AEROMECHANICAL DESIGN OF A 10 MWE SCO2 TURBINE

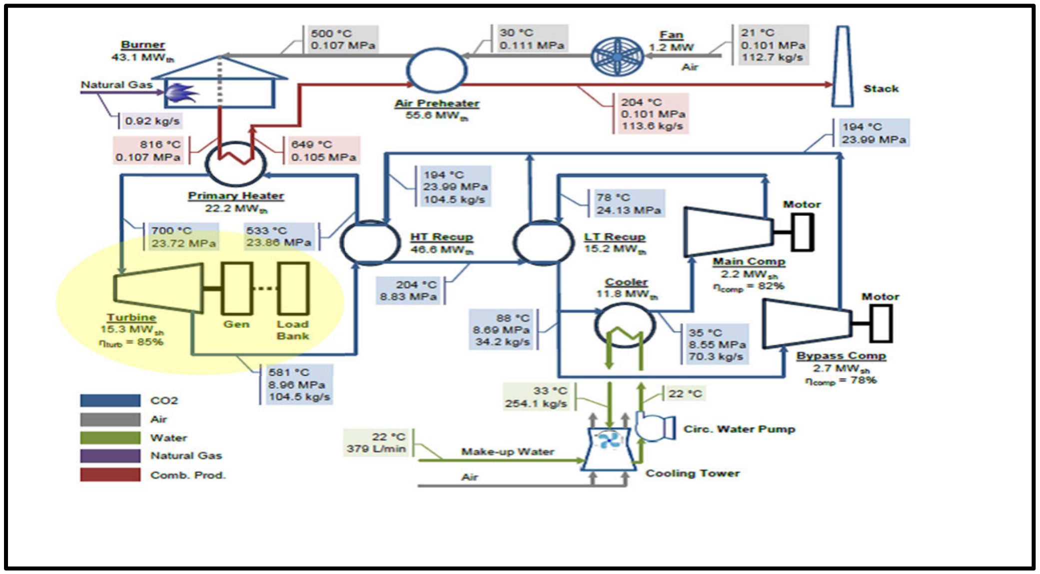
Stefan D. Cich

Jeff Moore, PhD

Jason Mortzheim

Rajkeshar Singh

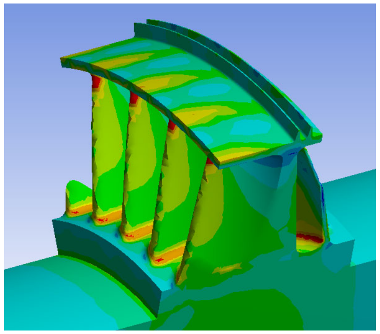
Overview



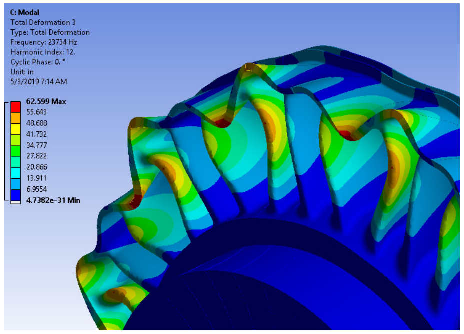
- This presentation is focused on the mechanical design of the STEP Turbine rotor that will be used in the pilot scale demonstration of a 10 MWe RCBC at Southwest Research Institute
- Primary Focus is on Blade Aeromechanics

Blade Aeromechanics?

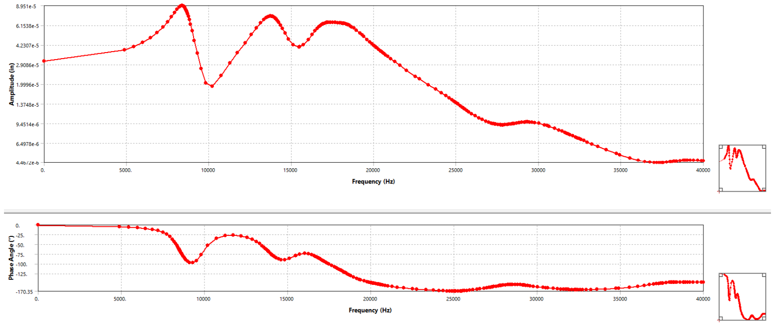
- Evaluate performance of Turbine Blades with a focus on Stress, Modal, and Harmonic Response
- Ensure appropriate separation margin to blade modes
- Ensure high cycle fatigue limits are met if blade modes are excited
- Suggest design changes to shift modes or reduce pull load and bending stresses as needed to meet design requirements of the machine



Von Mises Equivalent Stress

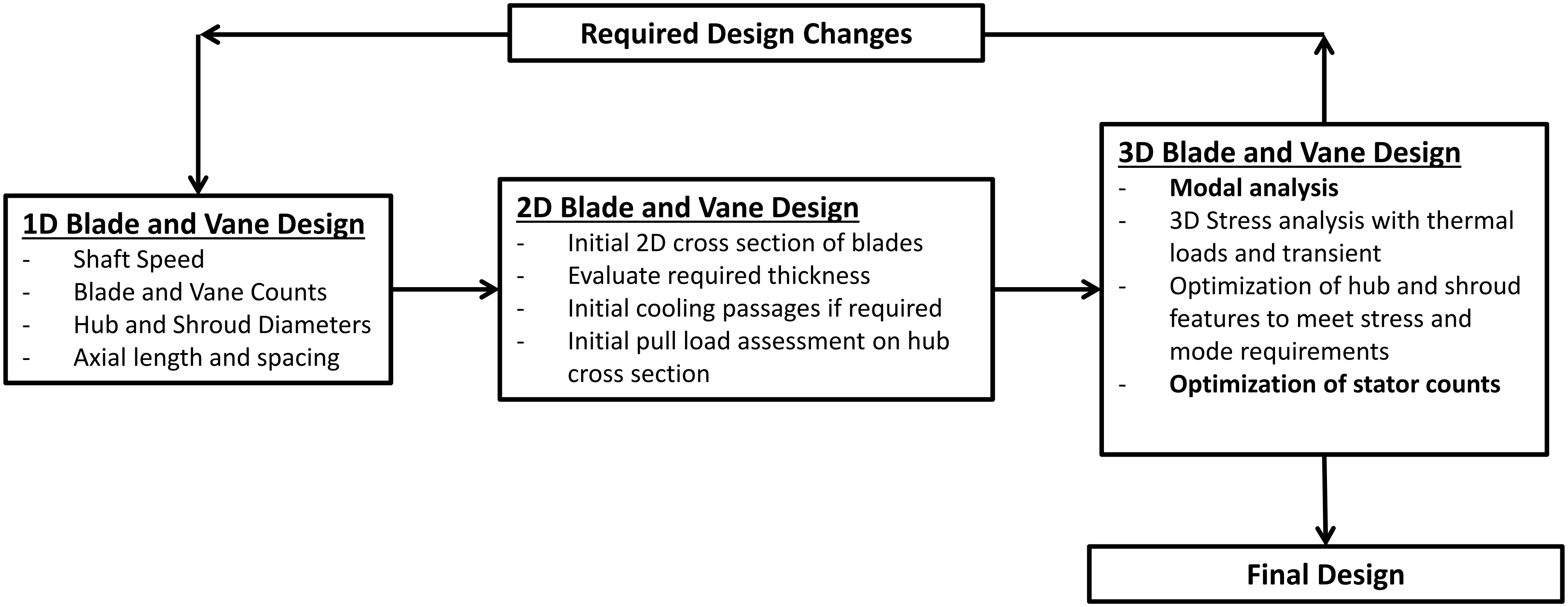


Modal Frequencies



Harmonic Response

Design Process



Required Design Changes

1D Blade and Vane Design

- Shaft Speed
- Blade and Vane Counts
- Hub and Shroud Diameters
- Axial length and spacing

2D Blade and Vane Design

- Initial 2D cross section of blades
- Evaluate required thickness
- Initial cooling passages if required
- Initial pull load assessment on hub cross section

3D Blade and Vane Design

- **Modal analysis**
- 3D Stress analysis with thermal loads and transient
- Optimization of hub and shroud features to meet stress and mode requirements
- **Optimization of stator counts**

Final Design

Fundamentals

- ω is natural frequency of an object. Increased with stiffness and decreases with mass
- k is the stiffness of an object
- m is the mass of an object

$$\omega = \sqrt{\frac{k}{m}}$$

Stiffness of blade. Affected by geometry, thickness, length, and material modulus of elasticity

Mass of blade. Affected by overall thickness, internal geometry, and density of the material

Defines frequency of various blade modes: 1st bending, torsional, 2nd bending, etc.

- F is the applied force
- δ is deflection
- k is stiffness
- E is the material modulus of elasticity
- I is the area moment of inertia
- L is the unsupported length

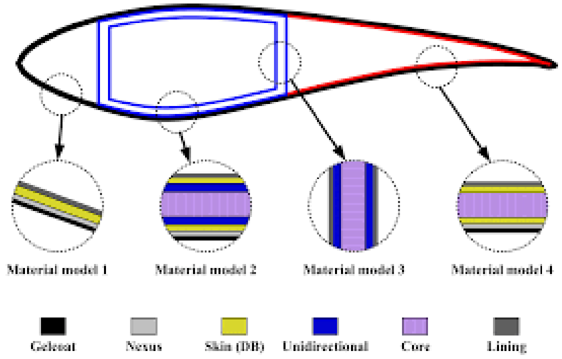
$$\frac{F}{\delta} = k = \frac{3EI}{L^3}$$

Higher Modulus leads to higher stiffness. Modulus decreases with higher temperatures and will decrease the objects stiffness

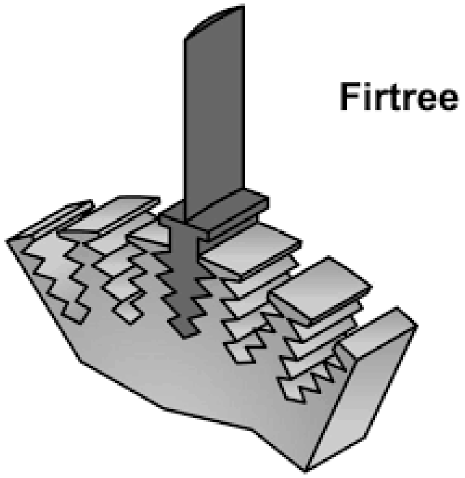
Area moment of inertia is highly effected by the objects cross section. Hollow objects have lower area moments of inertia AND lower mass

Is affected by the blade height. Full shrouded blades have L = ½ the height. Unshrouded blades, L = blade height

Other Applications



Wind turbine blades utilizing different materials to reduce weight and maintain high stiffness

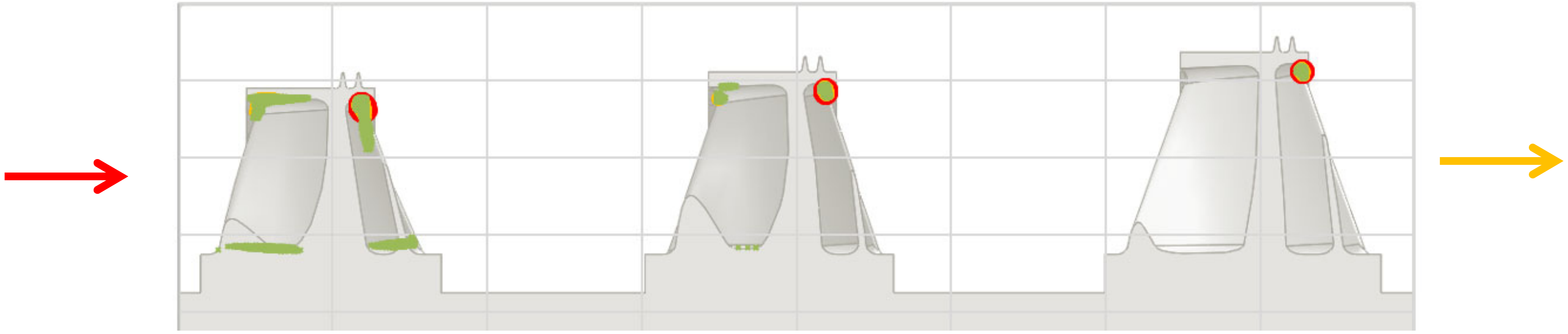


Gas and steam turbine blades utilizing fir tree connections to distribute pull load stresses while also allowing for frictional damping

Low Pressure turbine blades utilizing snubbers to reduce unsupported blade length and increase blade modes / allow for frictional damping

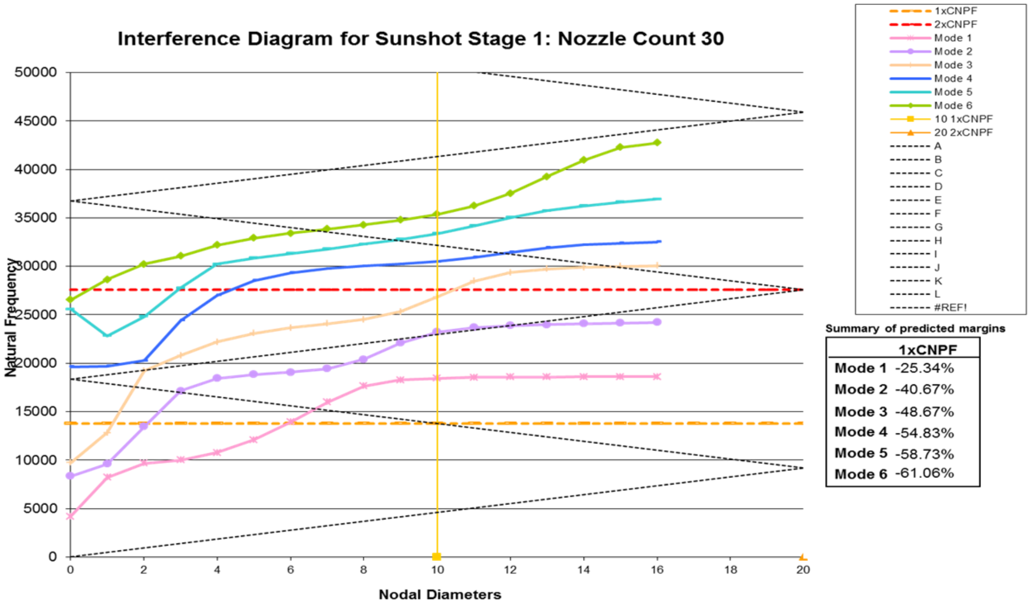
sCO$_2$ Turbines

- sCO$_2$ offers the benefit of high power density (high mass flow) and lower enthalpy (work) across turbomachinery
  - High power density → Smaller flow paths
  - Lower enthalpy changes → Fewer stages
- With the benefits comes some of the unique challenges for sCO$_2$ flow paths
  - Fewer stages + High pressure → Large pressure drop per stage
  - High Pressure → Thicker blades, small throat areas, high blade count
  - High blade count → High frequency excitations
  - Smaller Flow path + Thicker blades → monolithic shafts (no blade inserts)
  - Monolithic shafts → No external damping



STEP Turbine

- Turbine Boundary Conditions
  - Speed: 27,000 rpm
  - Temperature: 715^{o}C
  - Pressure Ratio: ~3X
  - Inlet Pressure: ~250 bara
  - Power: ~16 MW$_{mech}$
- Turbine Sizing
  - Initial sizing based on Sunshot rotor design (4 stages, smaller hub)
  - To improve rotordynamics, decision was made to go with 3 stage and larger hub
  - Initial Design – 40 Blades per Stage with 28 Nozzles per stage



Summary of predicted margins

	1xCNPF
Mode 1	-25.34%
Mode 2	-40.67%
Mode 3	-48.67%
Mode 4	-54.83%
Mode 5	-58.73%
Mode 6	-61.06%

Preliminary Layout → Initial Stress & Modal Assessment → Iterations to meet design requirements

Design Requirements

- Design Life
    - 30 years (100,000 hours) → Creep limitations
    - 11,000 cycles (daily start up and shut down) → Low cycle fatigue
    - < 30 minute start up → High thermal strains
- Design Goals
    - At steady state operating conditions, meet design life (stress limits)
    - At peak stresses during start up and shutdown, meet cyclic life (strain limits)
    - Fast start up (low thermal stresses)
    - Due to no damping, mode avoidance (modal frequencies)

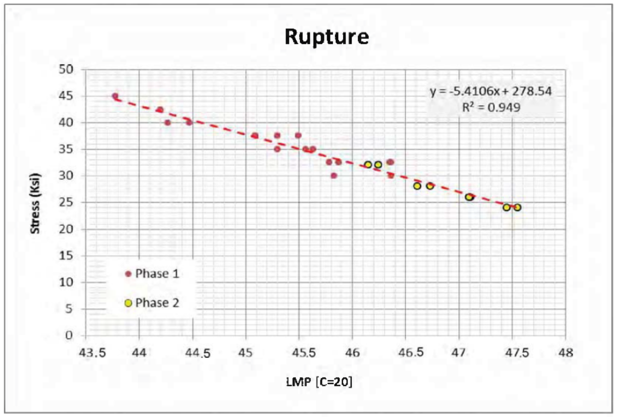
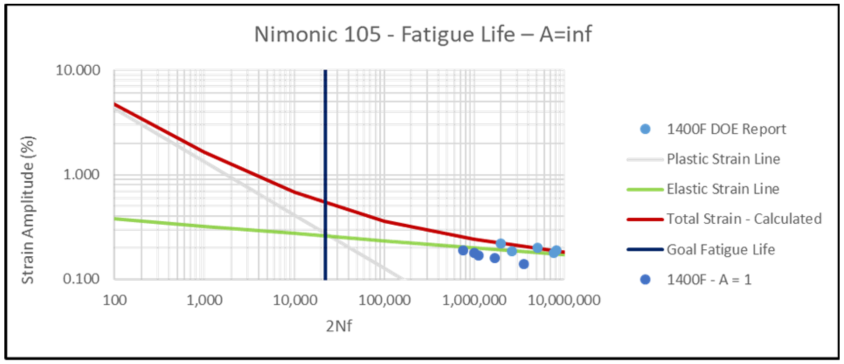
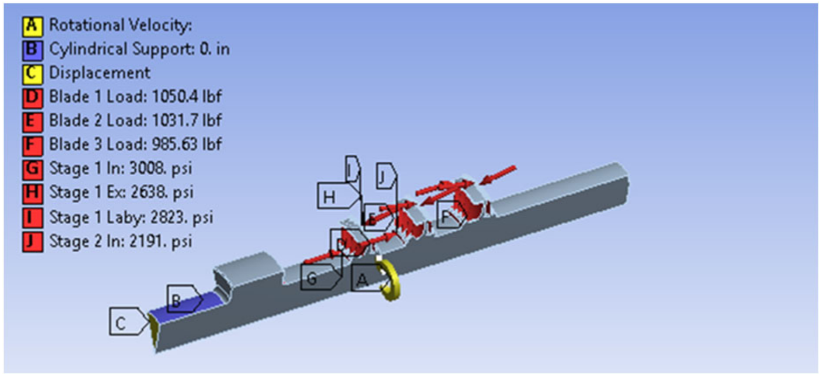


Figure 16: Larson-Miller Parameter (LMP) – Rupture Stress plot of Nimonic 105

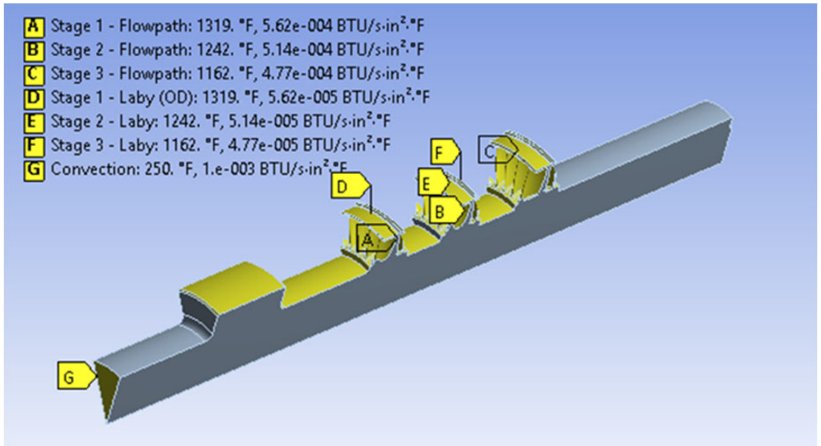


Stress Analysis

- Boundary Conditions
  - Apply ALL loads to the turbine flow path
    - Torque (High)
    - Pressure differential (High)
    - Inertial loads (High)
    - Thermal gradients (Low)
    - Centrifugal loads (Low)
- Stress only analysis with Pressure and Centrifugal loads ONLY. Limitations based on Creep Rupture
- Thermal ONLY analysis with Transient thermal gradients. Limitations based on LCF



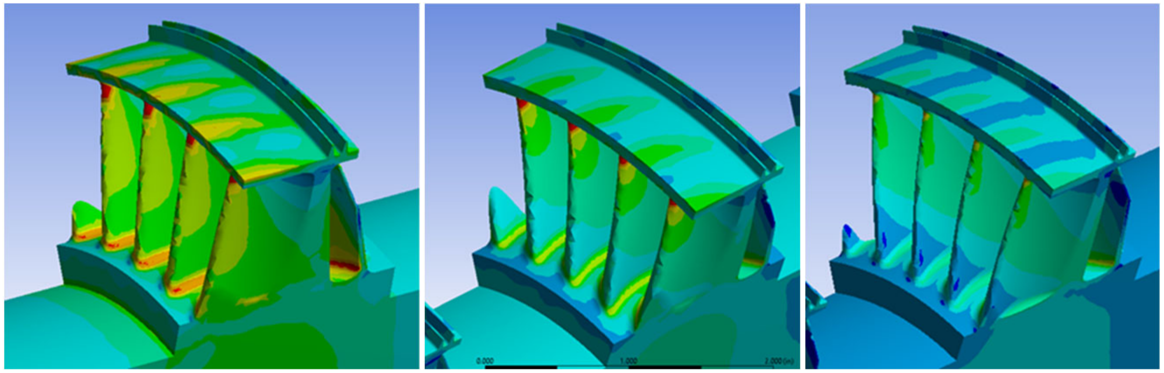
A Rotational Velocity:
B Cylindrical Support: 0. in
C Displacement
D Blade 1 Load: 1050.4 lbf
E Blade 2 Load: 1031.7 lbf
F Blade 3 Load: 985.63 lbf
G Stage 1 In: 3008. psi
H Stage 1 Ex: 2638. psi
I Stage 1 Laby: 2823. psi
J Stage 2 In: 2191. psi

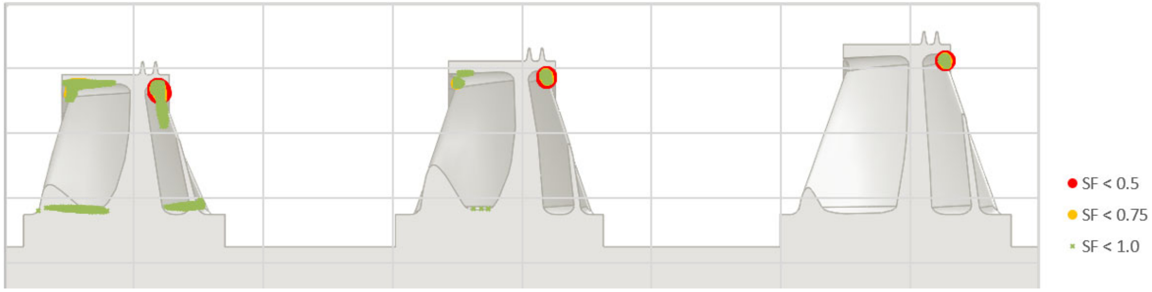


A Stage 1 - Flowpath: 1319. °F, 5.62e-004 BTU/s·in²·°F
B Stage 2 - Flowpath: 1242. °F, 5.14e-004 BTU/s·in²·°F
C Stage 3 - Flowpath: 1162. °F, 4.77e-004 BTU/s·in²·°F
D Stage 1 - Laby (OD): 1319. °F, 5.62e-005 BTU/s·in²·°F
E Stage 2 - Laby: 1242. °F, 5.14e-005 BTU/s·in²·°F
F Stage 3 - Laby: 1162. °F, 4.77e-005 BTU/s·in²·°F
G Convection: 250. °F, 1.e-003 BTU/s·in²·°F

Stress Results

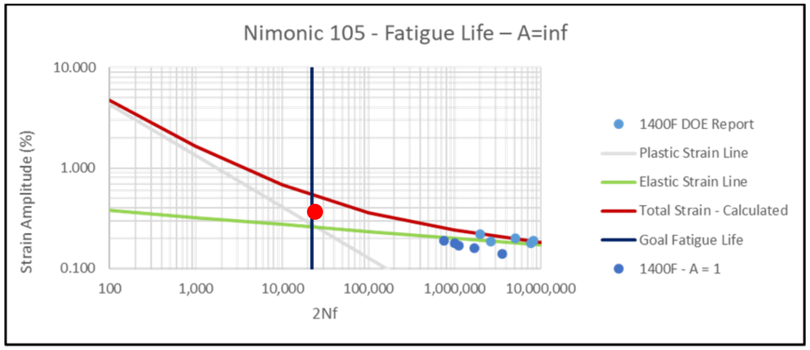
- Due to smaller blades, stresses due to loads and strain are relatively low, especially compared to gas turbines
- Besides localized high stress points, the entire blade is below creep rupture limits
- Localized areas are concern for LCF

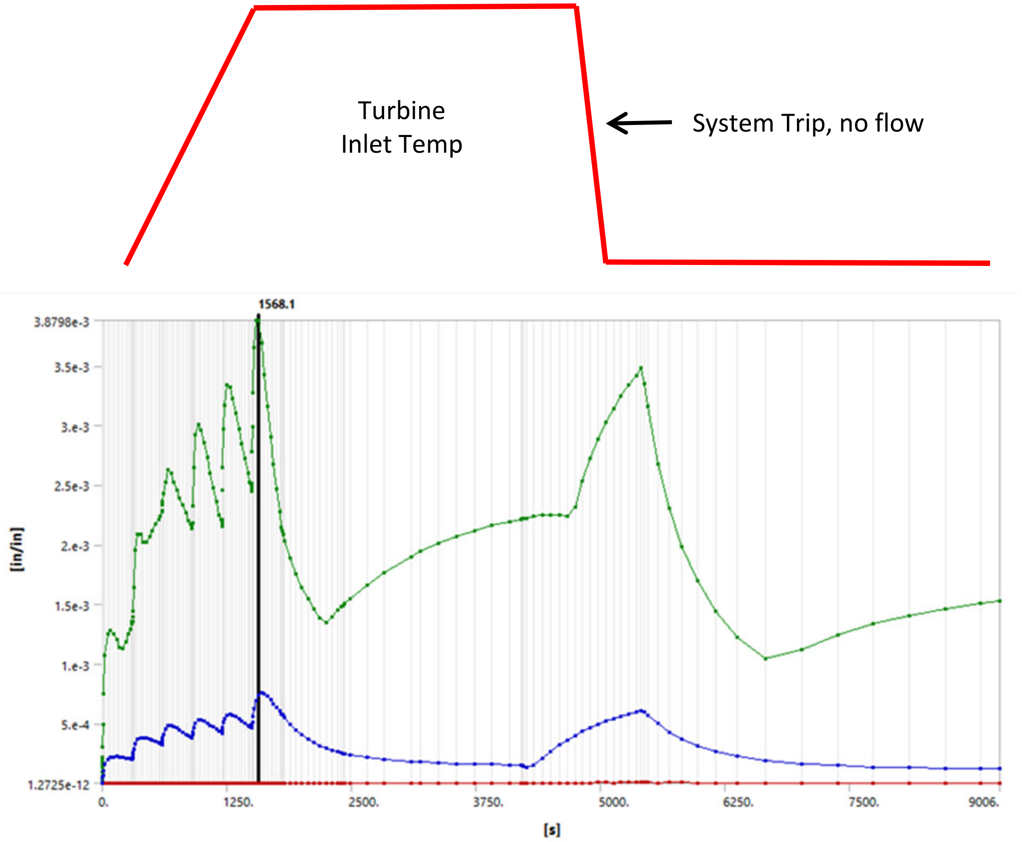




Stress Results

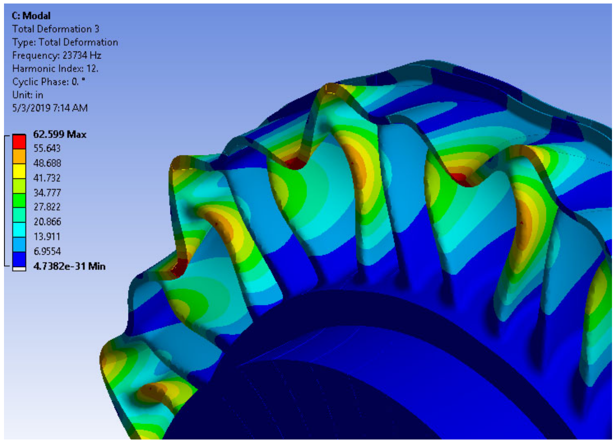
- For thermal transients, a start up and shut down profile have to be established
- For this system:
    - 40 Minute start up
    - Steady Hold at Full Operating Conditions
    - Emergency shutdown (flow cut off)
    - Natural Convection cool down
- Peak stresses occur when turbine flow is ramped up to max flow after pre-heating
- Based on testing experience for Sunshot, worst case is an emergency trip with throttle valve closing and system settling out
- Initial analysis looks at Elastic ONLY stresses. If high enough, elastic-plastic would be evaluated

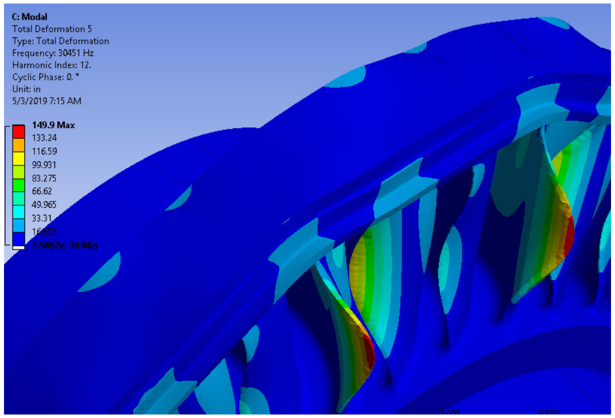




Modal Analysis

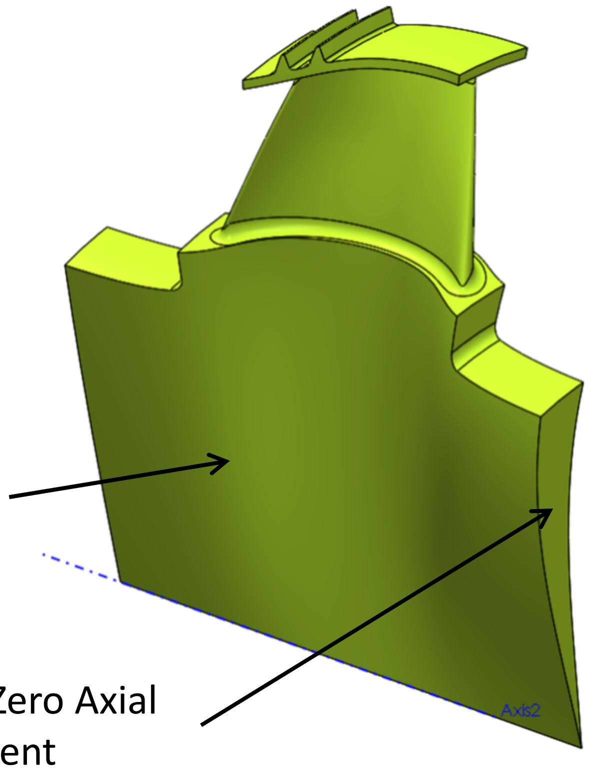
- Perform modal assessment to look for ALL blade modes within the operating range with 15% margin
- Frequency Range = Max Speed X 1.15 X Max(Upstream Vane Count; Downstream Vane Count) X 2
    - 1.15 Factor adds on 15% margin to max rotational speed
    - 2X factor includes the 2X interaction frequency
- In most cases, downstream interactions can be ignored. Based on blade spacing and fluid density
- If modeling an assembly, all connections will be assumed bonded
- To look at effect of frictional contacts, a harmonic response model will have to be set up
- **Singh's Advanced Frequency Evaluation (SAFE) Diagram**
    - Shows ALL blade modes for Frequency vs Nodal Interaction
    - Good for assessing 1X and 2X interaction frequencies and determining an optimum upstream / downstream stator count
    - Congested diagram since it shows ALL of the blade modes
- **Campbell Diagram**
    - Shows blade modes for a single nodal interaction
    - Good for detailed look at single area of concern. Can easily plot how the blade mode adjusts with rotational speed and also additional lines at different temperature
    - Bad for assessing if there is another stator count that could lead to better separation margin





Modal Analysis

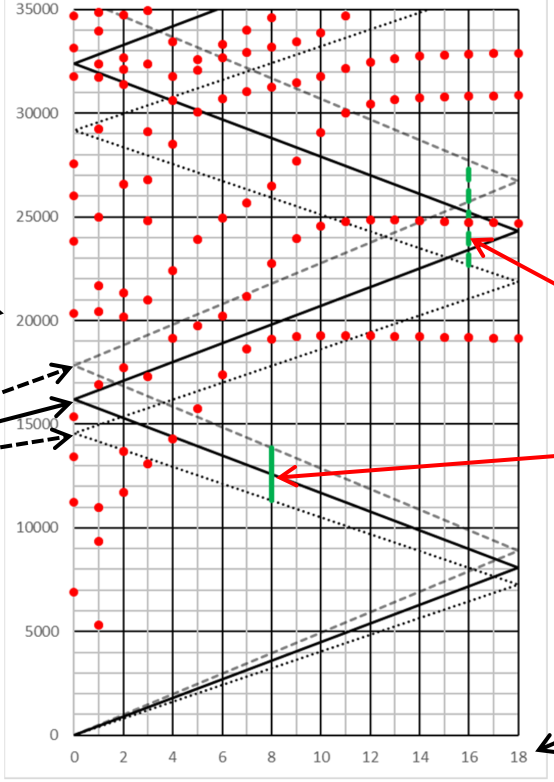
- Key material properties: Density and Modulus of Elasticity at operating temperature
- Rotation and blade loading will stiffen the blade and increase modes slightly
- Boundary conditions are critical. Artificially stiff / soft supports will lead to incorrect modal results
- Cylindrical Symmetry about rotational Axis if solid shroud
- No symmetry if split at shroud



Cylindrical Symmetry about rotational Axis

Planar or Zero Axial Displacement

SAFE Diagram



Blade Mode based on nodal interaction

Blade mode frequency

15% Above Running Speed
Running Speed
15% Below Running Speed

56X Interaction

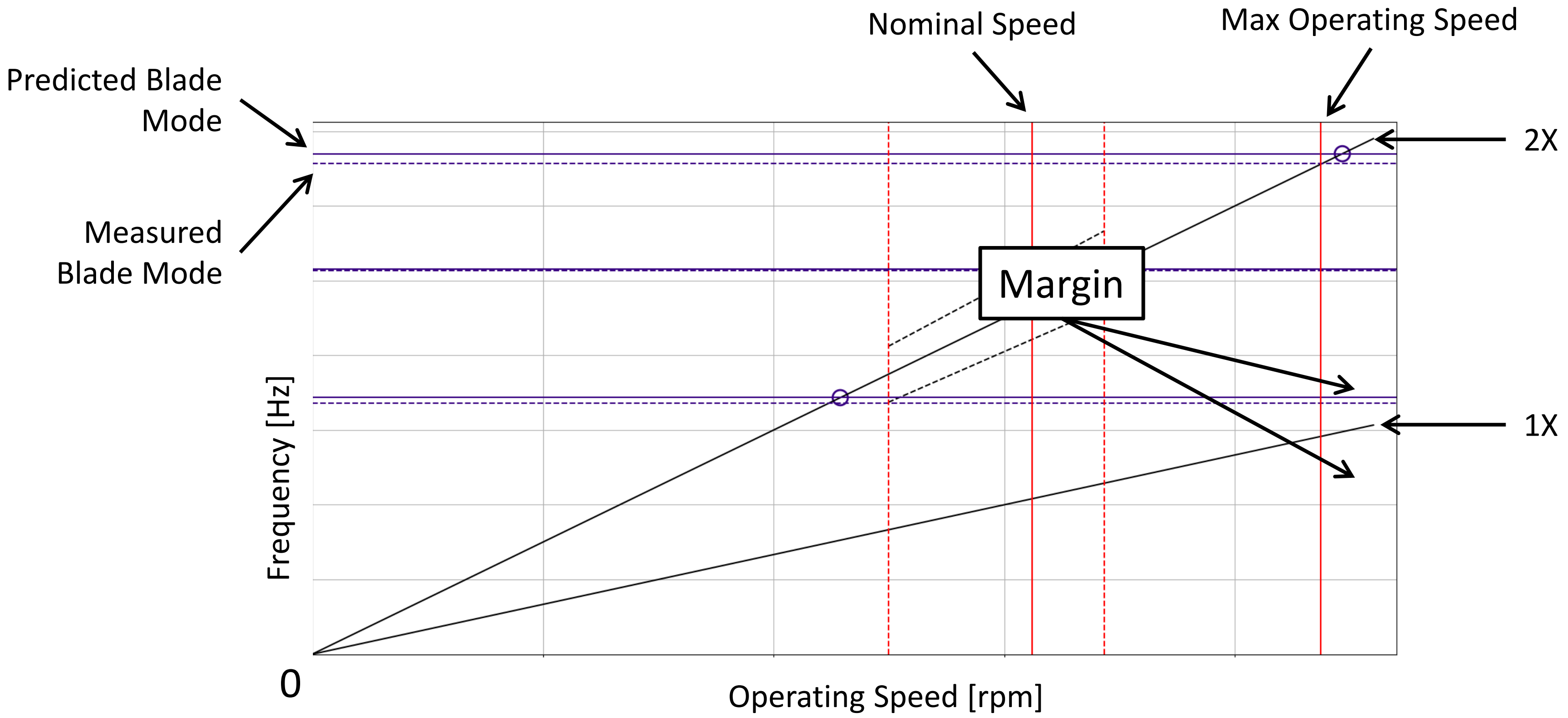
28X Interaction

Blade Count / 2
Max Nodal Interaction

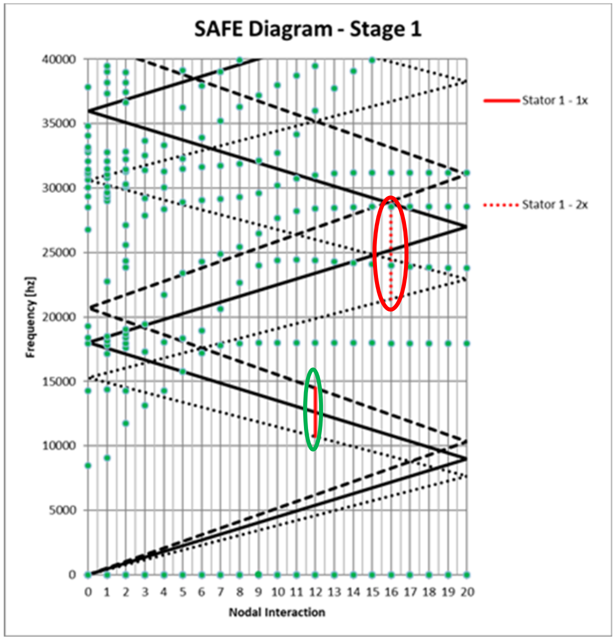
SAFE Diagram Example

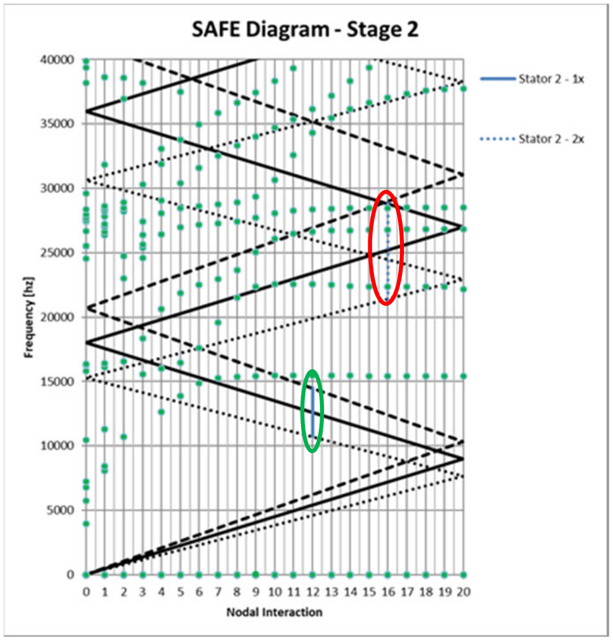
- 36 Blades
- 28 Upstream Stator Vanes
- Evaluate 1X and 2X Interaction Frequency
- Rotor spins at 27,000 rpm (450 Hz)
- 15% separation Margin

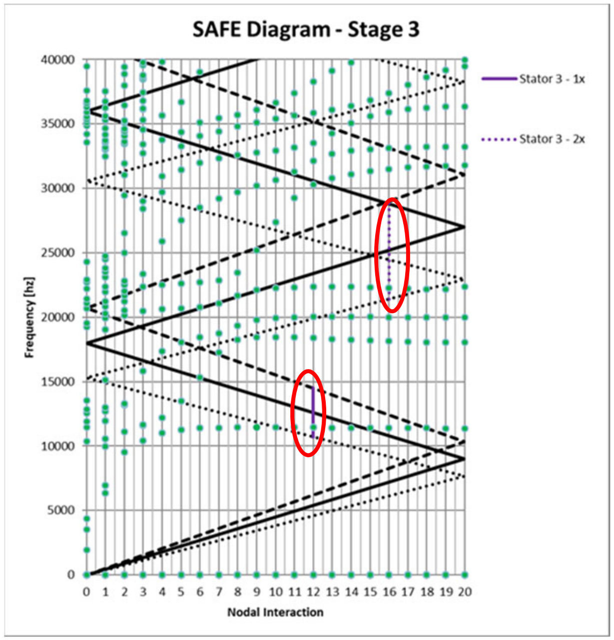
Campbell Diagram



Modal Results

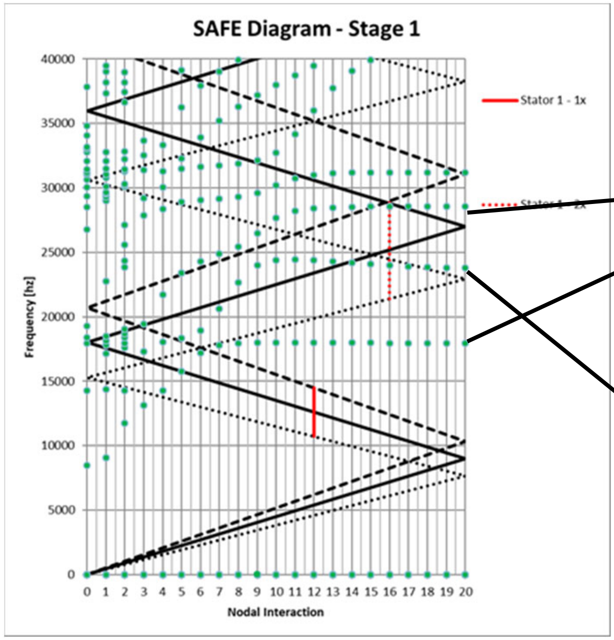

SAFE Diagram - Stage 1

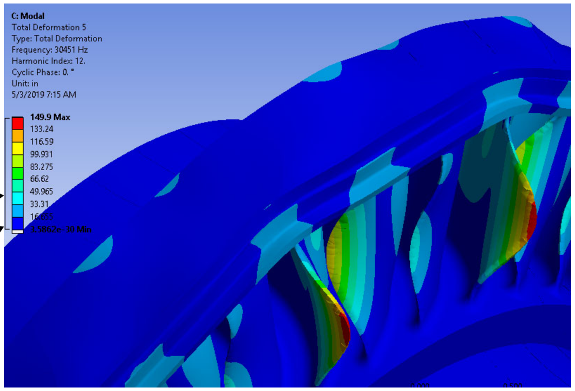

SAFE Diagram - Stage 2

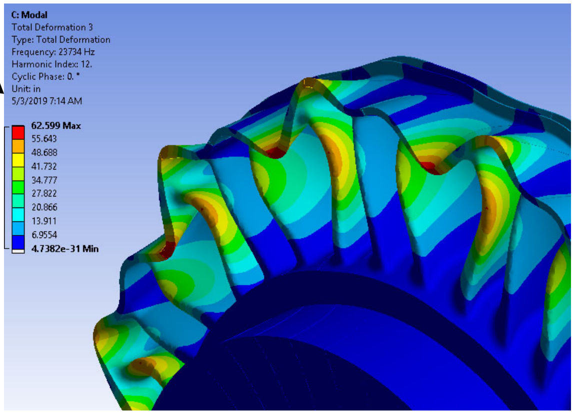

SAFE Diagram - Stage 3

- Initial Modal assessment looks at 40 blades and 28 nozzles per stage
- Stage 1 and 2 have no modes of concern at the 1X Interaction
- All stages have 2X interactions and Stage 3 also has 1X Interaction
- Options: Adjust Blade / Vane Count or Blade Redesign

Modal Results

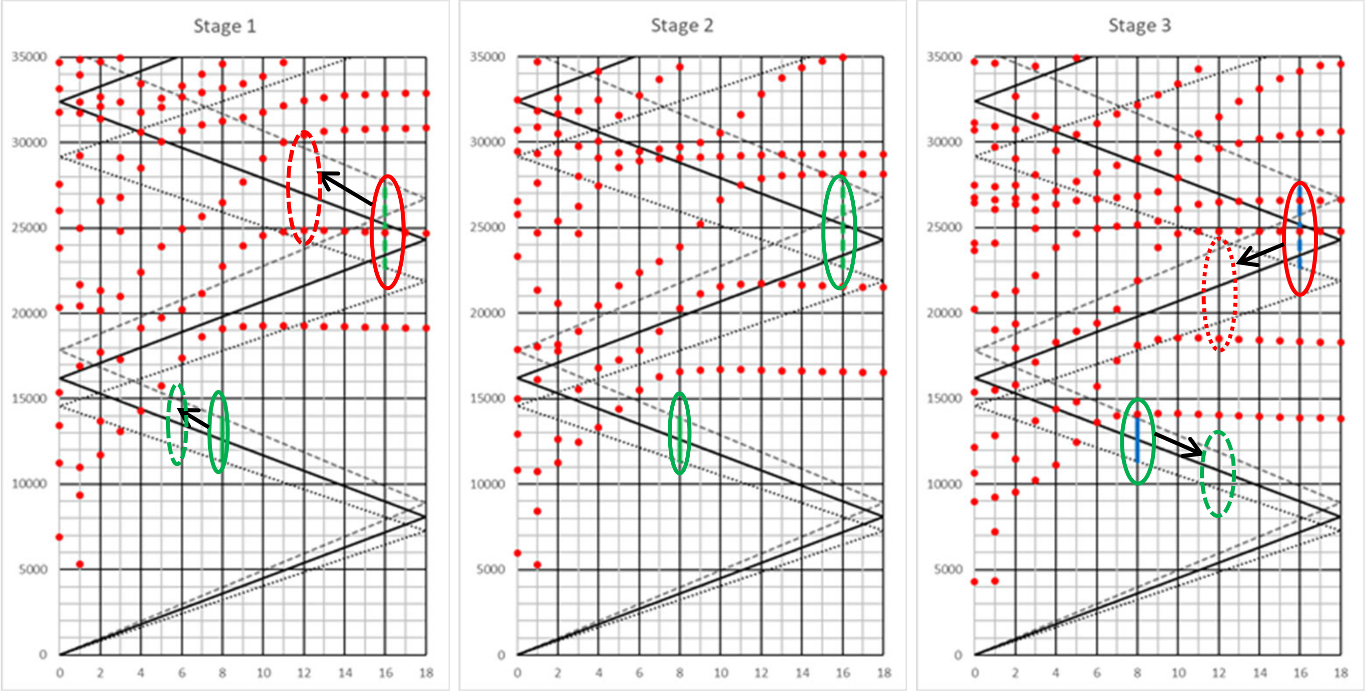



C: Modal
Total Deformation 5
Type: Total Deformation
Frequency: 30451 Hz
Harmonic Index: 12.
Cyclic Phase: 0. °
Unit: in
5/3/2019 7:15 AM


C: Modal
Total Deformation 3
Type: Total Deformation
Frequency: 23734 Hz
Harmonic Index: 12.
Cyclic Phase: 0. °
Unit: in
5/3/2019 7:14 AM

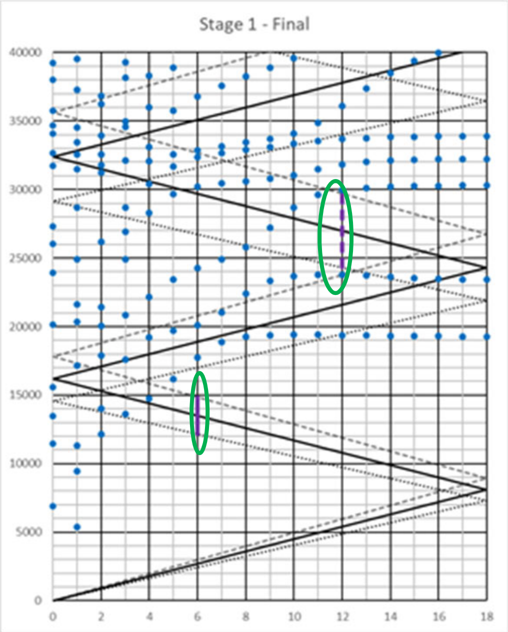
- From Top to Bottom
    - 1st Mode: 1st TE Bending
    - 2nd Mode: 1st LE Bending
    - 3rd Mode: 2nd TE bending

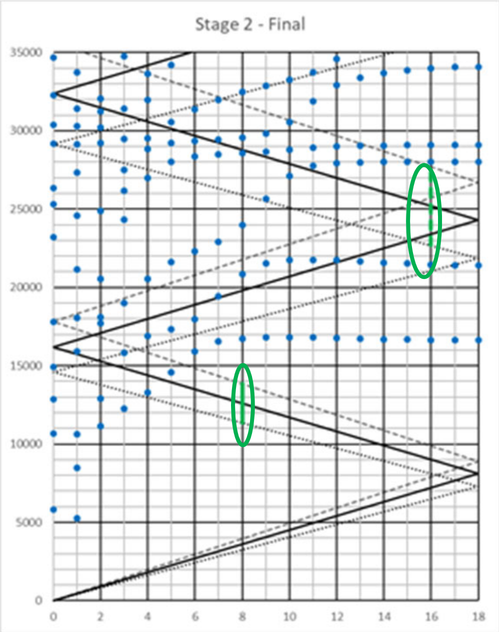
Modal Results

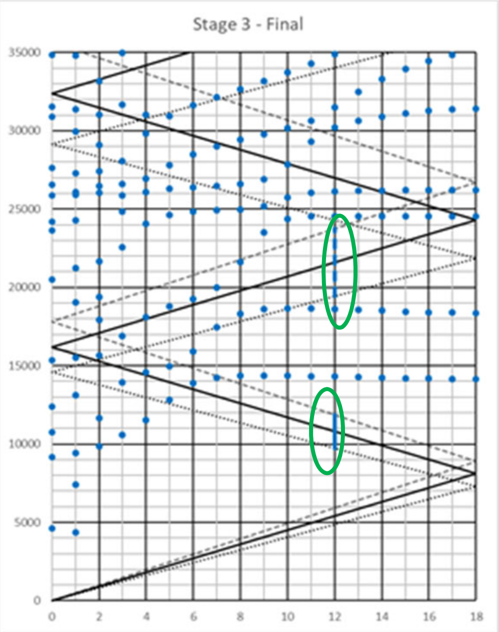


- Initial Modal assessment looks at **36 blades** and 28 nozzles per stage
- Stage 2 is acceptable as is and Stage 1 and 3 have 2X Interactions
- Adjust nozzle counts before looking at blade redesign: 30 Stage 1 Vanes & 24 Stage 3 Vanes
- Still need to shift the 2nd mode down (LE bending) on Stage 1

Modal Results


Stage 1 - Final


Stage 2 - Final


Stage 3 - Final

- Final Counts with 36 blades for all stages and Vane Counts: 30 / 28 / 24
- No concerns with 1X Interactions on all stages and all 2X Interaction is between 2nd and 3rd mode on all stages
- Besides adjusting counts, design changes iterated between blade stagger, TE and LE radius, Shroud thickness and width, labyrinth seal location

Conclusion

- Due to small size, sCO_2 turbine blades are relatively low risk due to centrifugal pull loads and pressure loading across each stage
- Also, due to small size, turbine flow paths heat up fast and are low risk for LCF concerns
- Due to high speed, high blade counts, and high vane counts, blade modes are a significant concern. In addition, with high density flow, 2X interactions need to be taken into concern
- Important to have iterative process between blade aero design and mechanical designer to finalize blade and vane counts along with minor design details
  - LE and TE Radius
  - Shroud and Labyrinth details
  - Blade lean, stagger, tip length

Acknowledgements

This material is based upon work supported by the Department of Energy, National Energy Technology Laboratory (NETL), under Award Number DE-EE0028979. This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Questions?