Structural Strength Analysis of OTEC Turbine

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Turbine in OTEC System

- Very critical and important component of a power generation system.
- Components undergo various loads but centrifugal loads are major
- Loads do vary in time.
- Failure of any component may cause serious damages

Critical Components:

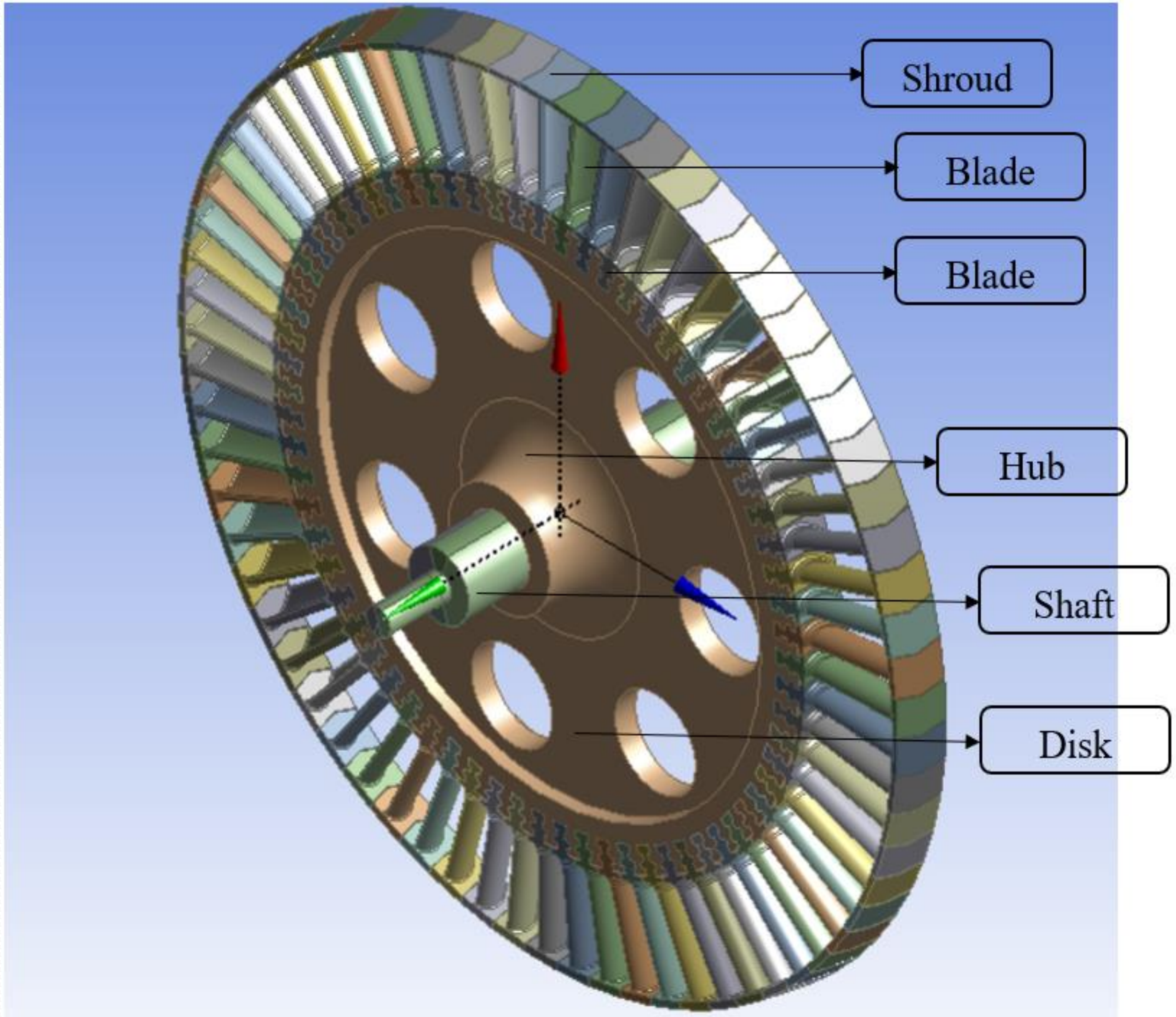
- Turbine Shaft
- Disk and Blades

Turbine Configuration

- Single stage
- Axial flow turbine
- Open Cycle
- Design similar to Steam Turbine

Based on Design by NIOT

- **Objectives**
  - Structural Analysis of Turbine Components and Assembly
  - Design of Shaft and Disk Assembly
  - Design of Blade Roots



Scope of the Project:

- **Finite Element analysis**
  - Stress Analysis: -
    - Centrifugal Load: Applied using Rotational speed as Input
      - Operational Speed [3000 Rpm]
      - Design Speed [3800 Rpm]
    - Aerodynamic Load using Pressure Distribution
  - Modal analysis (For studying vibrational response)
    - Obtain Mode shapes and Natural Frequencies
    - Generate Campbell diagram
    - Obtain critical speed
- Grid Independence Test
  - To Obtain optimal no of elements
  - To validate results
- Selection of suitable design

Model and Boundary Conditions

Shaft

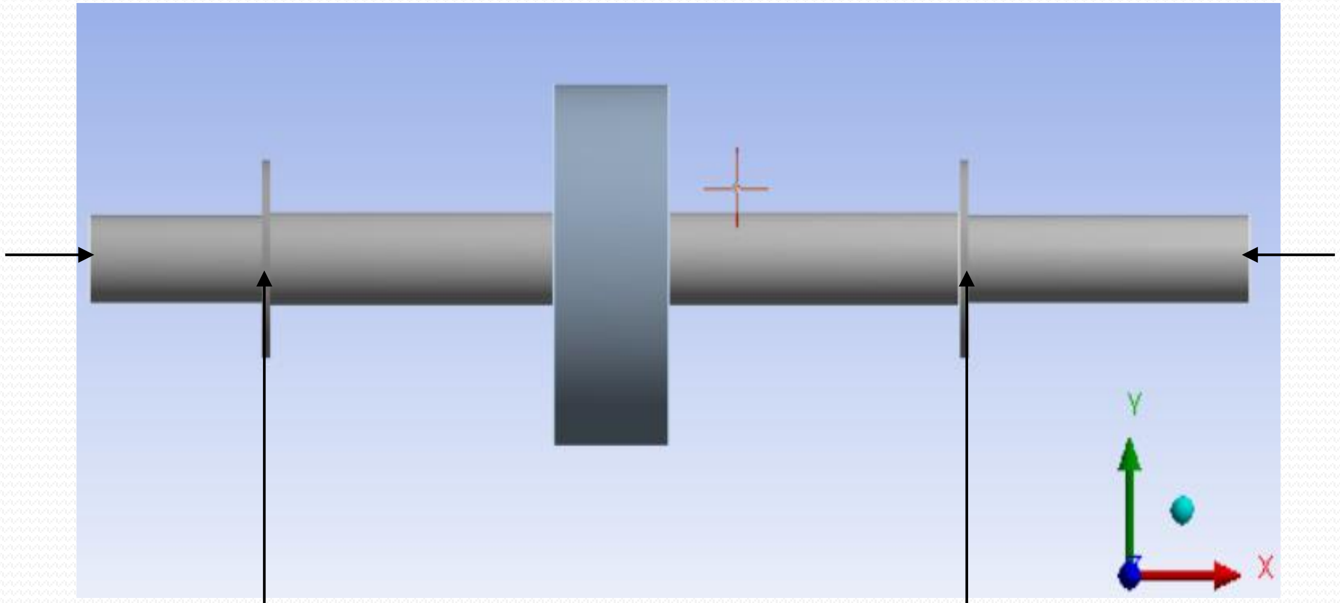
- L= 1m
- d= 60mm (min)

Disc

- D= 1.3 m
- $I_{min} = 83.5\ \text{kg}m^2$

Blades

- Z= 70
- Load applied:
  - Centrifugal Load
    - Operational Speed (3000 Rpm)
    - Design Speed (3800 Rpm)
  - Pressure on Blade



Assembly Supported on Bearings

Translations are Constrained, Rotations Allowed

Validation Study

Aim:- To find the Natural Frequency and Mode Shape of Rotor and Shaft assembly and validation of results with different FEA tools for comparison and choose the best suitable one.

Article Reference

Shin-Yong Chen, Chieh Kung, Jung-Chun Hsu. 2011 Dynamic Analysis of a Rotary Hollow Shaft with Hot-Fit Part Using Contact Elements with Friction. Transactions of the Canadian Society for Mechanical Engineering. 35(3):461- 474

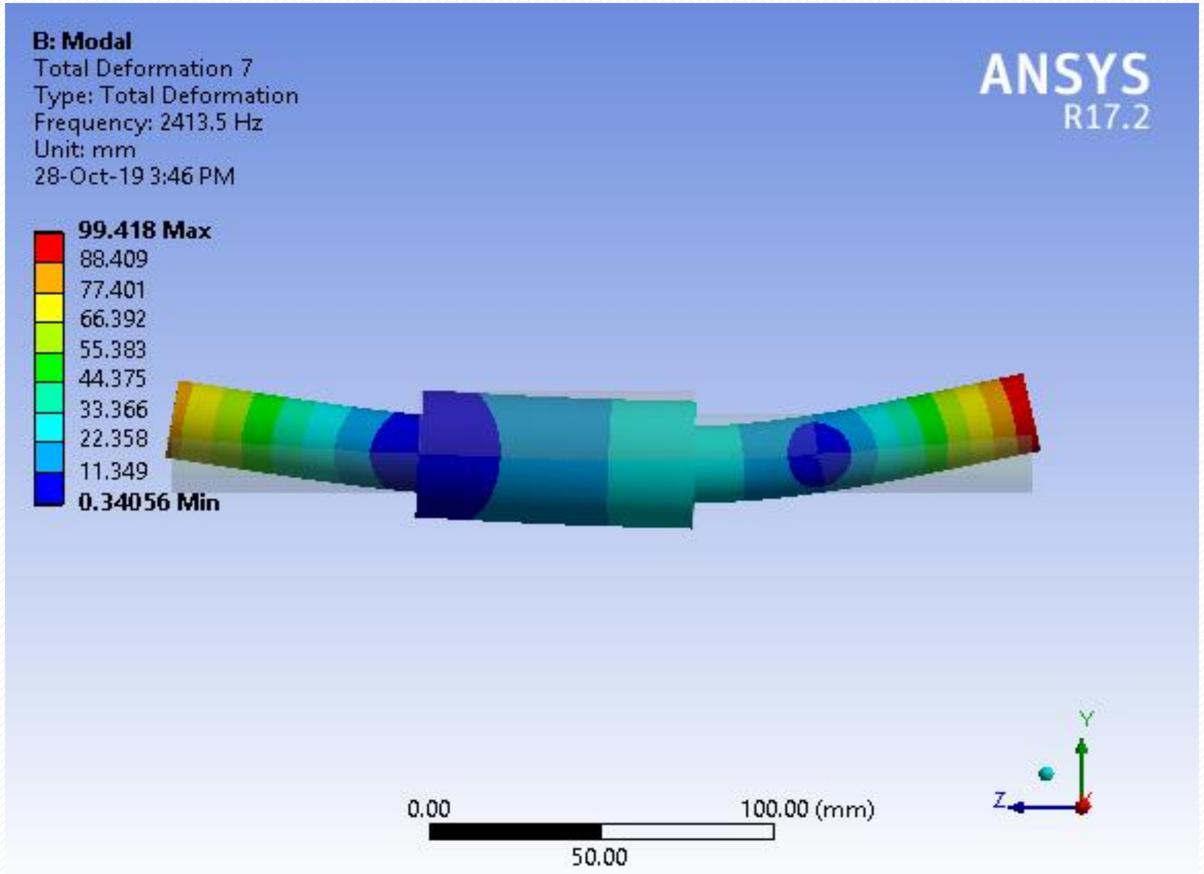
- Shaft and Rotor assembly considered with given dimensions.
- Rotor fitted on shaft with interference fit of 0.028mm.
- Both considered flexible type.
- Surface to surface Frictional contact provided with COF= 0.029 & 0.0745
- Similar Meshing and Analysis settings are used as in Literature.
- Modal analysis performed with free-free boundary condition to find natural frequency of the system.
- Two mode shapes are validated with the literature.

Results Comparison

First Mode shape

- cof= 0.029 fn= 2384.05 hz
- cof= 0.0745 fn= 2396.39 hz
- Model testing (experiment) fn= 2379.71 hz

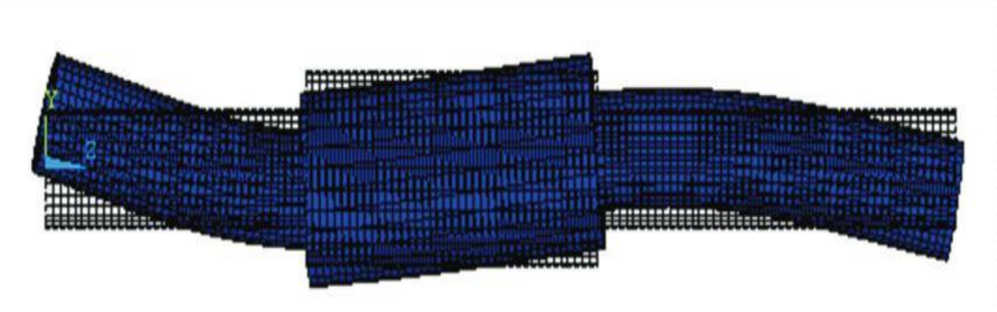
Result obtained



- cof= 0.029 fn= 2397.7 hz
- cof= 0.0745 fn= 2413.5 hz

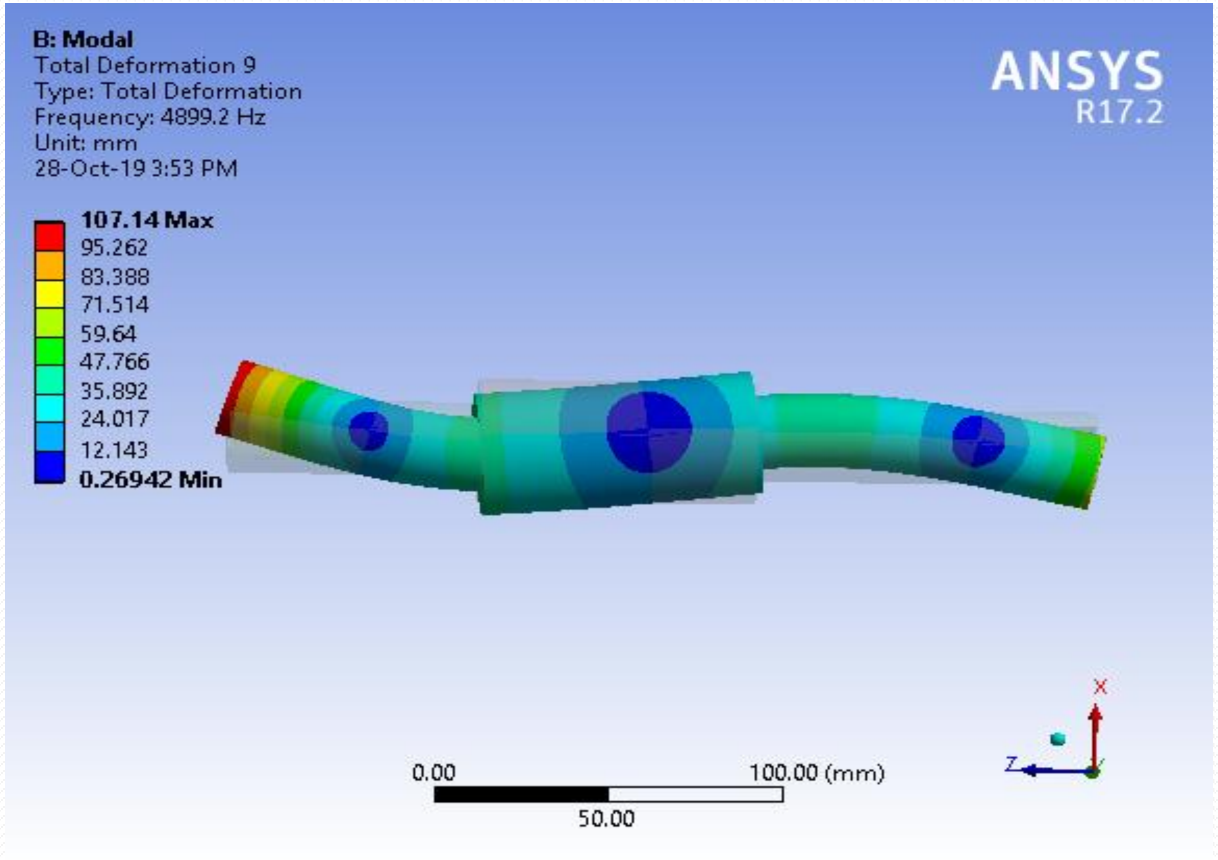
Results Comparison

Second Mode shape



- cof= 0.029 fn= 4871.68 hz
- cof= 0.0745 fn= 4892.74 hz
- Model testing (experiment) fn= 4849.32 hz

Result obtained



- cof= 0.029 fn= 4870.8 hz
- cof= 0.0745 fn= 4899.2 hz

- Comparison of Prediction by Various Tools

Natural Frequency (hz)	REFERENCE	ANSYS MECHANICAL	APDL MECHANCIAL	ABAQUS
COF= 0.029/ First Mode				
EXP	2379.71			
NUM	2384.05	2397.7	2421.72	2428.8
Diff	0.18%	0.76%	1.76%	2.06%
COF= 0.029/ Second Mode				
EXP	4849.32			
NUM	4871.68	4870.8	4911.5	4926.9
Diff	0.46%	0.45%	1.28%	1.6%

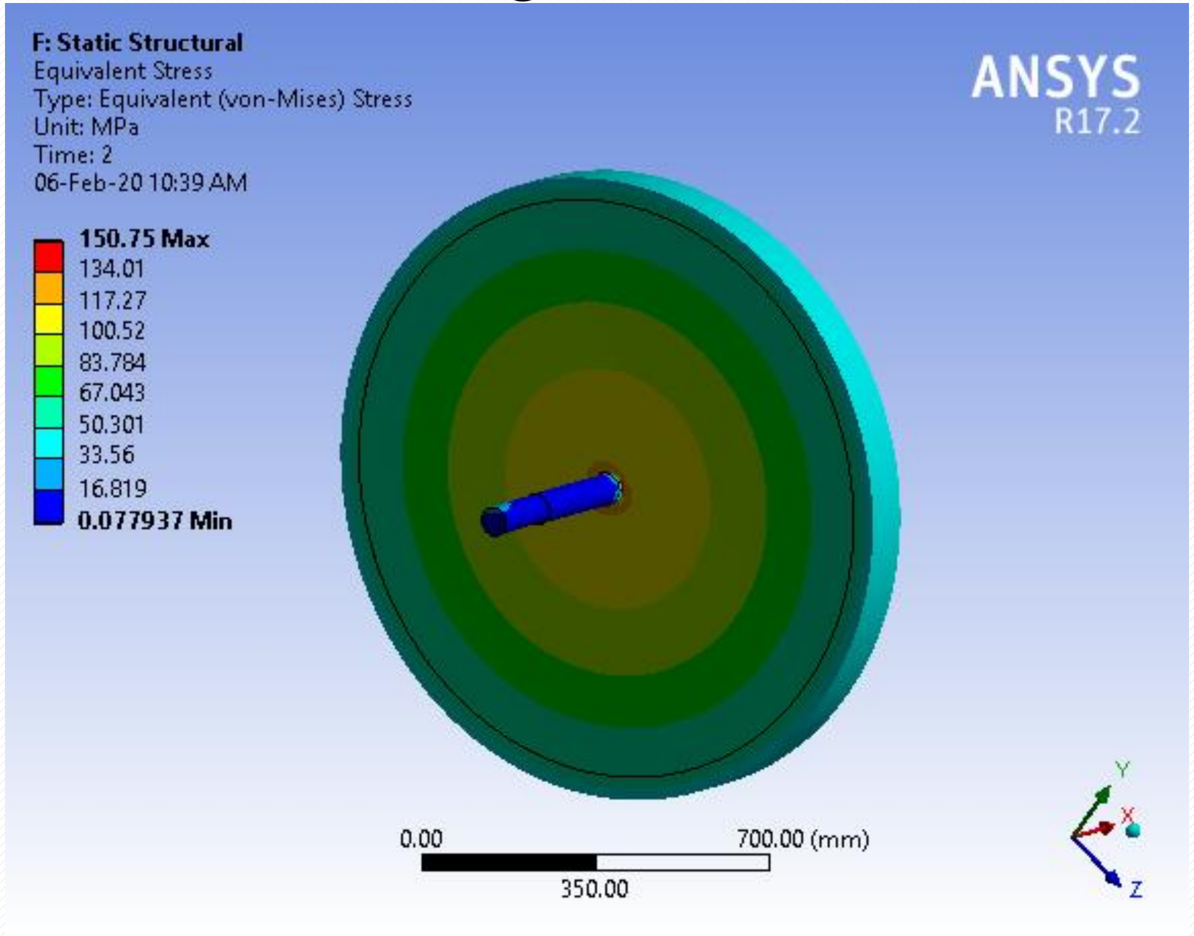
- Ansys Mechanical was selected.

Design of Disk

Configuration 1

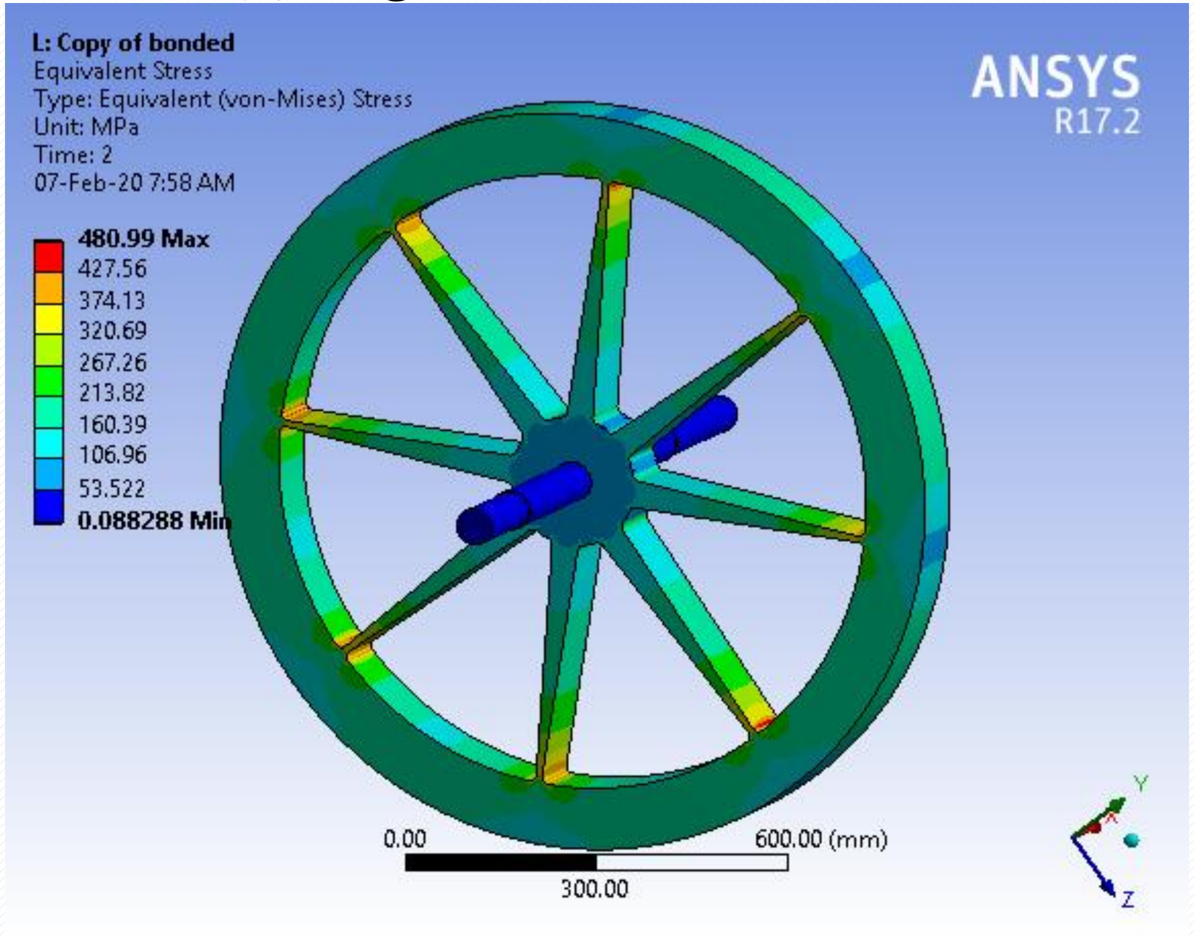
- Disk, $D_o = 1.3m$

M= 887.8 kg, $I_x = 159.8\ kgm^2$



Configuration 2

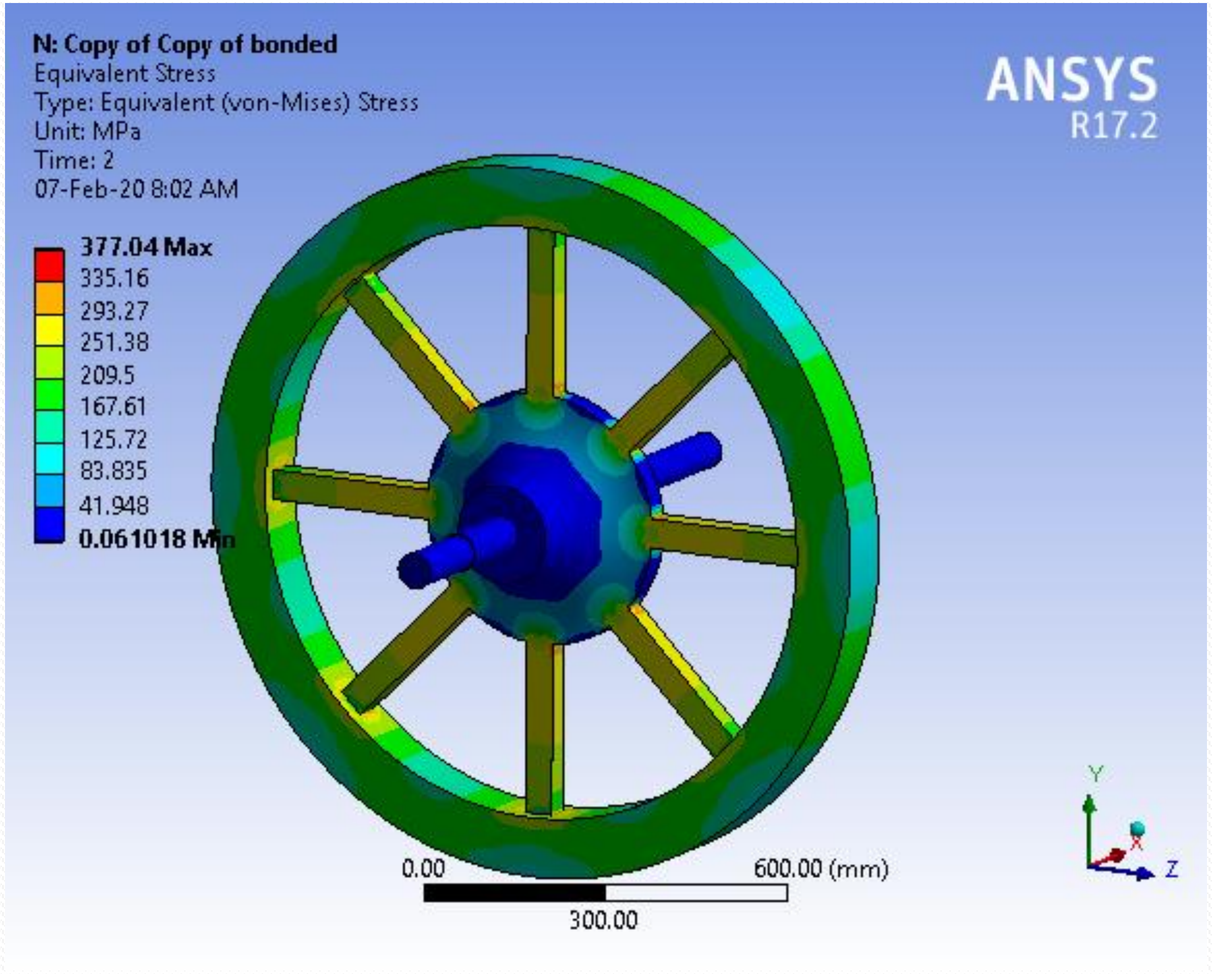
M= 358kg, $I_x = 86.4kgm^2$



Configuration 3

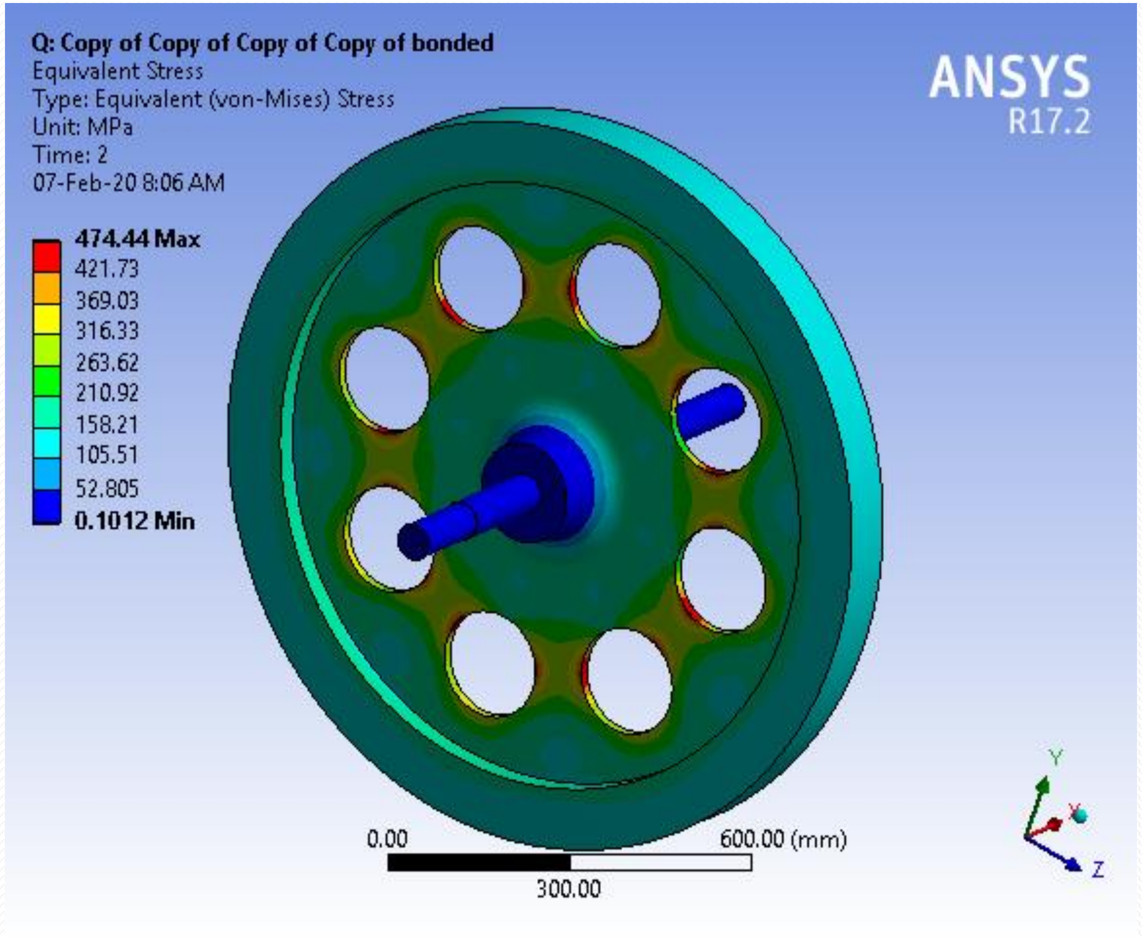
- Disk, $D_o = 1.3m$

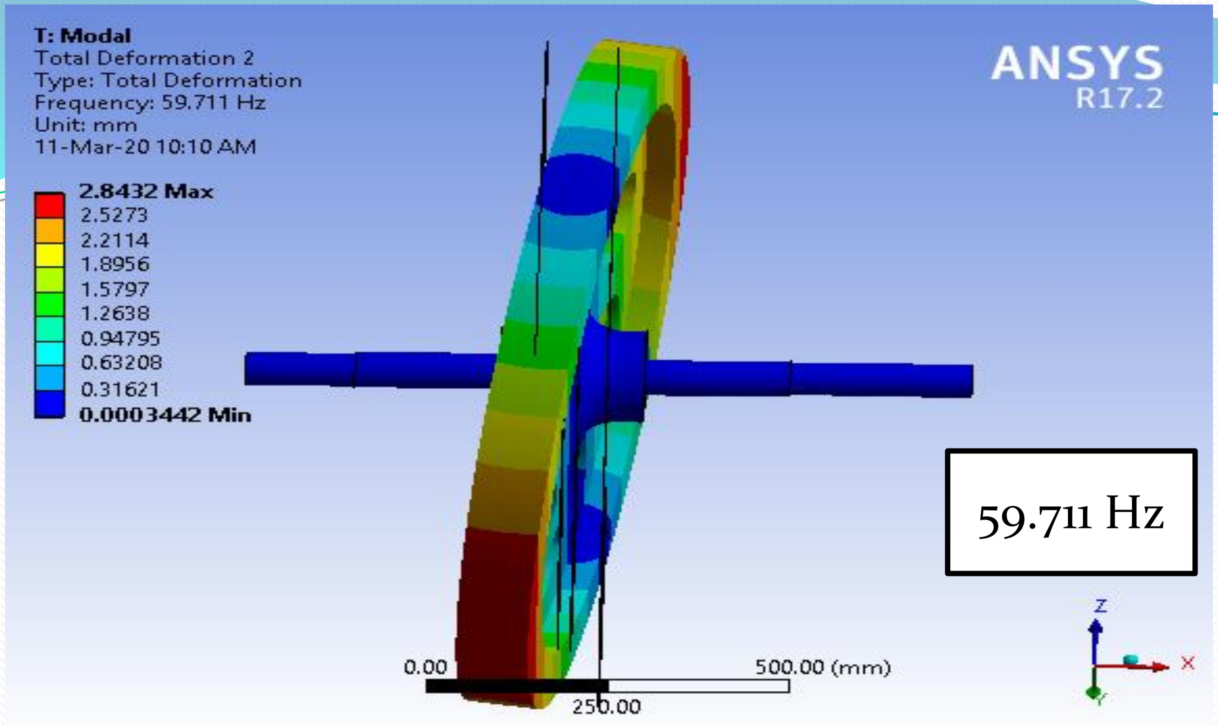
M= 421kg, $I_x = 87.94kgm^2$



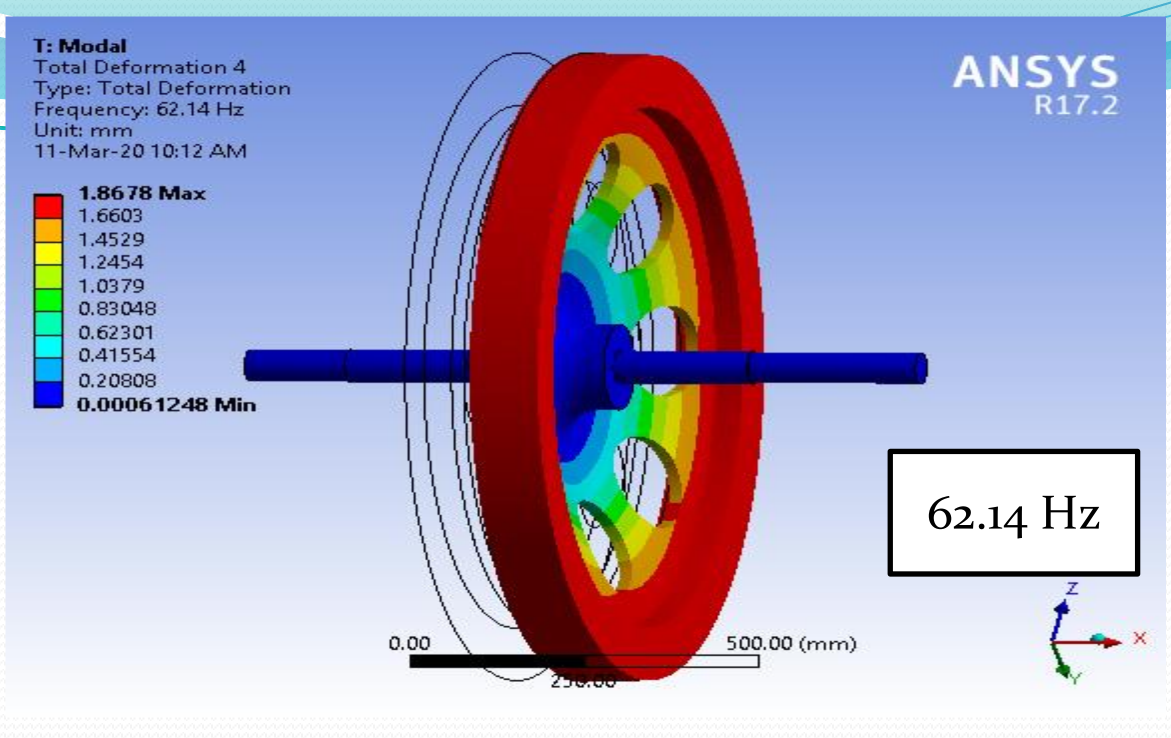
Configuration 4

M= 384kg, $I_x = 91.8kgm^2$

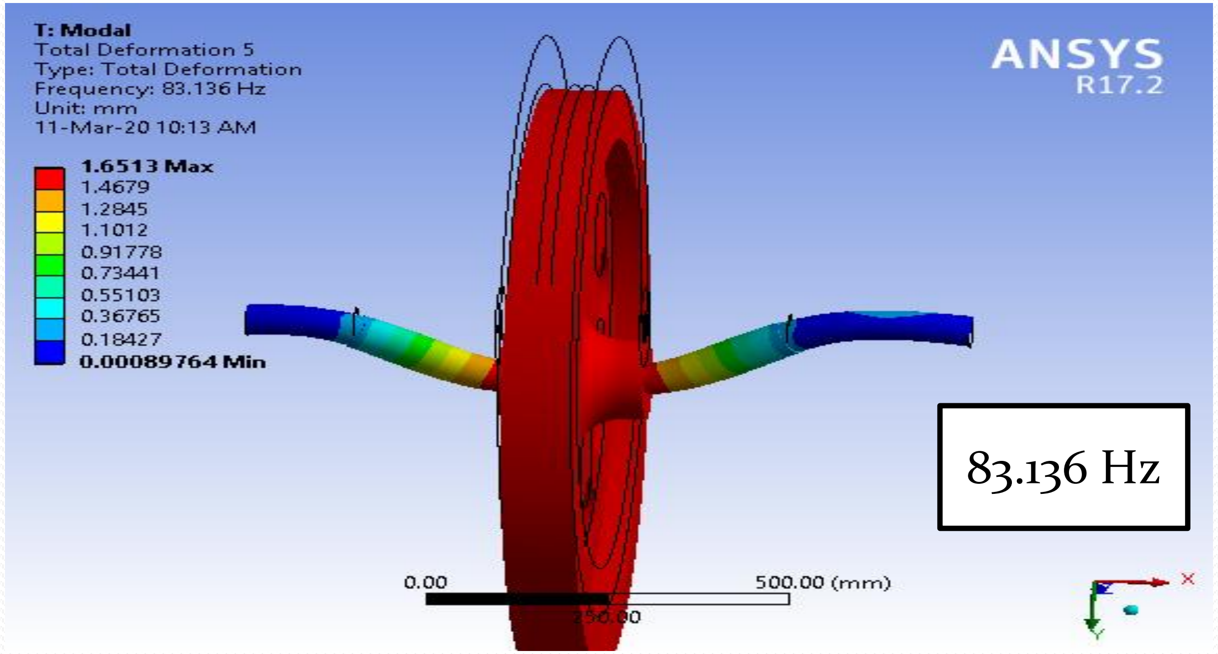




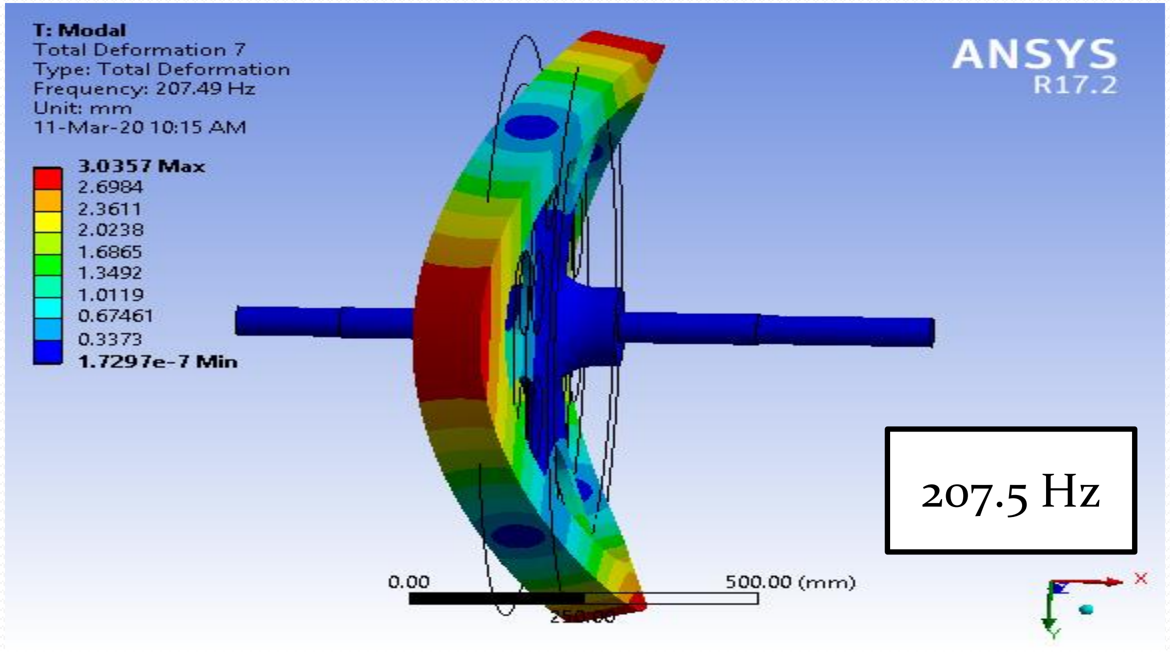
T: Modal
Total Deformation 2
Type: Total Deformation
Frequency: 59.711 Hz
Unit: mm
11-Mar-20 10:10 AM
2.8432 Max
2.5273
2.2114
1.8956
1.5797
1.2638
0.94795
0.63208
0.31621
0.0003442 Min
ANSYS
R17.2
59.711 Hz
0.00
250.00
500.00 (mm)



T: Modal
Total Deformation 4
Type: Total Deformation
Frequency: 62.14 Hz
Unit: mm
11-Mar-20 10:12 AM
1.8678 Max
1.6603
1.4529
1.2454
1.0379
0.83048
0.62301
0.41554
0.20808
0.00061248 Min
ANSYS
R17.2
62.14 Hz
0.00
500.00 (mm)



T: Modal
Total Deformation 5
Type: Total Deformation
Frequency: 83.136 Hz
Unit: mm
11-Mar-20 10:13 AM
1.6513 Max
1.4679
1.2845
1.1012
0.91778
0.73441
0.55103
0.36765
0.18427
0.00089764 Min
ANSYS
R17.2
83.136 Hz
0.00
500.00 (mm)

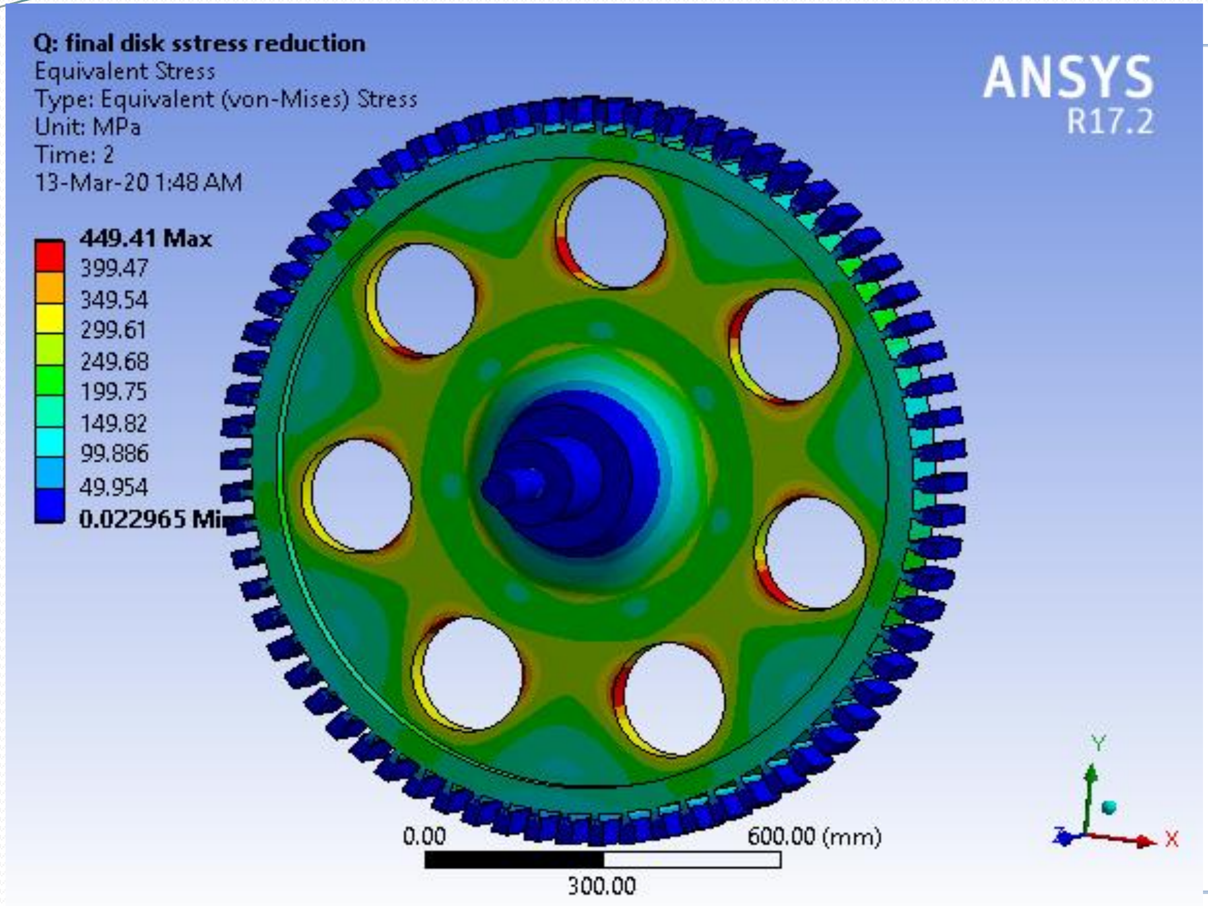


T: Modal
Total Deformation 7
Type: Total Deformation
Frequency: 207.49 Hz
Unit: mm
11-Mar-20 10:15 AM
3.0357 Max
2.6984
2.3611
2.0238
1.6865
1.3492
1.0119
0.67461
0.3373
1.7297e-7 Min
ANSYS
R17.2
207.5 Hz
0.00
500.00 (mm)

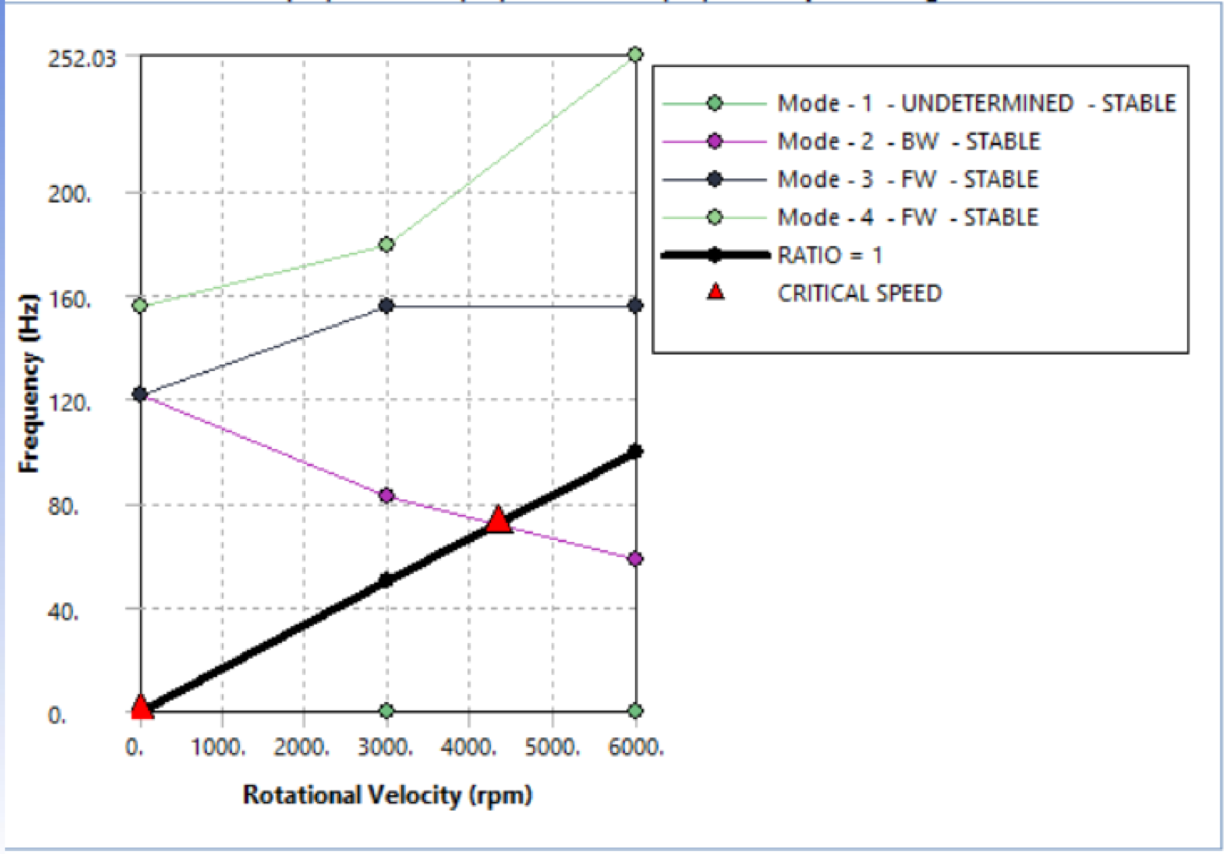
Design Refinements of Selected Configuration

S.No	Shaft Día (mm)	No of Holes	Hub Dia (mm)	Hub length (mm)	Disk width (mm)	Disk Inertia (Kgm^2)	Mass of Disk (Kg)	Critical Speed (Rpm)	Max Stress at Operation speed (MPa)	Total Def. (mm)
1	64	8	284	200	20	91.86	385	3582.6	474.44	0.42
2	80	8	475	300	40	104.87	537.84	2897.4	371.69	0.31
3	100	8	460	330	70	140	689	3969.1	351.23	0.33
4	100	8	460	330	60	132	636.56	3703.1	380.05	0.35
5	100	0	460	300	40	112	602	3596.4	155.36	0.21
6	100	8	460	200	40	101.3	524	3252.6	445.83	0.41
7	150	8	440	300	50	114	575	4319.5	305.61	0.36
8	150	7	440	300	50	116	588	4337.8	280.1	0.36
9	150	7	440	300	60	117.57	614.89	4809.8	249.43	0.37

Static & Rotordynamic Analysis of Final Design



Model (P4) > Modal (P5) > Solution (P6) > Campbell Diagram

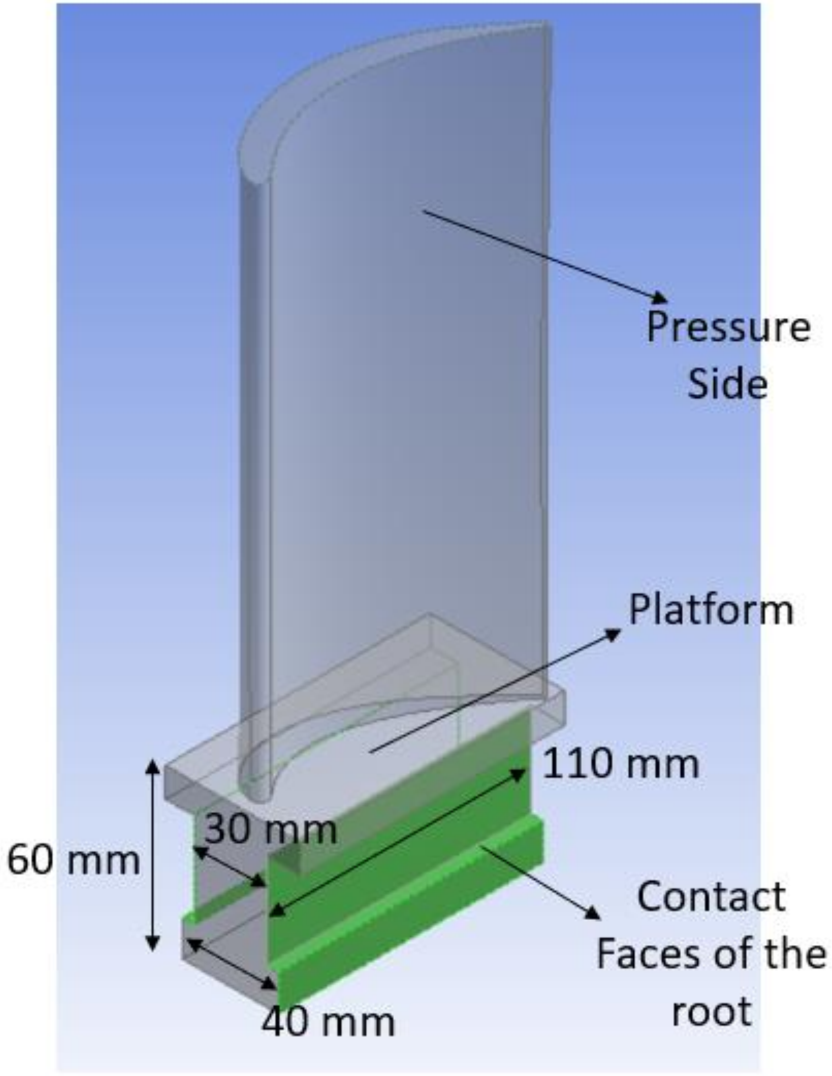


	Operational Speed	Design Speed
	3000 RPM	3800 RPM
Stresses	280.1 Mpa	449.41 Mpa

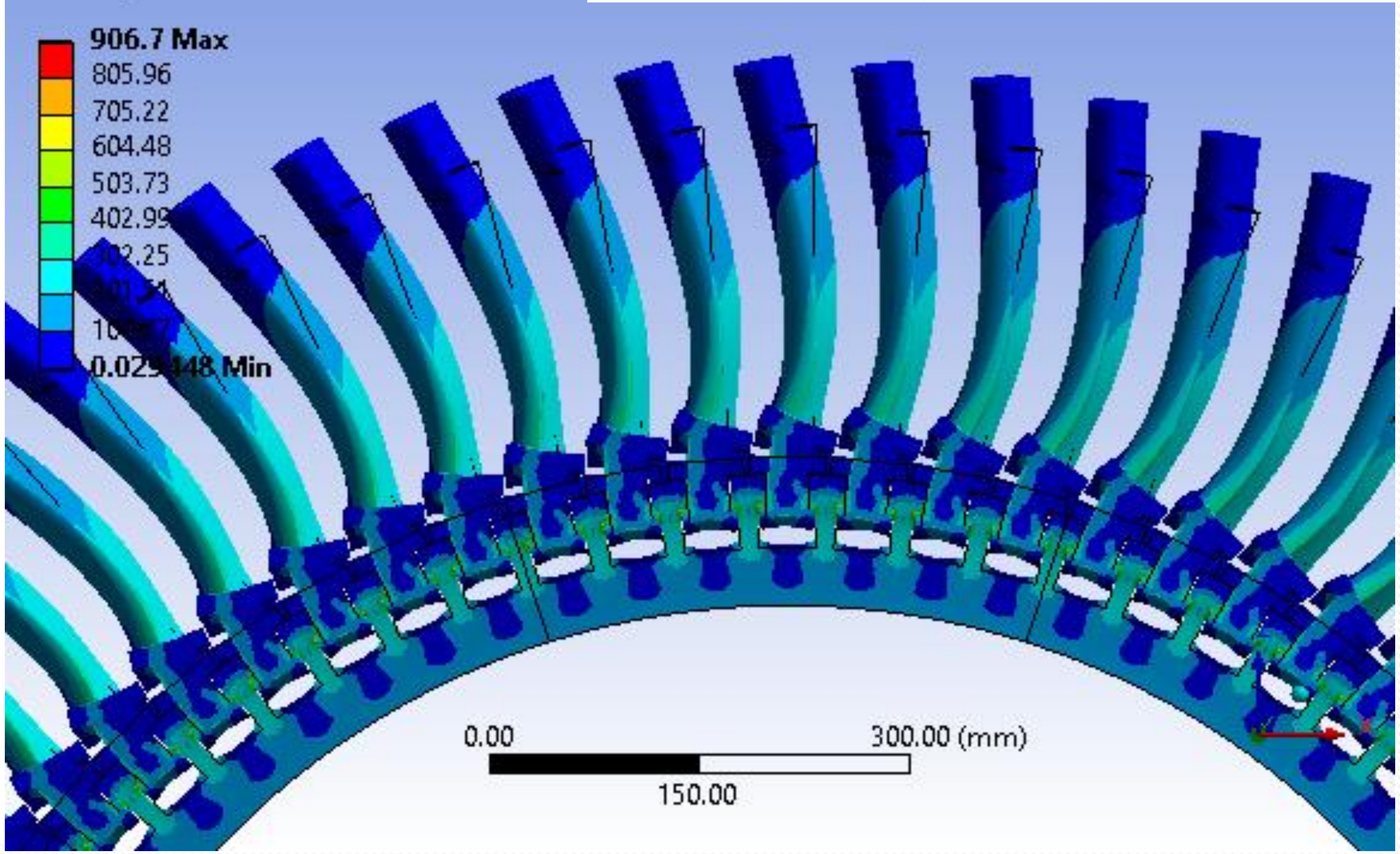
Model (P4) > Modal (P5) > Solution (P6) > Campbell Diagram

Mode	Whirl Direction	Mode Stability	Critical Speed	0. rpm	3000. rpm	6000. rpm
1.	UNDETERMINED	STABLE	0.97063 rpm	1.6177e-002 Hz	1.6177e-002 Hz	1.6177e-002 Hz
2.	BW	STABLE	4319.5 rpm	121.56 Hz	82.478 Hz	58.636 Hz
3.	FW	STABLE	NONE	121.57 Hz	155.28 Hz	155.28 Hz
4.	FW	STABLE	NONE	155.28 Hz	179.17 Hz	252.03 Hz

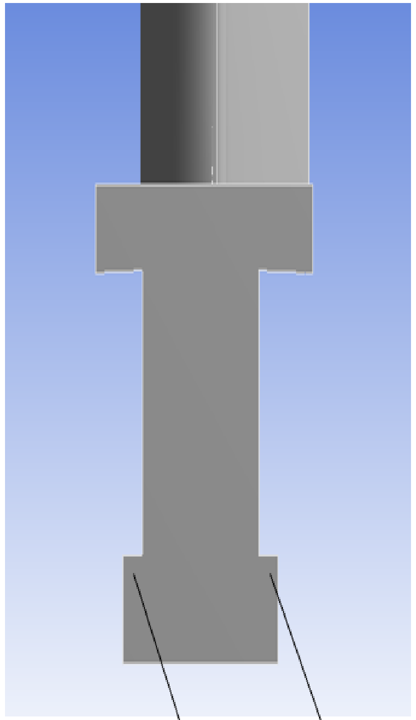
Design & Analysis of Blade Roots, T- type



Loads=>	Operational Speed 3000 RPM	Design Speed 3800 RPM
Stresses	566.45Mpa	906.7 Mpa
Total Def.	0.25 mm	0.40 mm

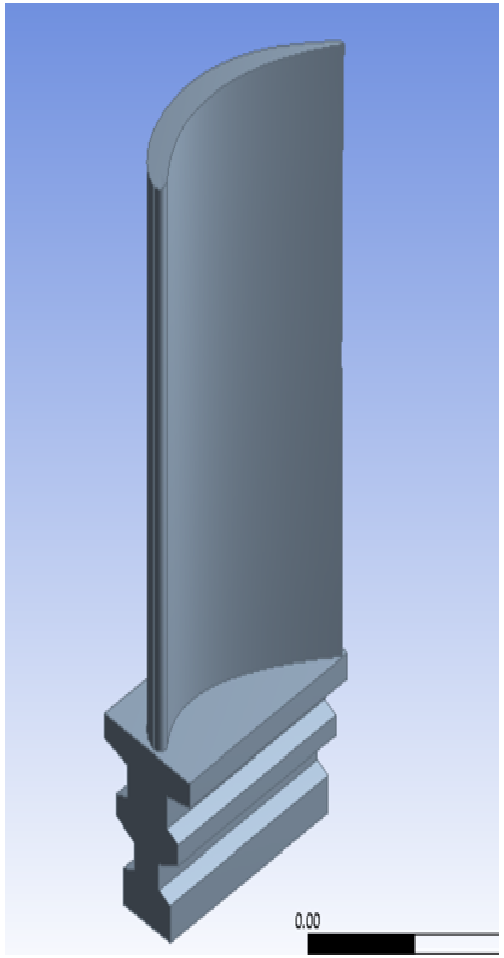


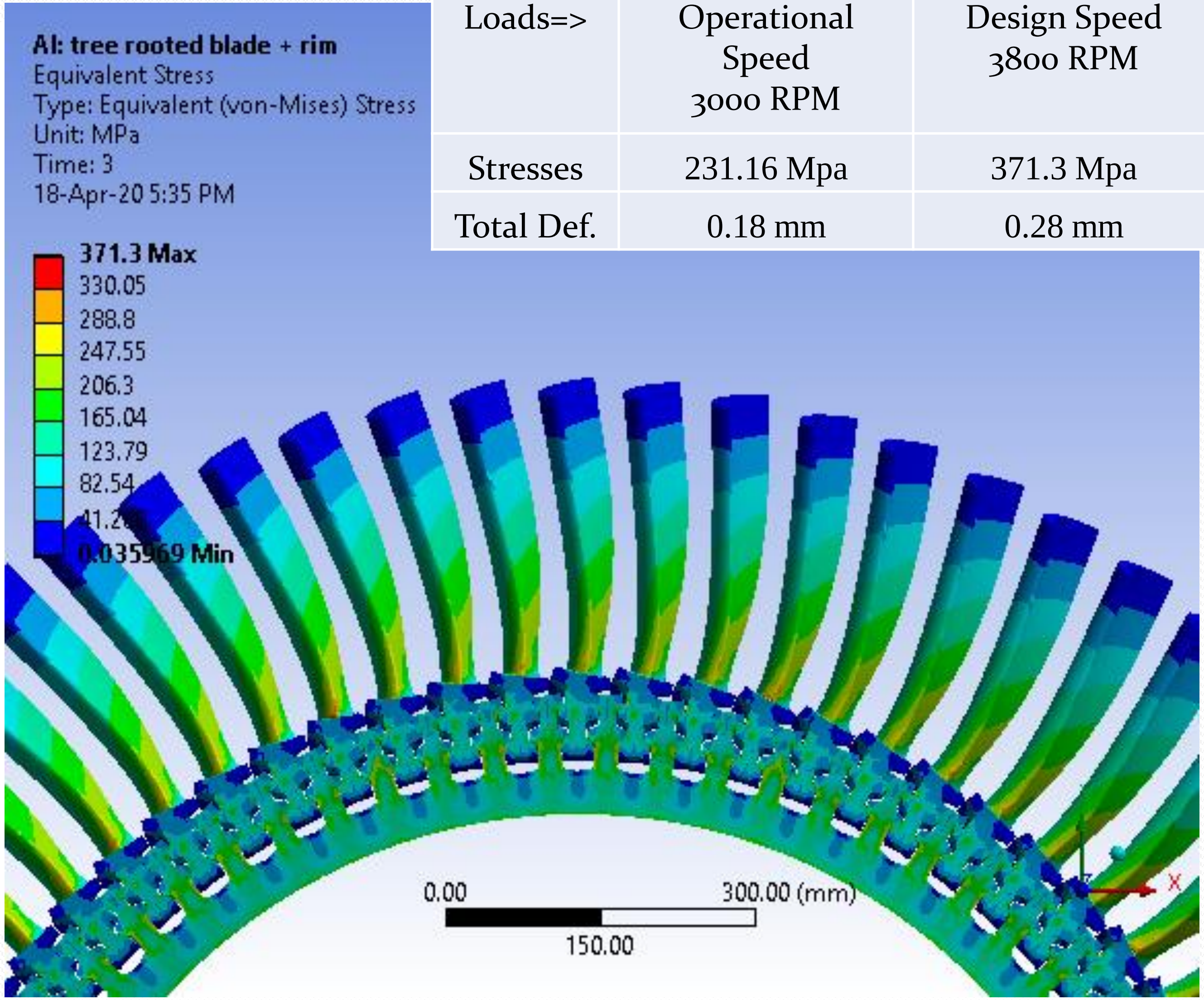
Improvement to Fir-Tree type Roots



566.45 Mpa at 3000 rpm (Operational Speed)

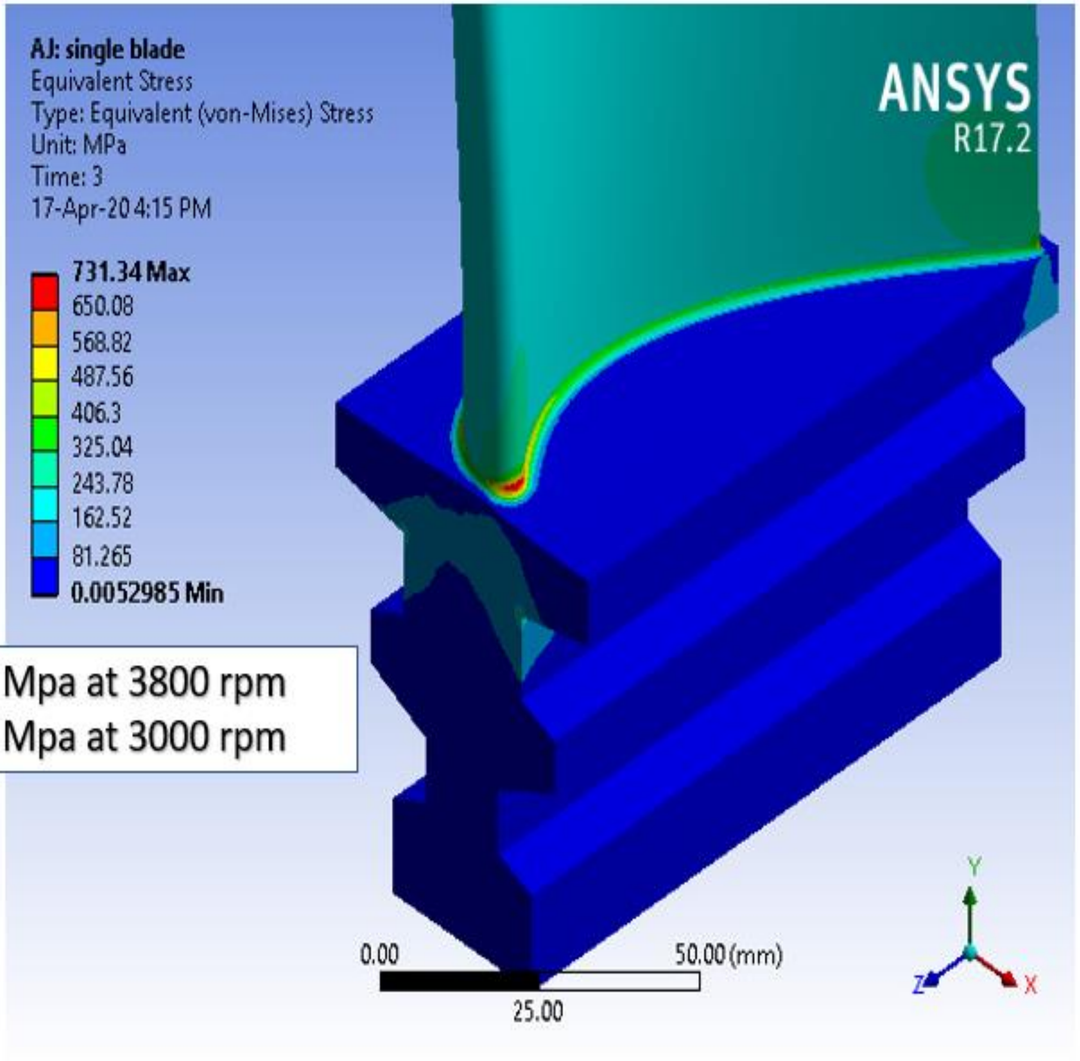
High contact stresses as Load bearing area was less, So changed the Root Design to Fir- Tree Type



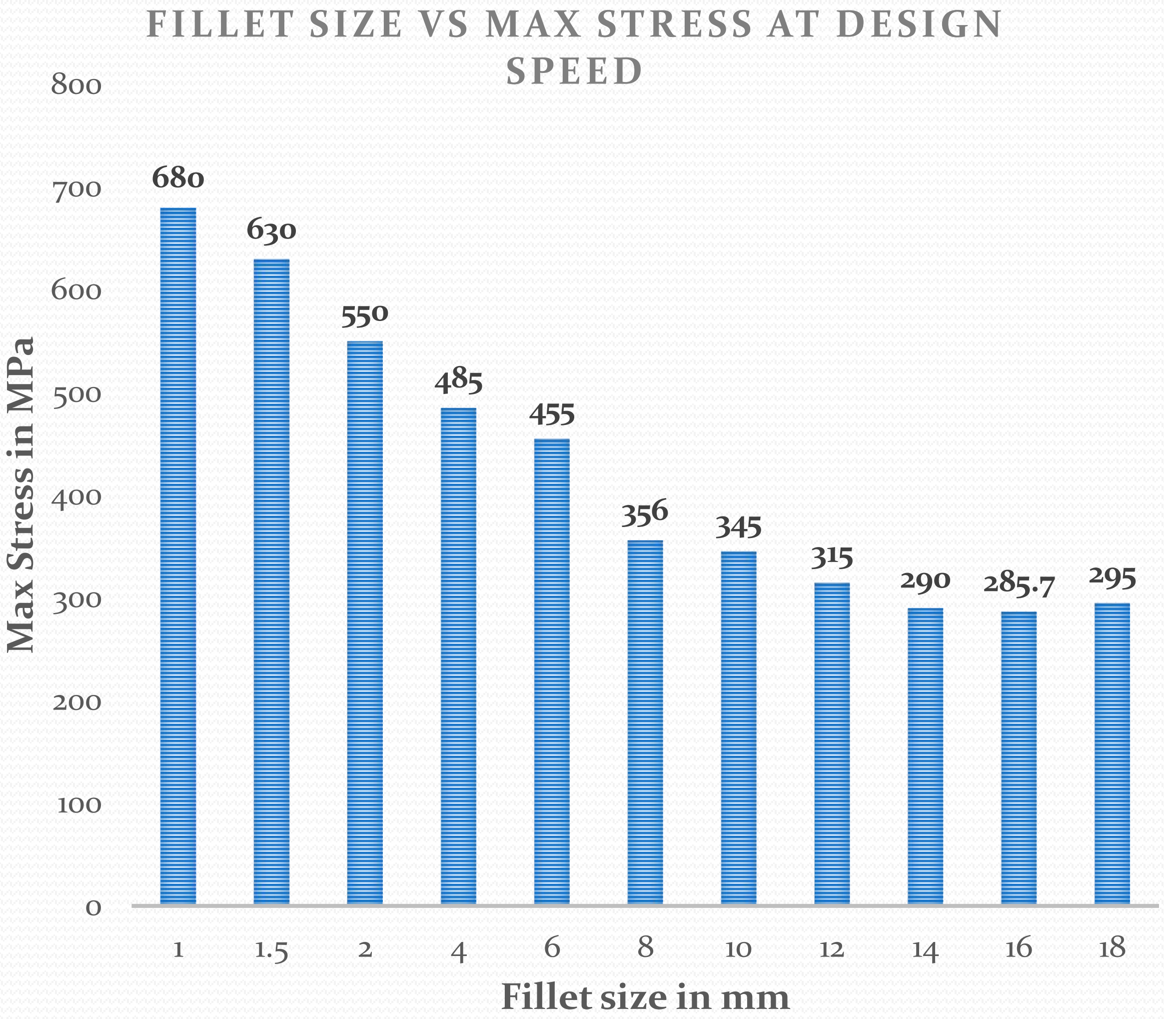


Loads=>	Operational Speed 3000 RPM	Design Speed 3800 RPM
Stresses	231.16 Mpa	371.3 Mpa
Total Def.	0.18 mm	0.28 mm

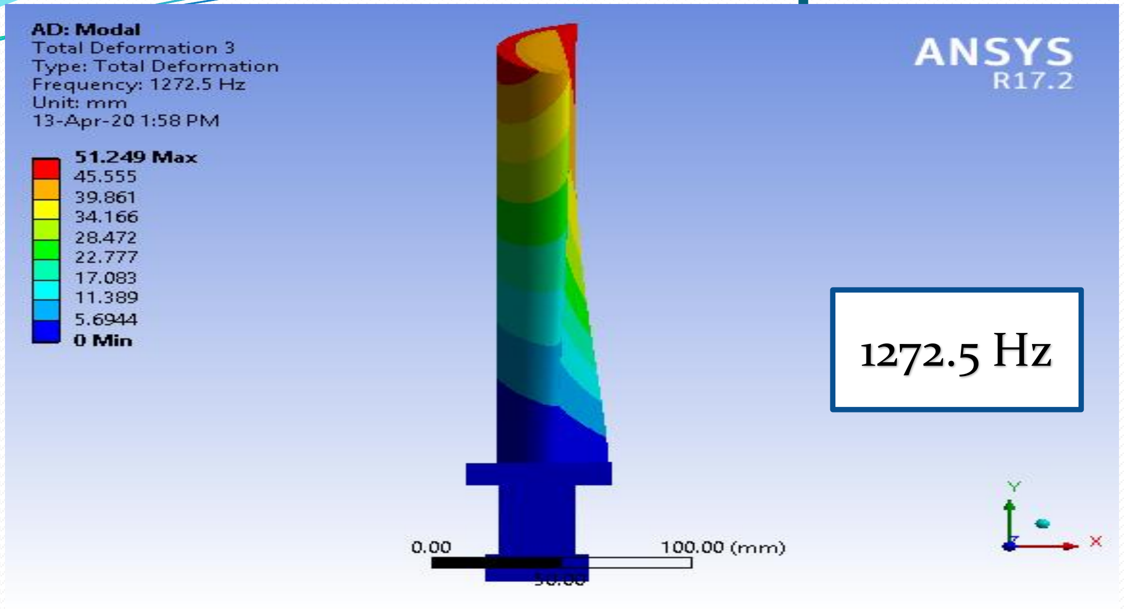
Single Blade Analysis and Effect of Fillet

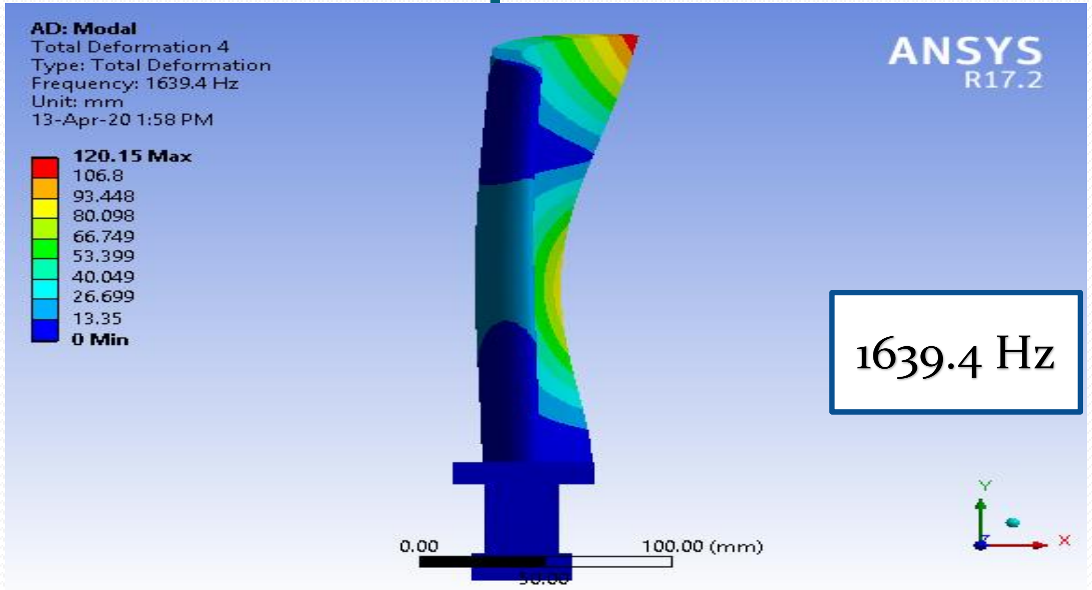


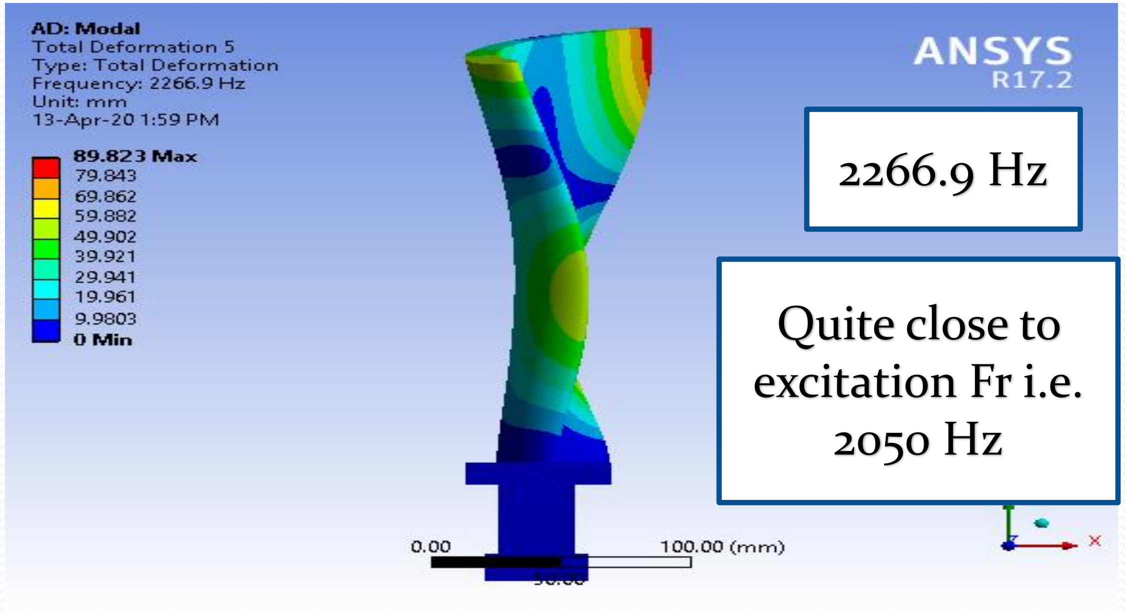
732 Mpa at 3800 rpm
460 Mpa at 3000 rpm

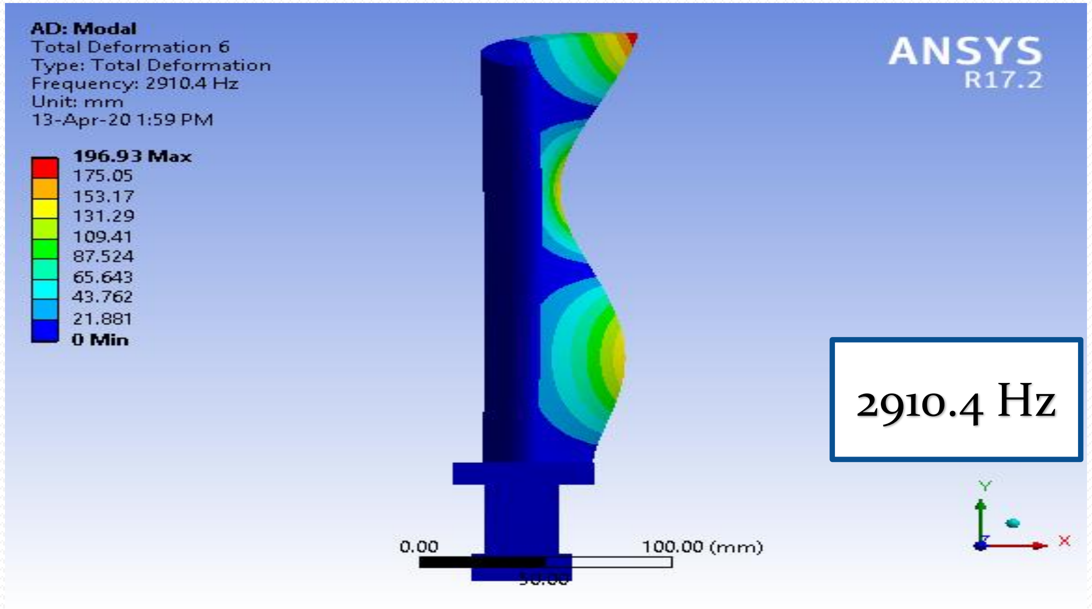


Blade Mode shapes & Natural Frequencies





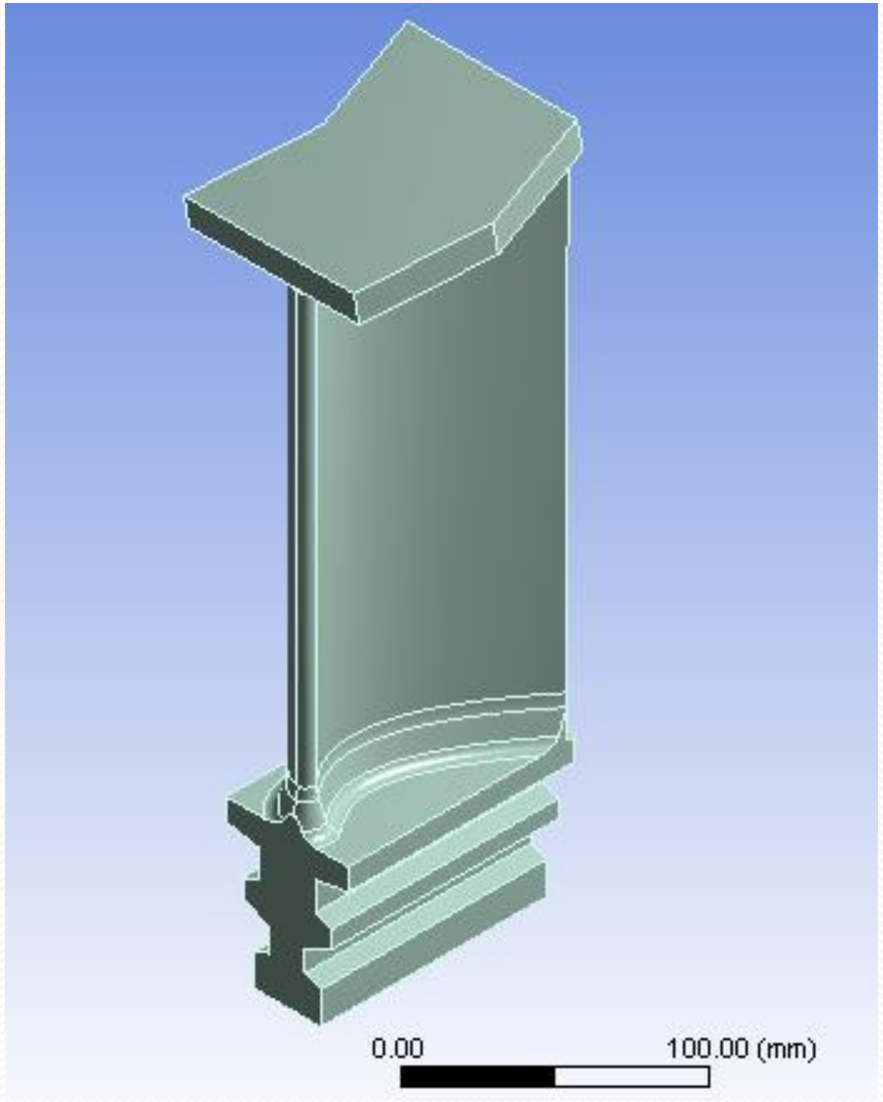




Effect of Shroud on Blade

- Effect of shroud thickness on the blade is studied.

Shroud Thickness	Operation Speed	Natural Frequencies (Hz)					
	Stress (Mpa)	f1	f2	f3	f4	f5	f6
6mm	640.14	264.35	540.5	1042.4	1429.9	1956.1	2306.3
8mm	516.76	243.05	499.8	961.91	1400	1927.6	2509
10mm	450.79	225.85	466.9	896.22	1371.1	1896.6	2638.4
12mm	403.19	211.54	439.7	841.33	1343.7	1871.4	2711.9
14mm	380.54	199.38	416.5	794.52	1317.6	1851	2749.9
16mm	399.31	188.91	396.7	753.95	1293.1	1835.5	2768.7



- Shows Natural Frequencies being varied with shroud.
- Increases the centrifugal stresses as well.
  - So thickness has to be minimum

Conclusion & Summary

- A Validation study was done for comparing various FEA Tools & Found ANSYS Mechanical more suitable for our work
- Configuration 4: Disk with holes, was selected for the design refinement
- Effect of various parameters involved in the design were studied on the basis of Critical speed, max equivalent stress, total deformation criteria with required inertia and lesser weight.
- For final design, obtained critical speed of 4319.5 Rpm is away from operation and design speed, max equivalent stress of 280 Mpa < yield strength of material with small Radial def. of 0.356 mm
- Two type of blade roots were compared and found Fir-tree roots showing smaller contact stresses with the disk than T-type roots.
- Analysis of blade shows large stress concentration at the blade and blade roots junction.
- Addition of fillet to the junction increased the strength and reduced the stresses significantly.
- From Modal Analysis, one mode shape showed natural frequency close to excitation frequency
- For varying the natural frequency either blade thickness can be varied or shroud can be added.
- Shroud with various thickness were analyzed which showed shift in natural frequency but increase in centrifugal stresses as well.

Thank You