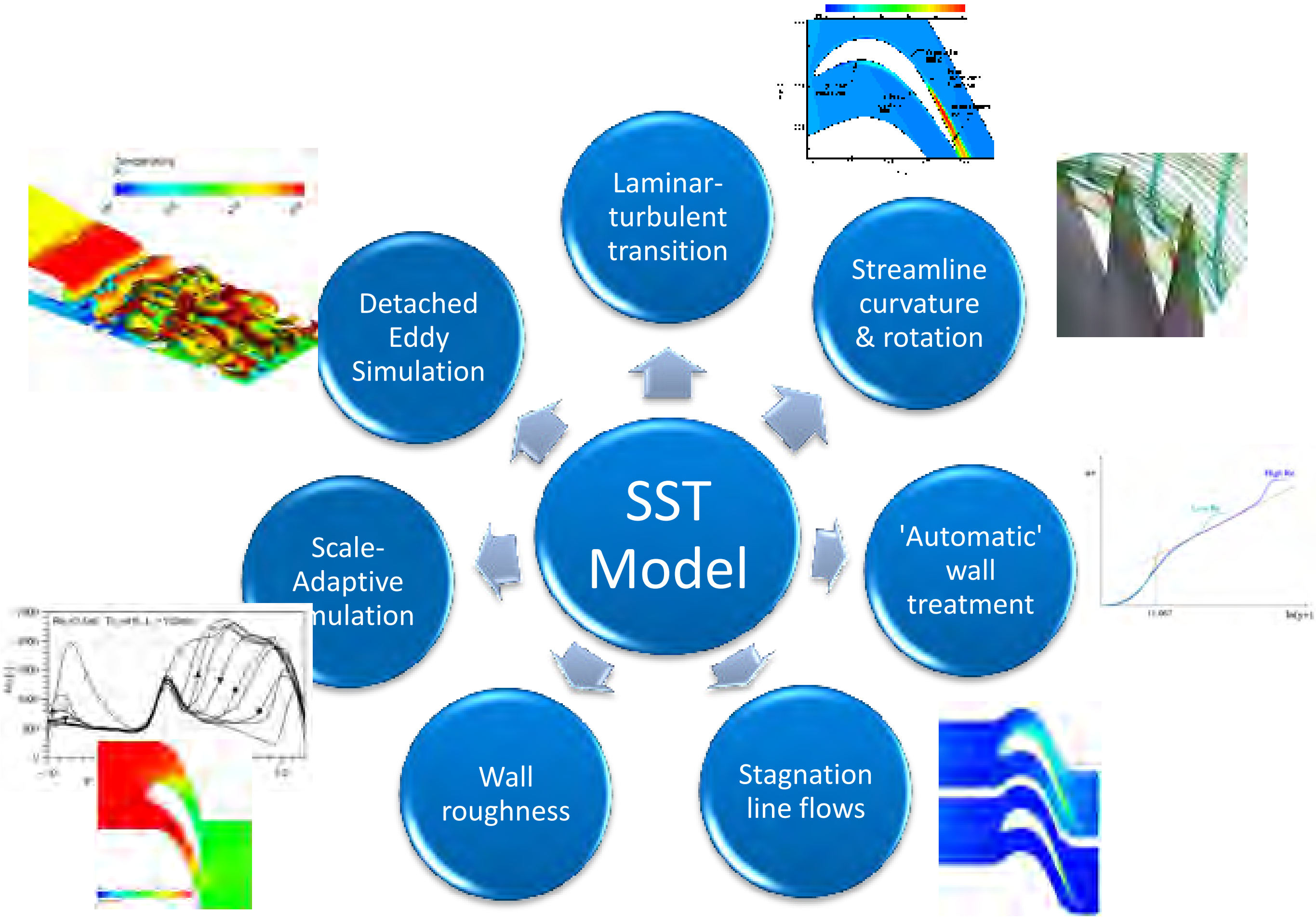
Analyze



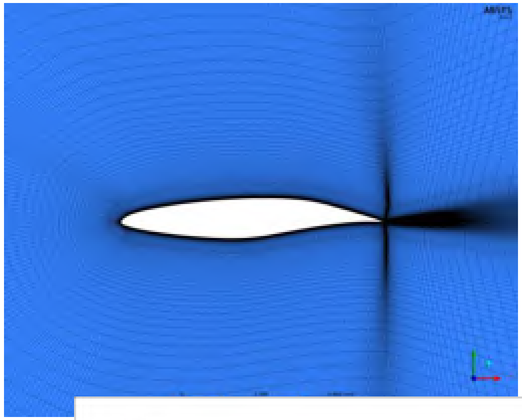


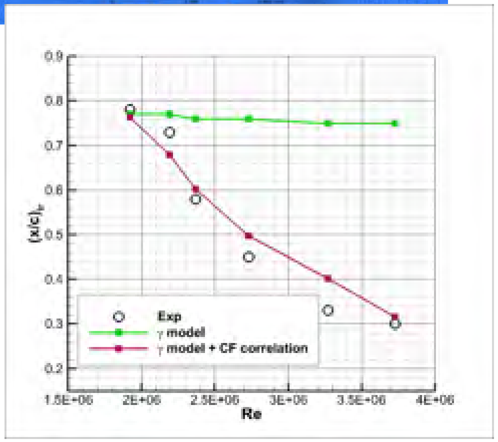
- **Advanced solver technology**
- **Broad range of physical models and capabilities**
  - Compressible, incompressible
    - **Low speed to supersonic**
  - Real and ideal fluids
  - Turbulence, CHT, multiphase, …
  - Full suite of rotor-stator interaction models for turbomachinery
    - Steady & transient

SST as Focal Point for RANS



Transition Modelling in CFX

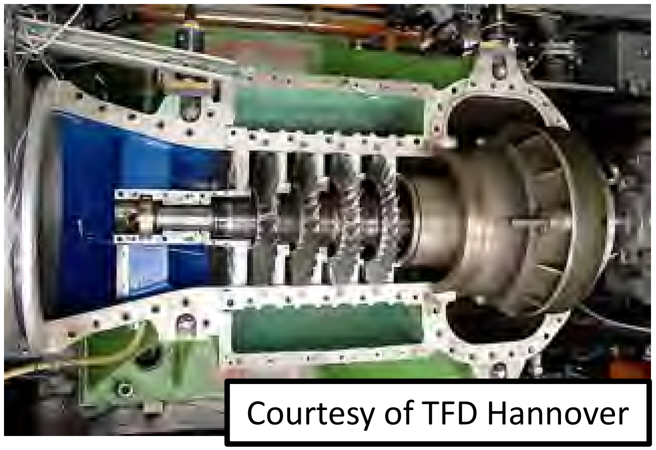




- **Original model in CFX: Two-equation γ-Re_θ model**
- **Recent significant advancement: One-Equation γ model**
  - Significant advancement of original model
    - Reduce number of equations
    - Galilean invariant
    - Simplified correlations
    - Crossflow instability

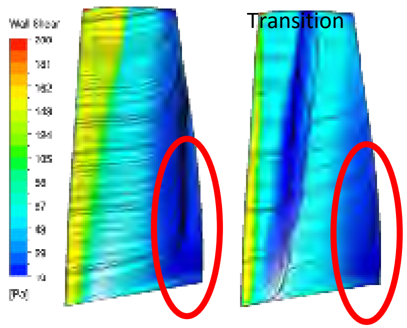
Impact of Transition Modelling on Compressor Design

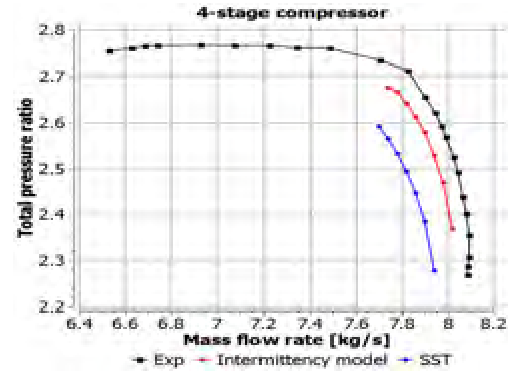
- 4 stage high-speed axial compressor

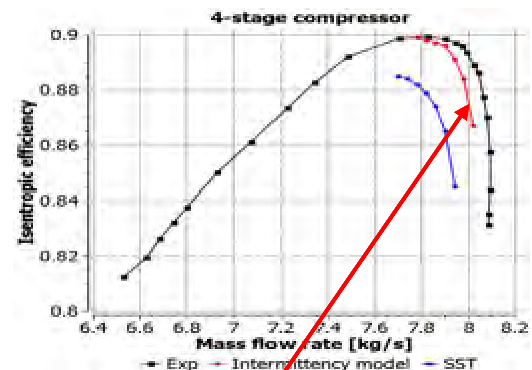


Courtesy of TFD Hannover

Transition re-energizes the flow and leads to less separation → lower losses





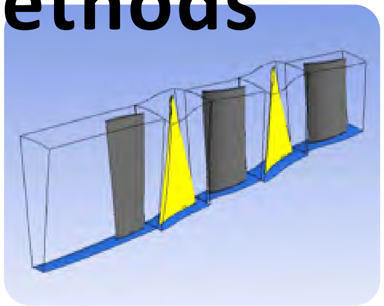


New 1-equation transition model !

ANSYS

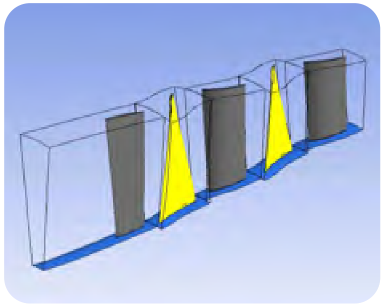
动叶与静叶间的数据传递

ANSYS Blade Row Analysis Methods

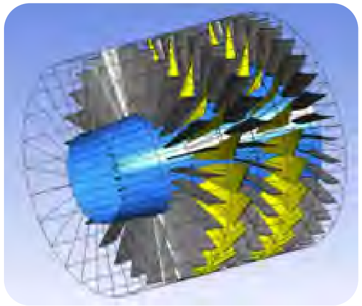


Steady
Stage/ Mixing-Plane

- Single Passage per Row
- Very accurate over broad range of performance map
- Low comp. expense, very fast to run
- Does not account for unsteady interaction



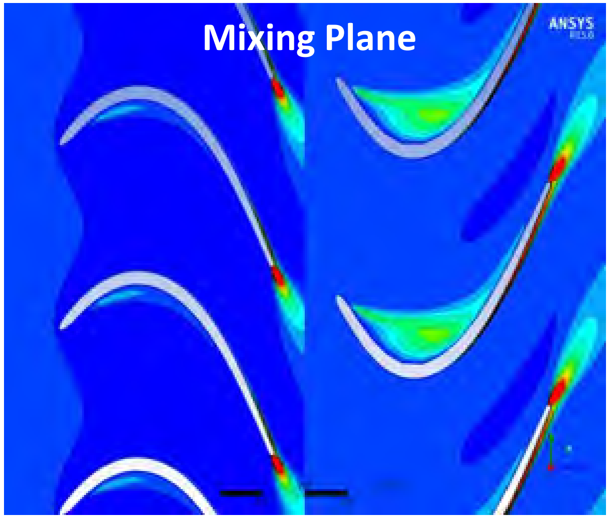
Transient
with
Pitch-Change

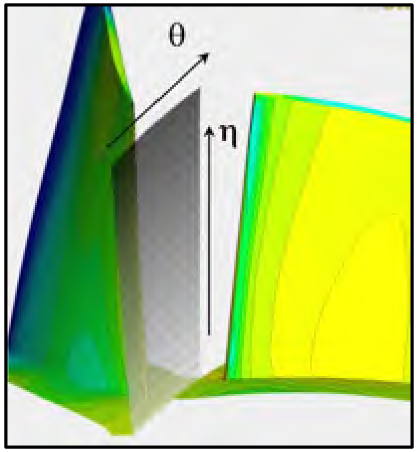


Transient
Full-Domain

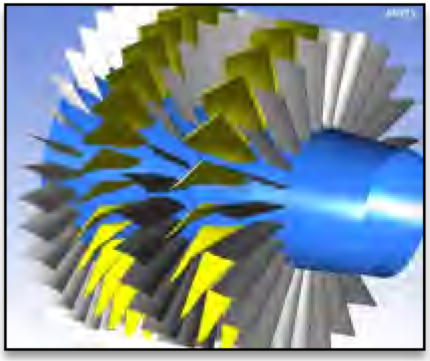
Stage (a.k.a. Mixing Plane) Analysis

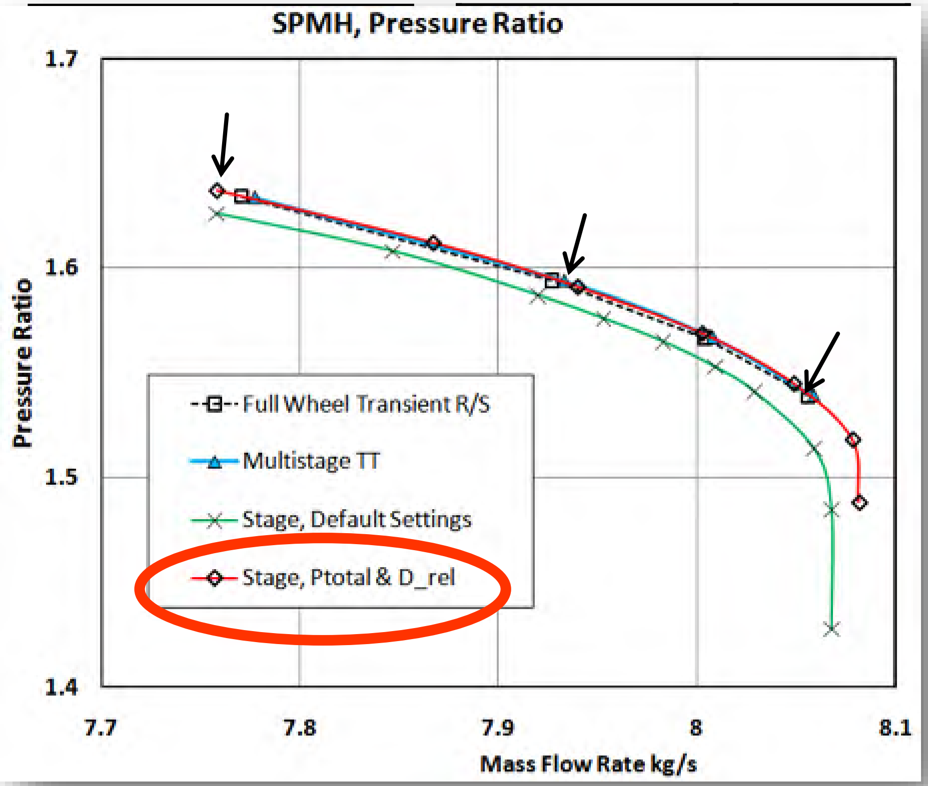
- **Principle:**
  - Average fluxes in circumferential bands
    - Conservative, implicit
  - Transmit averaged fluxes to downstream component
    - → Allows for variation in the meridional plane
  - Usually one passage per component modeled
  - Insensitive to component relative positions
- **Example Applications:**
  - Axial turbines & compressors
  - Axial & mixed-flow pumps
  - Fans





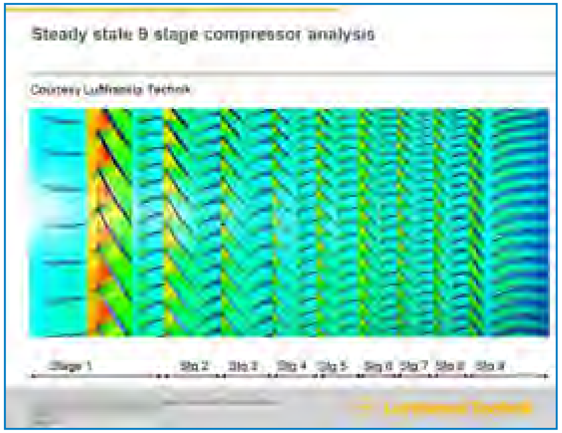
Case Study: Stage Numerics Example Hannover Compressor (Mod)

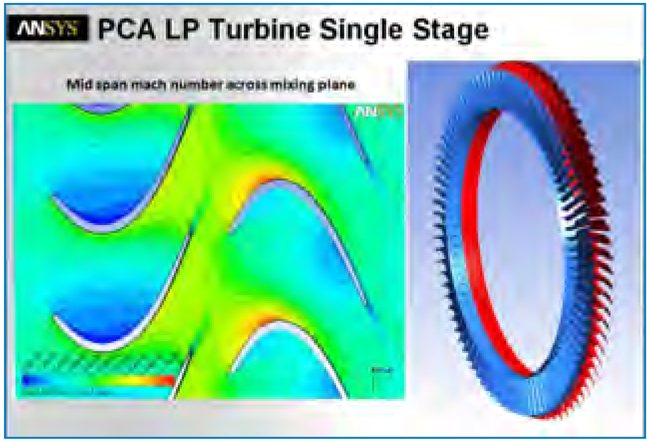


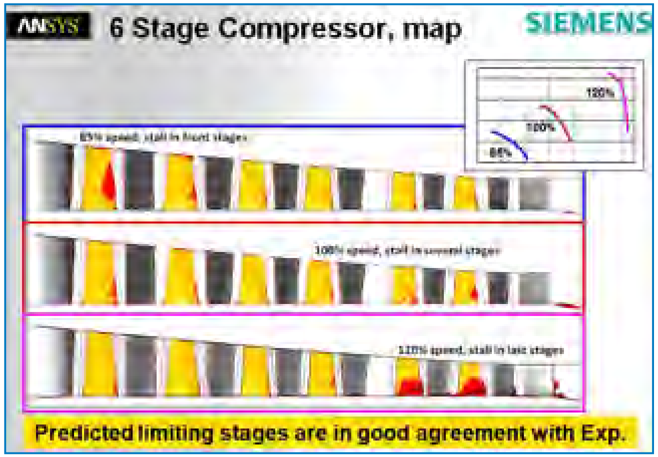


- Modified Hannover compressor
  - 2 ½ stage
  - IGV=24, R1=21, S1=27, R2=30, S2=33
  - Modeled with stage, multistage TT, full wheel transient

Steady State Often Sufficient!

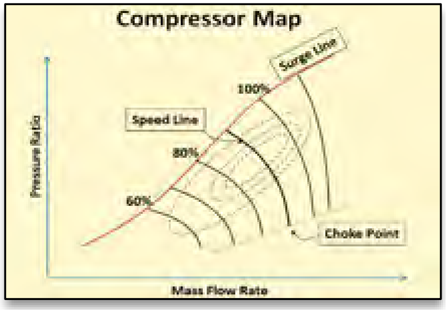


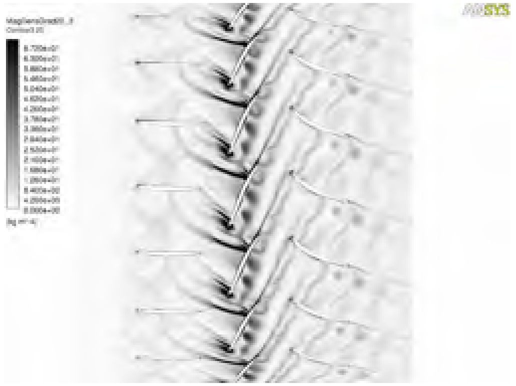




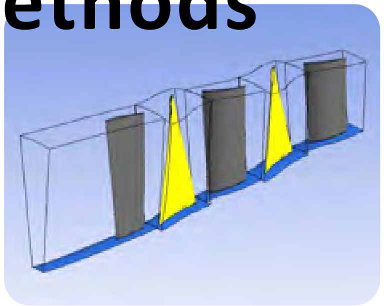
Next Level of Fidelity: Transient

- **Better Performance Mapping**
  - Pressure rise or drop
  - Loads
  - Efficiencies & stage losses
  - Flow instability and stall
  - Flow details
- **Aeromechanical Analysis**
  - Blade Flutter
  - Forced Response
- **Acoustics Analysis**





ANSYS Blade Row Analysis Methods



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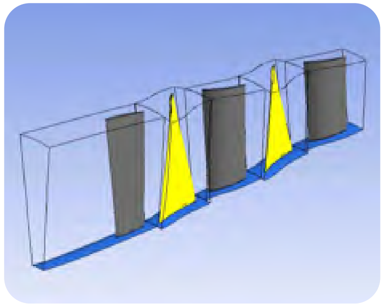
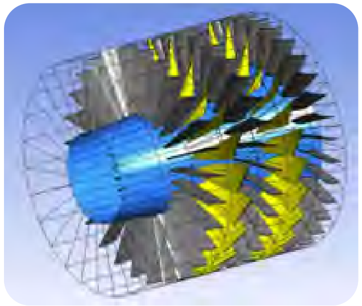


Transient
with
Pitch-Change



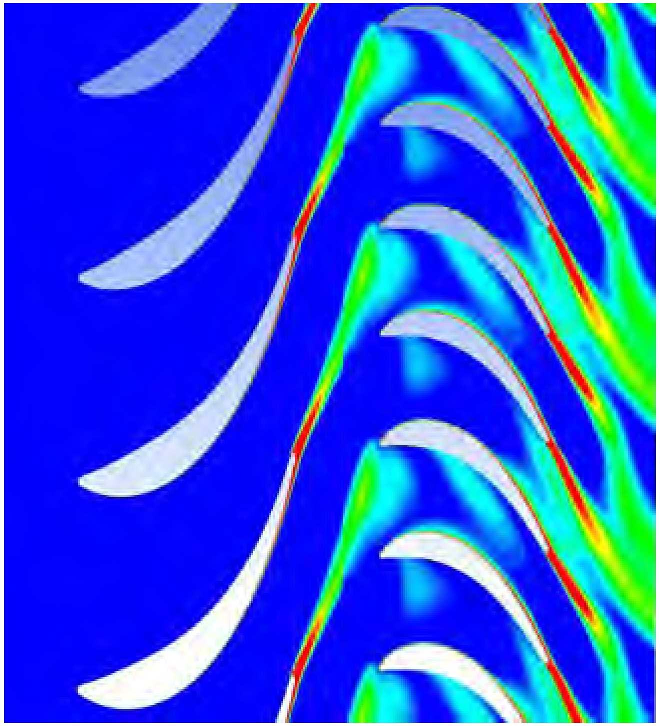
Transient
Full-Domain

- Accurate account for unsteady interactions
- Req. Full or Partial wheel modeling
- Large comp. expense
    - Memory
    - CPU

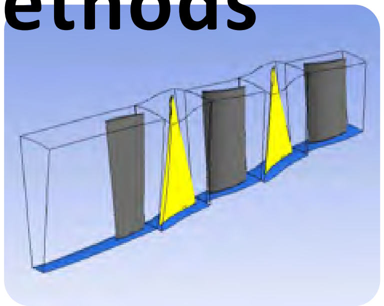
Transient Full Domain Analysis

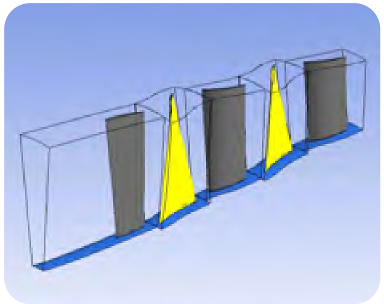
- **Principle:**
  - Geometry update every time-step
  - Same pitch

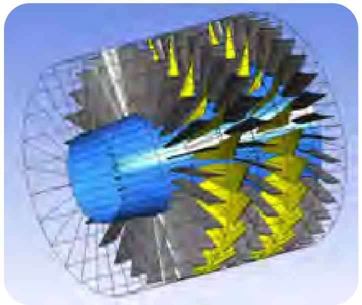
  → No model approximation except periodicity
  - Pitch change modeling → later
- **Advantages:**
  - 'Correct' physics
  - Robust (reverse flow)
  - Closely coupled components
  - Part load
- **Consider:**
  - Computational efforts
  - Post-processing of large amount of data
  - Correct frequencies require equal pitch



ANSYS Blade Row Analysis Methods







Steady Stage/ Mixing-Plane

- Single Passage per Row
- Very accurate over broad range of performance map
- Low comp. expense, very fast to run
- Does not account for unsteady interaction

Transient with Pitch-Change

- Accuracy of full domain
- Account for unsteady interaction
- Reduced domain model One or few passages per row
- low comp. expense

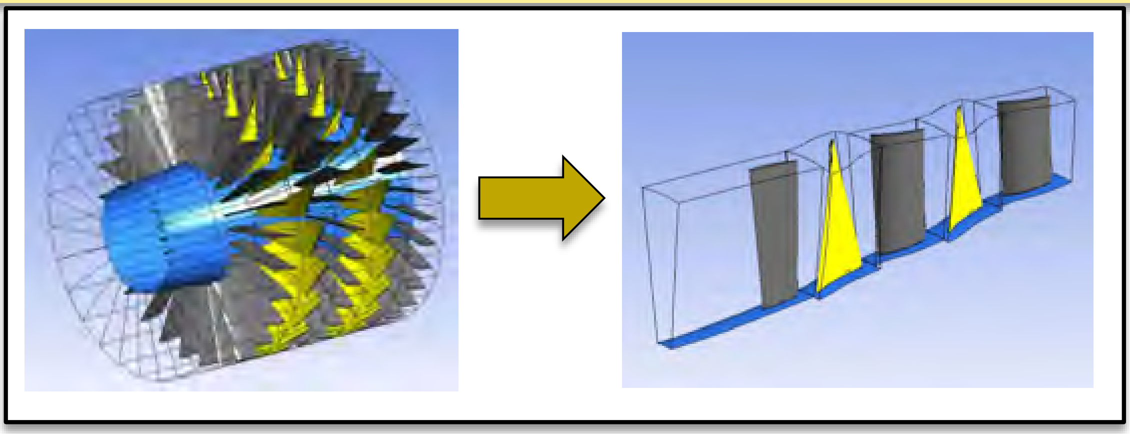
Transient Full-Domain

- Accurate account for unsteady interactions
- Req. Full or Partial wheel modeling
- Large comp. expense
    - Memory
    - CPU

Transient with Pitch Change: ANSYS Transformation Methods

Motivation:

Obtaining the full-wheel transient solution, but at low cost!



Solution:

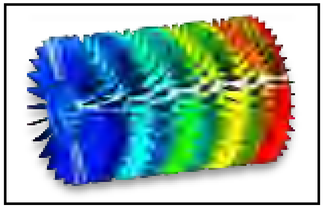
- The ANSYS TBR Transformation family of pitch-change methods

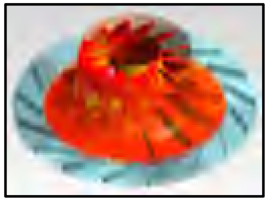
- New models minimize number of simulated passages

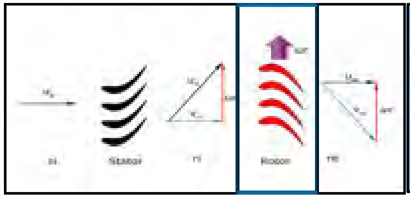
- Enormous efficiency gains and reduced infrastructure requirements

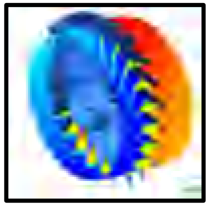
ANSYS TBR Flow Applications

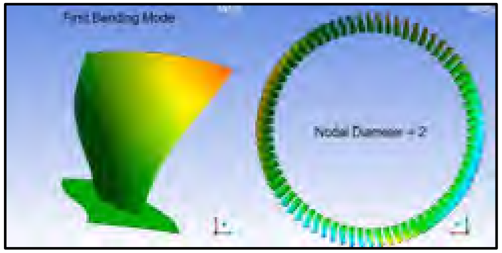
- **Rotor/Stator Interaction**
  - Single Stage & Multistage
  - Axial & Radial
- **Inlet Disturbance**
  - Frozen Gust Analysis
  - Fan Inlet Distortion
- **Aeromechanical Analysis**
  - Blade Flutter
  - Forced-Response





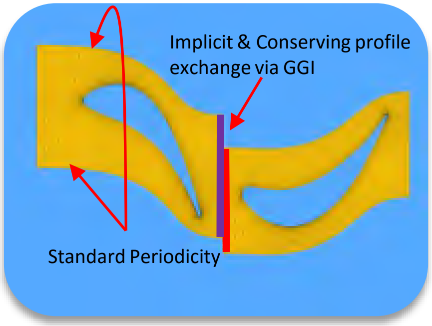


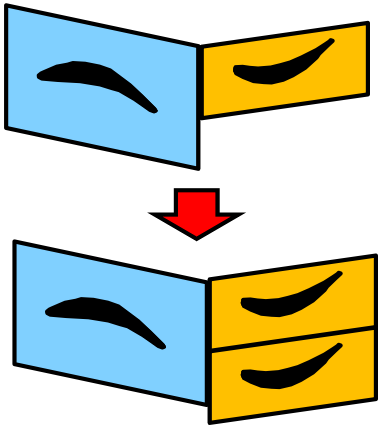




Pitch-Change Method: Profile Transformation (PT)

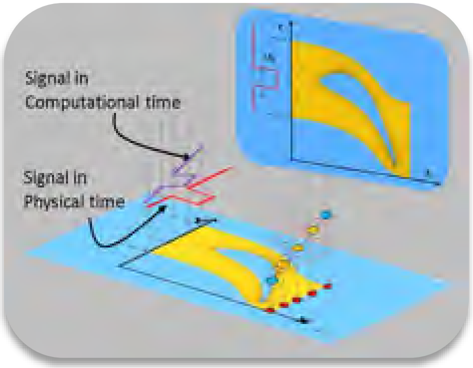
- **Profiles across the rotor/stator interface are stretched or compressed by the pitch-ratio while full conservation is maintained.**
- **Standard periodicity applied on pitch-wise boundaries**
- **Maintains true blade counts & geometry**
- **Computationally efficient and fast (fully implicit)**
- **Single-Stage and Multistage modeling**
  - Accurate prediction for machine performance for a wide range of pitch ratios
  - Good for maintaining frequencies when pitch ratio is small
    - For larger pitch ratios, the accuracy can be improved by adding more passages per row to reduce the ensemble pitch-ratio

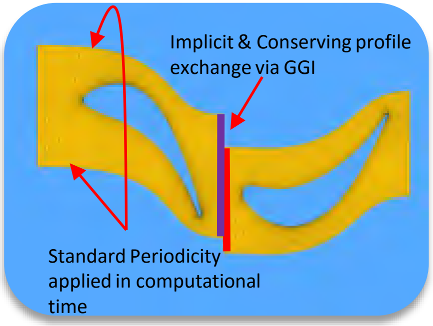




Pitch-Change Method: Time Transformation (TT)

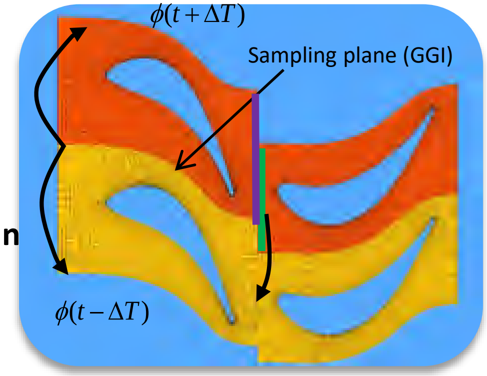
- **Based on the Time-Inclining method (Giles '88)**
- **Fully implicit , turbulence & transition models**
- **Transform equations in time so that instantaneous periodicity can be applied on pitch-wise boundary with no approximation**
  - Solution advanced in computational time
  - Results displayed in physical time
- **Efficient Fourier coefficient compression of results**
- **Inlet-disturbance, single-stage, multi-stage analysis**
  - Moderate pitch-ratio





Pitch-Change Method: Fourier Transformation (FT)

- **Based on the Shape-Correction method of L. He (1989) and Chorochronic interface periodicity of Gerolymos (2002)**
- **Fourier–series are used for reconstruction of solution history on pitch-wise boundary an inter-row interfaces for efficient data storage & convergence**



Pitchwise Boundary

$$\phi(t) = \sum_{k=-N}^{N} A_k e^{-j(k\omega t)}$$

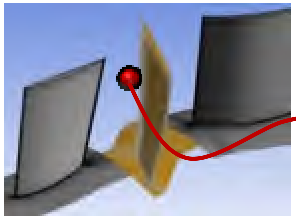
Inter-row interfaces

$$\phi(t,\theta) = \sum_{l=-M}^{M} \sum_{k=-N}^{N} A_{k,l} e^{-j(k\omega t + l\theta)}$$

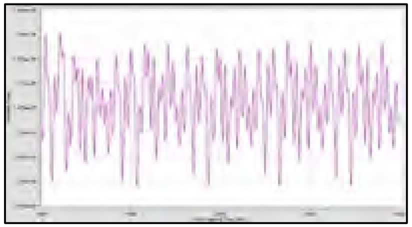
- **Double-passage strategy (faster convergence than single passage)**
- **Works for large pitch ratios – up to one per re**

Usability: Cyclic and Polar Plots

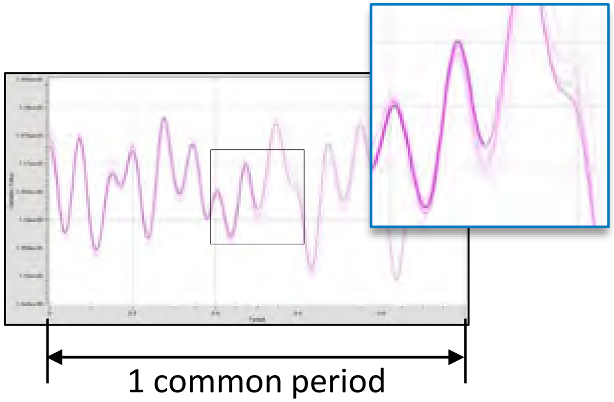
- Allows for easy way to monitor and judge TBR solution convergence
- Overlay multiple common blade passing periods



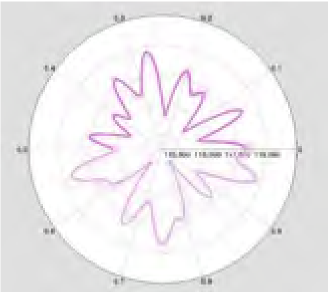
XY monitor plot



Cyclic plot



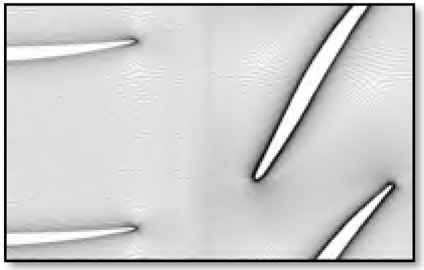
Polar plot



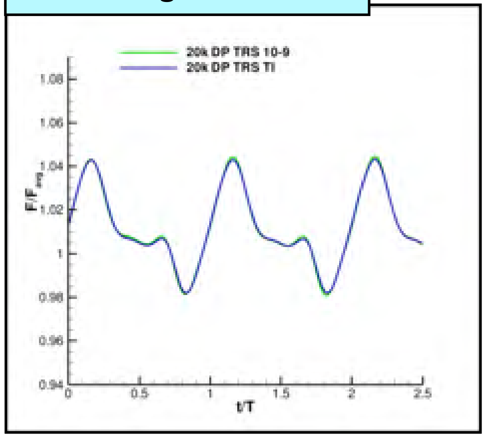
Case Study: Purdue Compressor

- **Verification of TT-TRS to true full domain transient solution**
- **Full domain 180°: 10 IGV / 9 R**
- **TT : 1 IGV/1R**
- **Published work GT2010-22762**

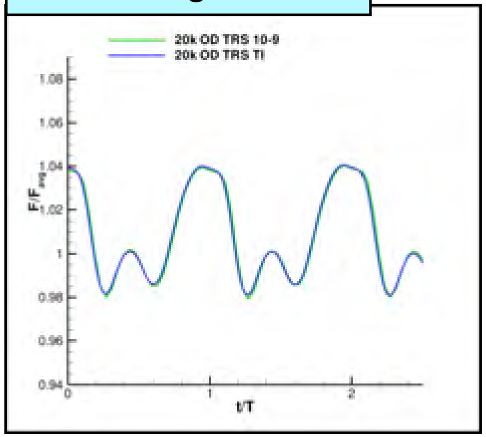
Forcing function on IGV: Integration of pressure distribution at 90% span from experiment and CFD

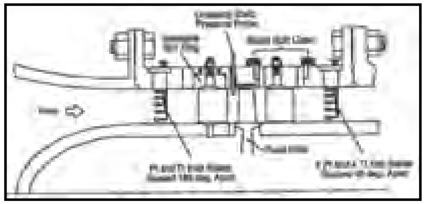


Design Point



Off-Design Point





ANSYS

Case Study: Purdue Compressor

	CPU Effort
TRS-TT	1.0
TRS-PT	1.0
Full Domain	10.5

Density-Gradient

TRS-TT

This animation is from a solution obtained on single passage per row using TT method and later reconstructed for the full geometry using a single results file

Density-Gradient

TRS 10-9 (Full Domain)

This animation is from a solution obtained on the Ref. geometry using TRS method. The post processing done using multiple transient files

New: Harmonic Analysis (HA) Method

- **Overall objective: fast & accurate transient blade row solution**
- **Previous releases introduced range of pitch-change methods:**
  - PT, TT and FT
  - (Full-wheel → Reduced geometry)
- **Harmonic Analysis (hybrid frequency/time solution method)**
  - Very Fast Solution
  - From analysis tool to design tool
  - First target application: Blade Flutter (aerodamping calculations)

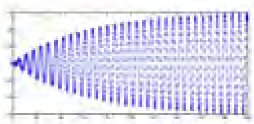
Harmonic Analysis (Harmonic Balance) and Frequency Based Methods

- The solution to transient and periodic flow can be obtained fast using Harmonic Balance method (frequency-based method), instead of using traditional time marching methods
- It assumes the solution can be represented by sin/cos based signals (Fourier-series)

$$\phi(t) = a_0 + \sum_{m=1}^{M} a_m \cos(m\omega t) + b_m \sin(m\omega t)$$

- Simple signal can be represented with few modes M (harmonics), while complex signal requires more modes to describe it.
- Originally used in microwave circuits, electromagnetic system design (i.e. ANSYS HFSS). Because transient circuit simulation is impractical.

Courtesy of Jacob White @ MIT



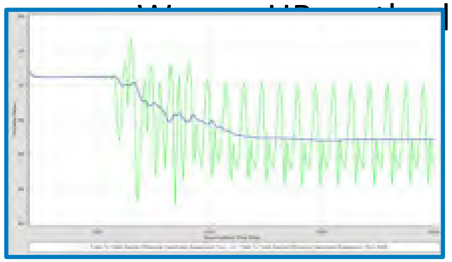
Nice example from Wikipedia

"The Fourier transform relates the function's time domain, shown in red, to the function's frequency domain, shown in blue."

"Time-domain graph shows how a signal changes over time, whereas a frequency-domain graph shows how much of the signal lies within each given frequency band over a range of frequencies"

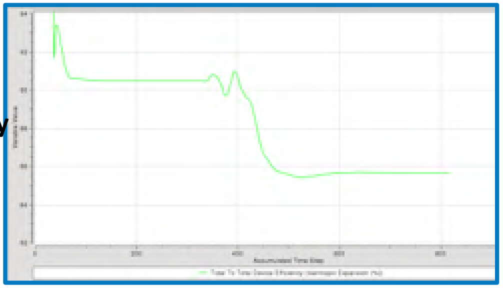
Harmonic Analysis (Harmonic Balance) and Frequency Based Methods

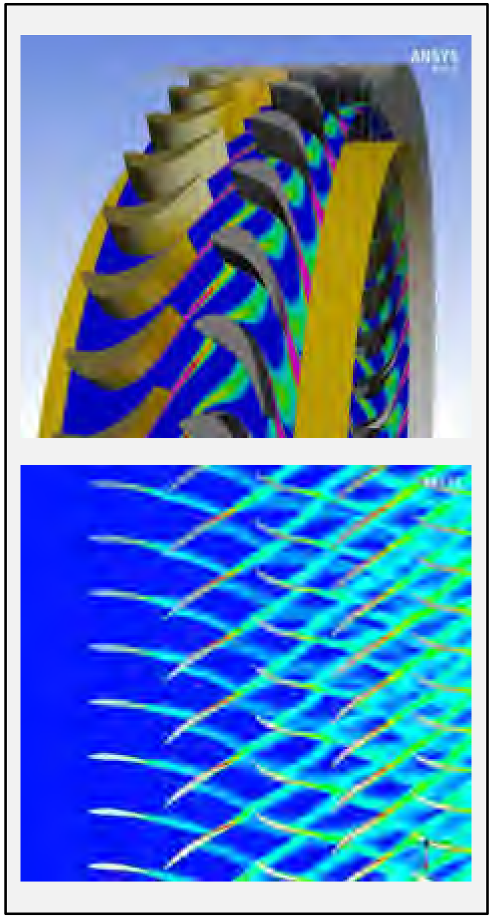
- **Turbomachinery flow: often transient and periodic**
  - Instead of marching in time to get final steady-periodic (some call it transient periodic) state
  - and converge fast on steady-periodic



Transient solution convergence

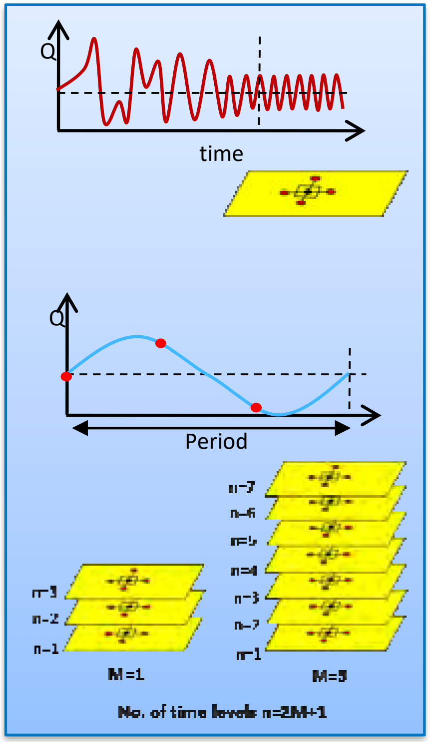
Hybrid time-frequency solution convergence



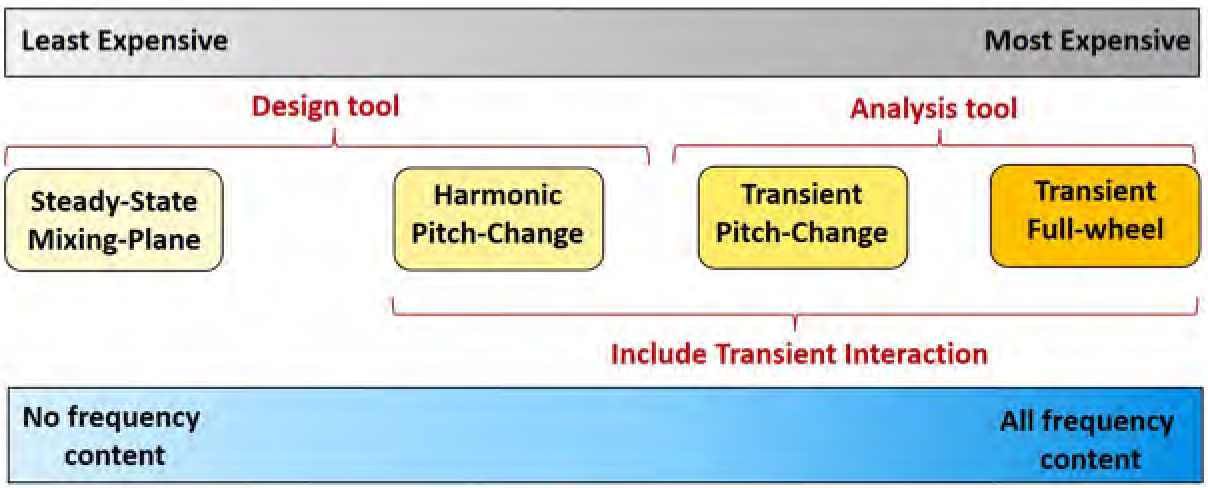


Harmonic Analysis ANSYS CFX Implementation

- Based on the Harmonic Balance/Time Spectral method of Hall et al. , Gopinath et al. (2002, 2007)
- Faster solution for transient periodic flow
- Transform time-dependent solution to a coupled set of steady "like" equations which correspond to uniform (minimum of 2M+1) sampling within a time period.



- **Full toolset of blade row methods available in ANSYS CFX**
  - Steady-state, transient with and without pitch change, time and frequency domain
- **New Harmonic Analysis (HA) method provides fast solution to transient periodic flow witl**



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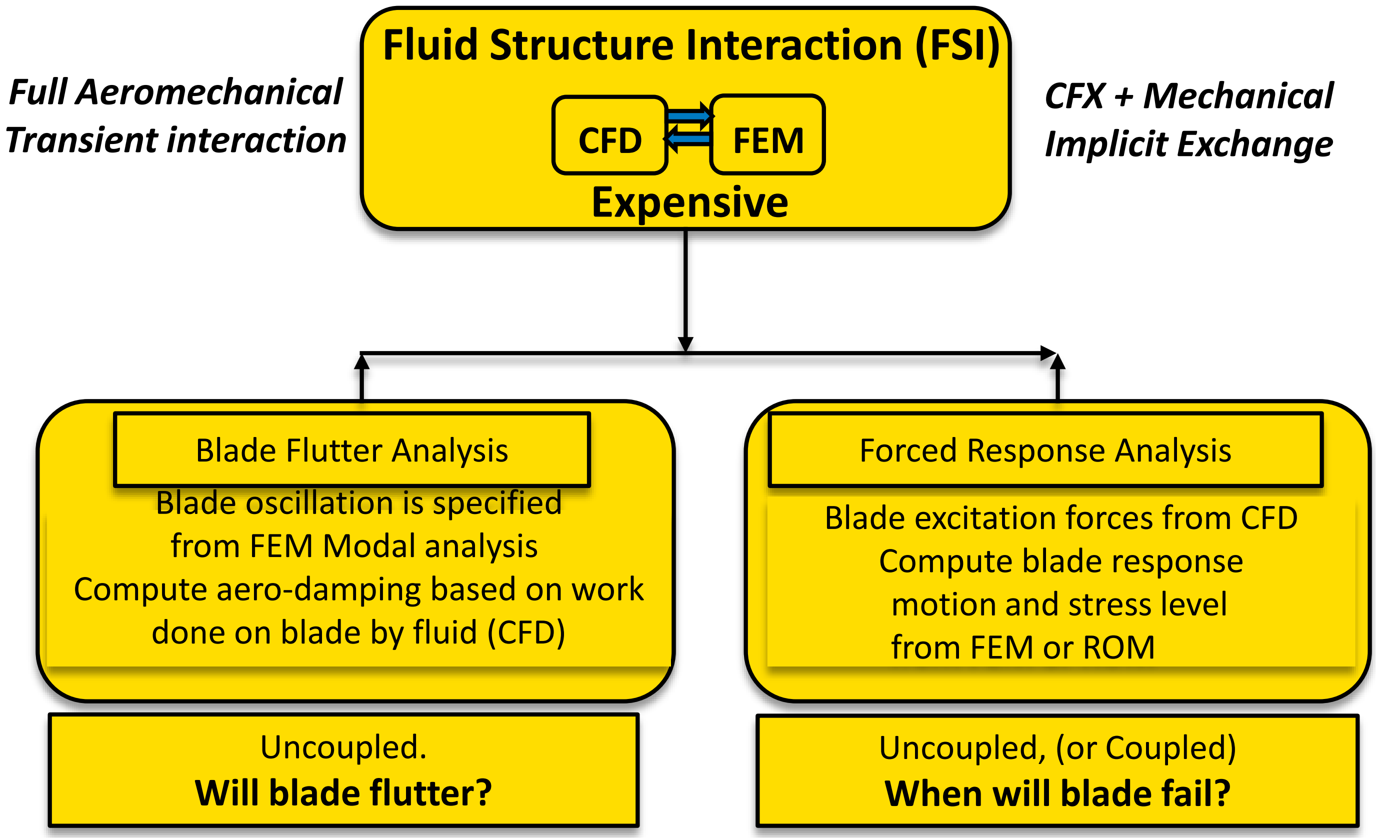
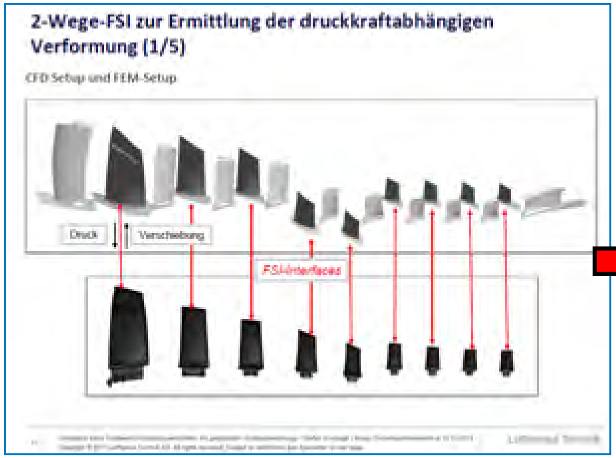
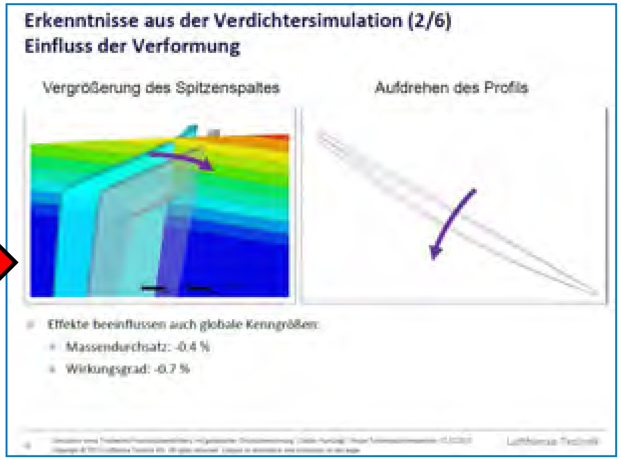
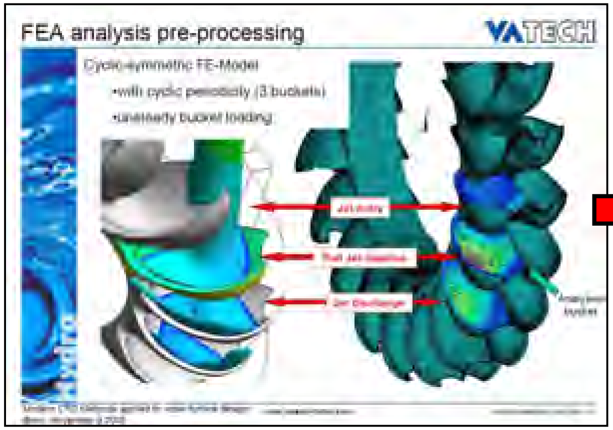
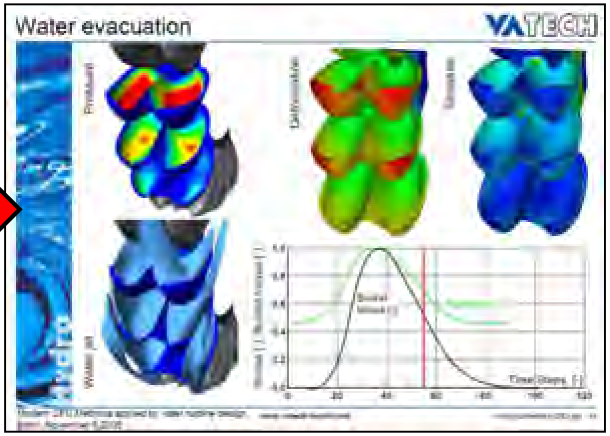

Full Aeromechanical
Transient interaction
Fluid Structure Interaction (FSI)
CFD
FEM
Expensive
CFX + Mechanical
Implicit Exchange
Blade Flutter Analysis
Blade oscillation is specified
from FEM Modal analysis
Compute aero-damping based on work
done on blade by fluid (CFD)
Forced Response Analysis
Blade excitation forces from CFD
Compute blade response
motion and stress level
from FEM or ROM
Uncoupled.
Will blade flutter?
Uncoupled, (or Coupled)
When will blade fail?

Full 2-Way FSI, R/S + Transient Mechanical Analysis







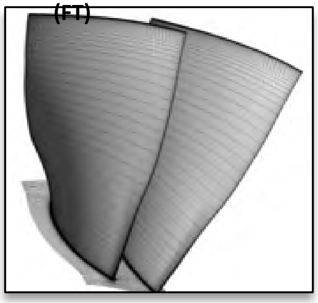


Flutter Analysis

- **Synopsis:**
  - Aeromechanical vibration damped by the flow, or destabilized?
  - Compute natural frequencies and mode shapes from Modal analysis, impose this motion on blade for CFD solve
  - Compute damping factor by integral of work done by blade on the fluid over an oscillating period (+ or -)
  - Explore a range of “nodal diameters” or IBPA
- **Pitch change:**
  - FT method critical for efficiency: nodal diameter specified
  - Huge CPU and setup savings relative to full wheel
  - Multi-disturbance: gust & modal frequencies
- **Typical application:**
  - Axial or radial rotor blade, isolated to multistage
  - Flutter of compressor fan under inlet distortion

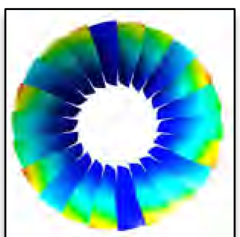
Full-wheel Model

Reduced Model (FT)



Blade Flutter Workflow

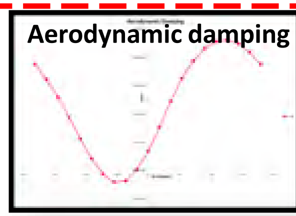
- **Determine if blade will potentially enter self-sustained harmful vibration (flutter), due to the cyclic loading experienced by the blade when its undergoing vibration at natural frequency**

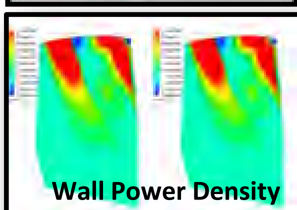


Import solid model

Pre-stressed modal analysis in ANSYS Mechanical

Export mode shapes and frequencies





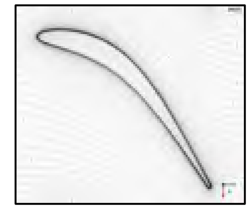
Generate CFD grid in TurboGrid

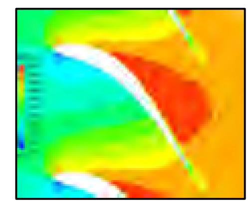
Steady CFX solution

Setup CFX for unsteady, oscillating blade

Obtain CFX FT-TRS for a range of mode shapes + frequencies, amplitudes and nodal diameters

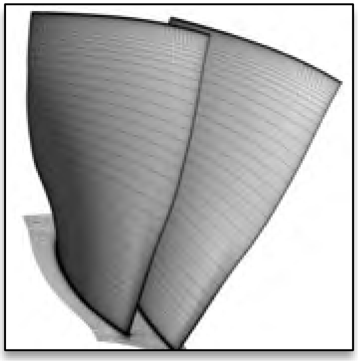
Post process results and examine for stability (damping)

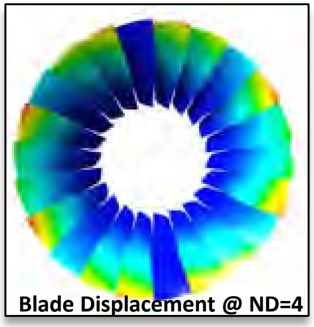


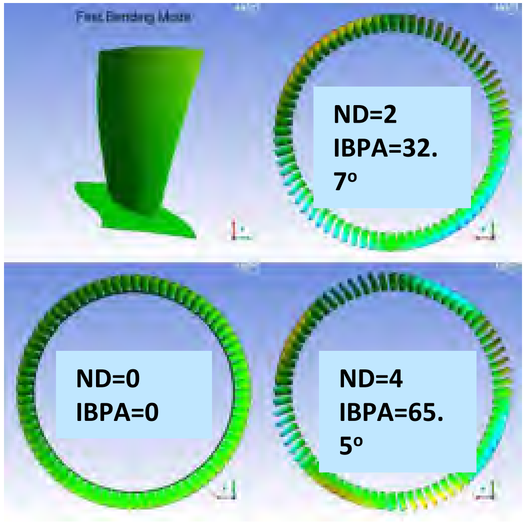


Example: Rotor 67 Aerodynamic Damping

- **GT2013-95005**
  - R. Elder, I. Woods, S. Patil , W. Holmes, R. Steed & B. Hutchinson
- **Geometry:**
  - Rotor-67 22 Blades
  - Design speed 16043 rpm
  - Frequency 534 Hz
- **Simulation:**
  - Modal analysis:
    - Fixed support Cyclic symmetry
    - 1st Bending mode
  - Steady-State → mesh sensitivity
  - Transient: FT & Ref-Periodic
    - 44 time step per blade vibration cycle
    - -8 to + 8 Nodal Diameter (IBPA)
    - Amplitude 1.5% & 3.0%



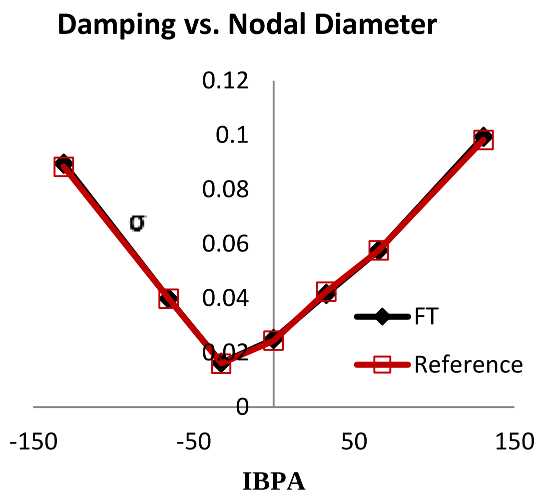


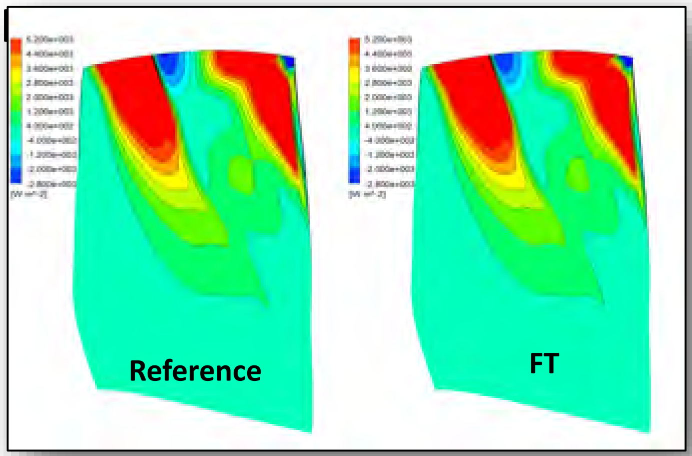


$$IBPA = \pm \frac{2\pi}{NB} \bullet ND$$

Example: Rotor 67 Aerodynamic Damping

- **FT solution compares well with Periodic -Ref. Solution**
- **FT solution is 7x faster than Reference full wheel solution (depends on ND)**
- **Computation savings is proportional to blade count for full**

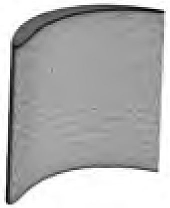


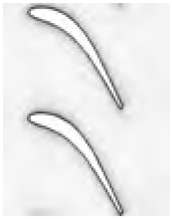


Distribution of time-average wall power density (w/m²)

Harmonic Analysis Example: STCF-11

- **Standard Configuration 11 (STCF-11)**
  - Annular Turbine Cascade
  - IGTI 2016-57962 (Sunil Patil et al.)
  - 20 Blades
  - Vibration defined by sinusoidal oscillation
  - Bending orthogonal to chord @ 209 Hz
  - Range of IBPA (Nodal Diameter) simulated
  - Subsonic case: Mach @ inlet 0.69
- **Compare Three simulations:**
  - Reference, Transient periodic sector @ 128 tspp
  - FT-Transient (2 passages) @ 128 tspp
  - FT-Harmonic (2 passages) @ m=1



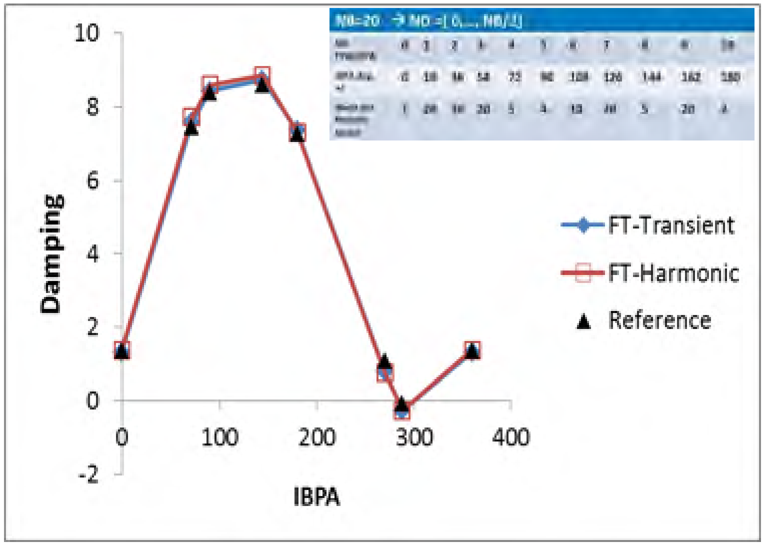


Harmonic: m=1 sufficient to resolve flow

Transient: 128 tspp is timestep independent solution

Harmonic Analysis Example: STCF-11 Subsonic

- **Aerodynamic Damping**

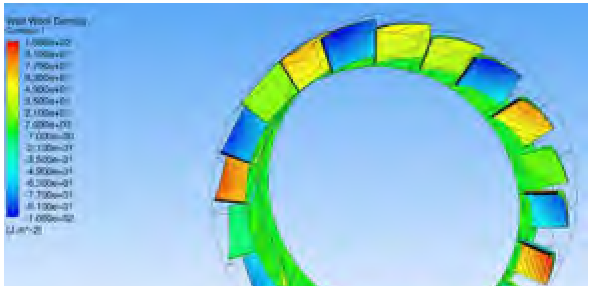


$$\text{Damping} = -\int_{A_i} \tilde{c}_p \cdot \sin(\Phi) dA_i$$

Excellent agreement between:

- **Reference** , Transient Periodic Sector (aka Symmetric Sector)
- 2-passage **FT-Transient**
- 2-passage **FT-Harmonic (m=1)**

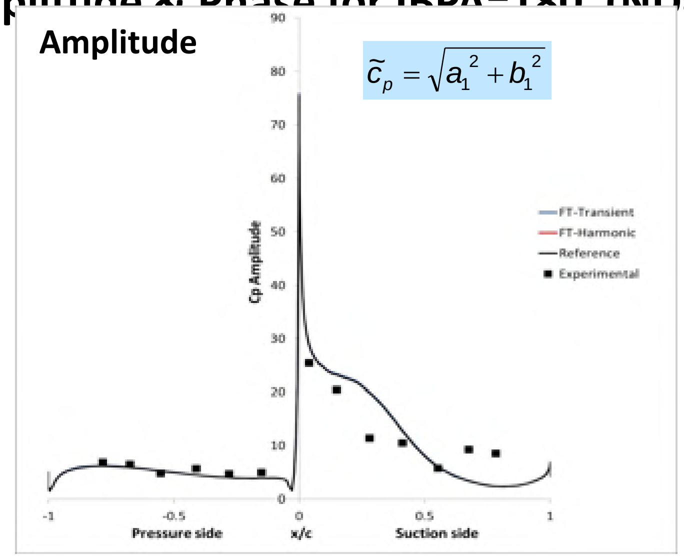
For all IBPA (nodal diameters)

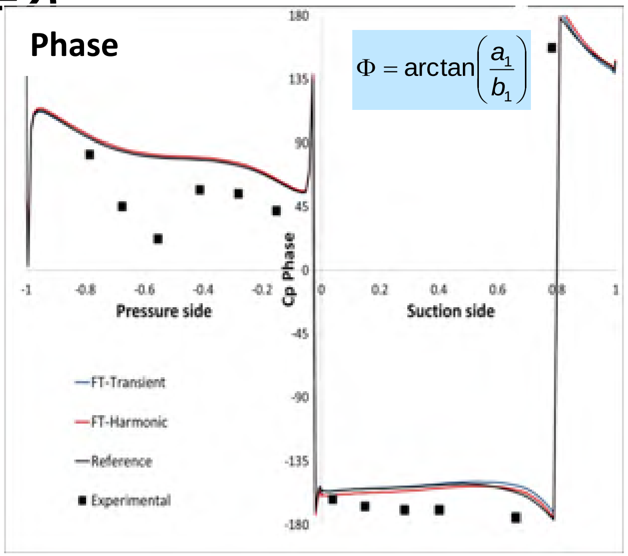


Wall Work Density
FT-Harmonic
IBPA=126 (ND=7)

Harmonic Analysis Example: STCF-11 Subsonic

- **Amplitude & Phase for IBPA=180 (ND=2)**





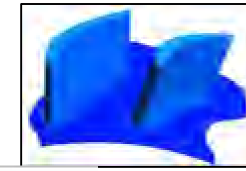
Good comparison between numerics and experimental data

FT-Harmonic: m=1 & 15 pseudo time-step per oscillating cycle

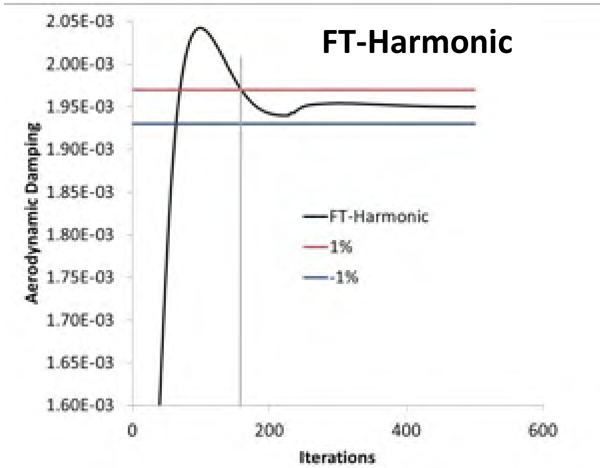
FT-Transient & transient full-periodic sector : 128 tspp

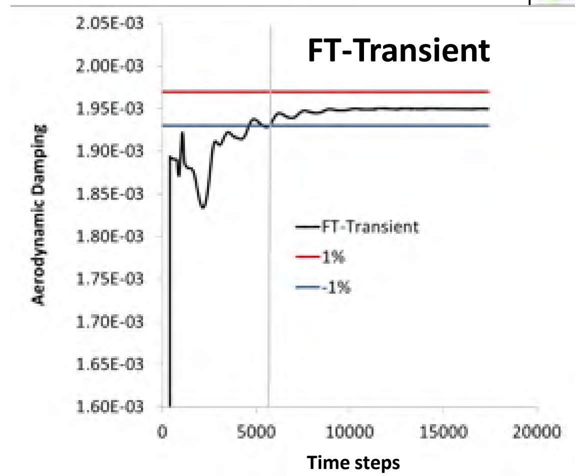
Other examples in IGTI 2016-57962

Harmonic Analysis Example: STCF-11 Subsonic



- **Computation efficiency**





IBPA=108 deg. (ND=6)	Reference Transient Periodic sector (10 passages)	FT-Transient (2-passages)	FT-Harmonic m=1 (2-passages)
Speed Up	1	4 X	100 X

25 X

感谢聆听

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