STRUCTURAL OPTIMISATION OF OFFSHORE DIRECT-DRIVE WIND TURBINE GENERATORS INCLUDING STATIC AND DYNAMIC ANALYSES

Kelly Tartt;

A McDonald; A Kazemi Amiri; P Jaen-Sola

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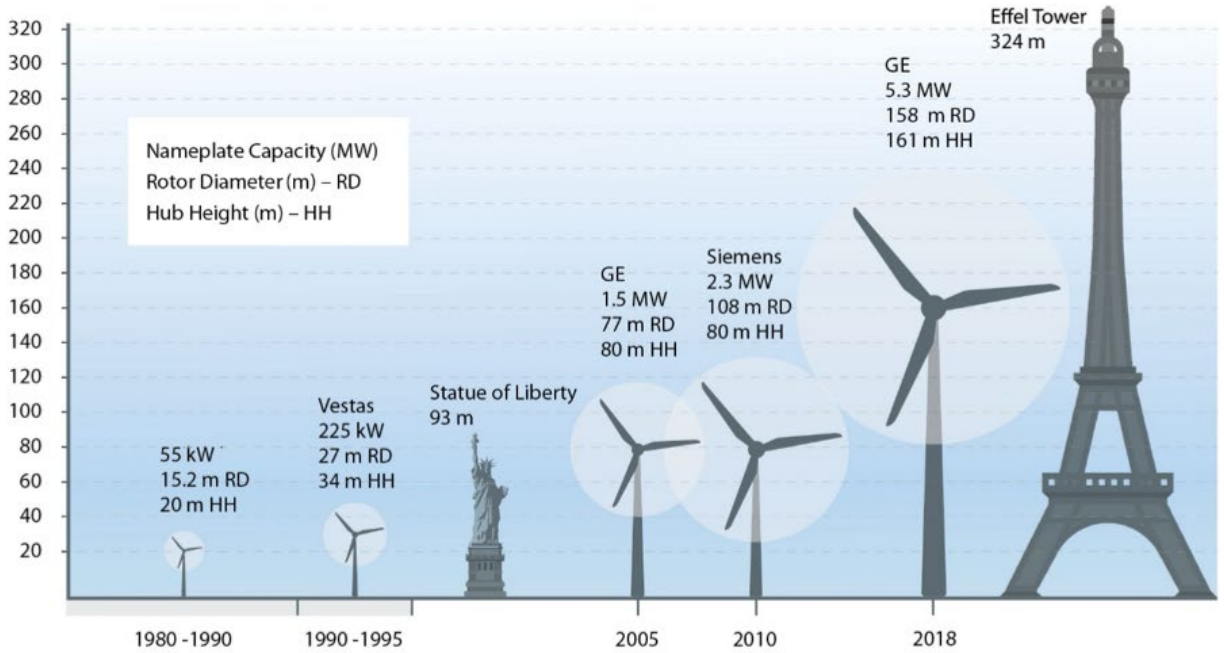
- Method
- Results
- Conclusion

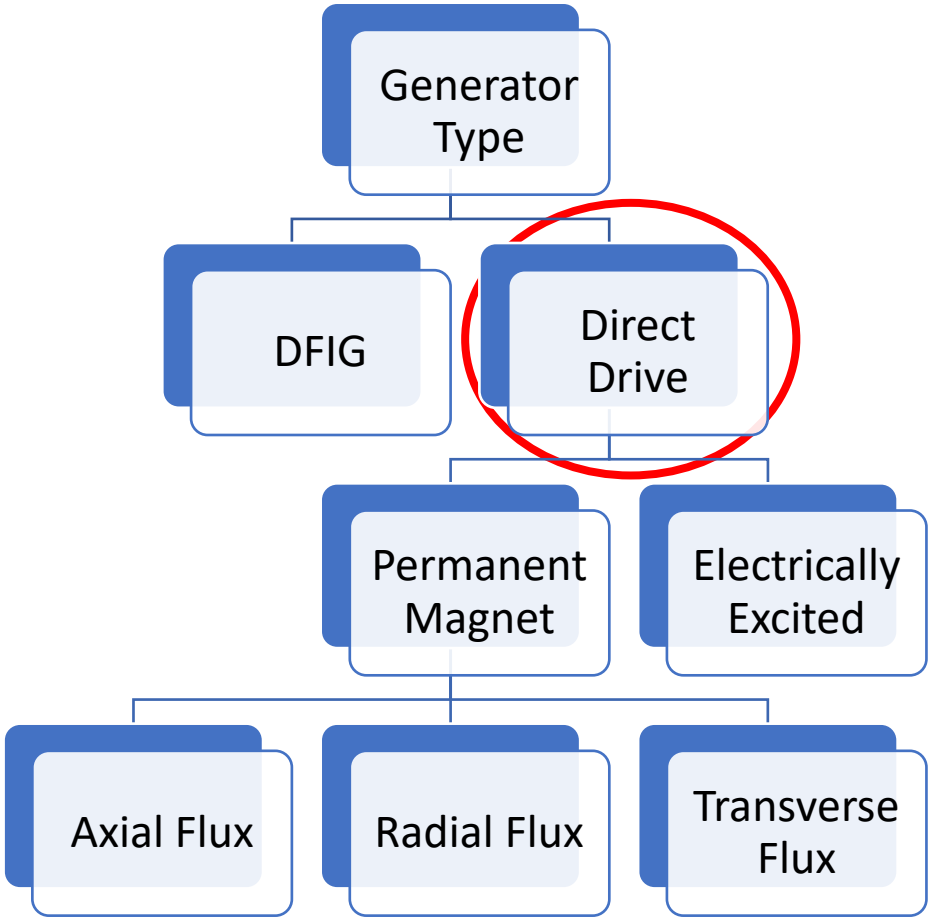
BACKGROUND

- Requirement to increase amount of energy extracted from the wind is growing.
- This can be achieved by installing larger wind turbines.
  - Larger wind turbines ☛ Larger generators.



Source: National Renewable Energy Laboratory [NREL]

BACKGROUND



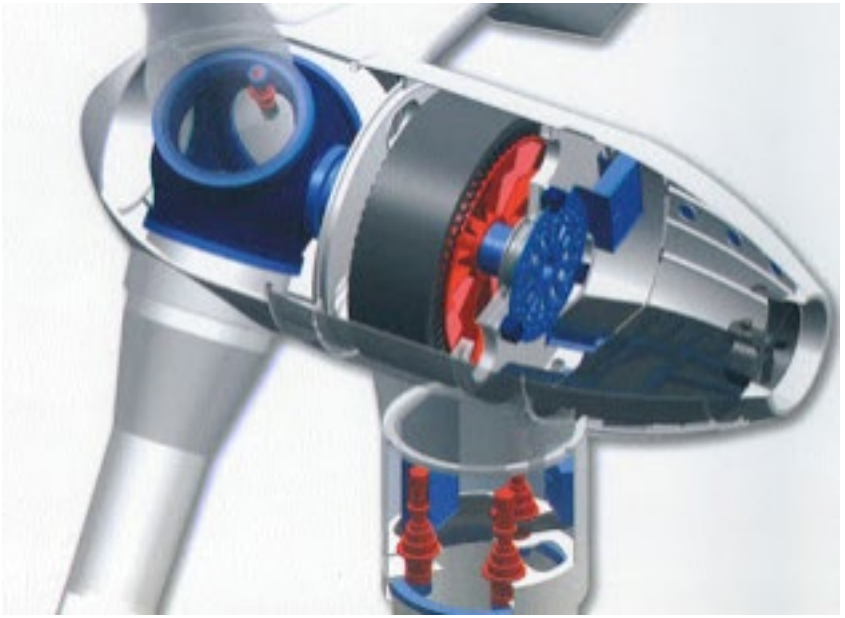
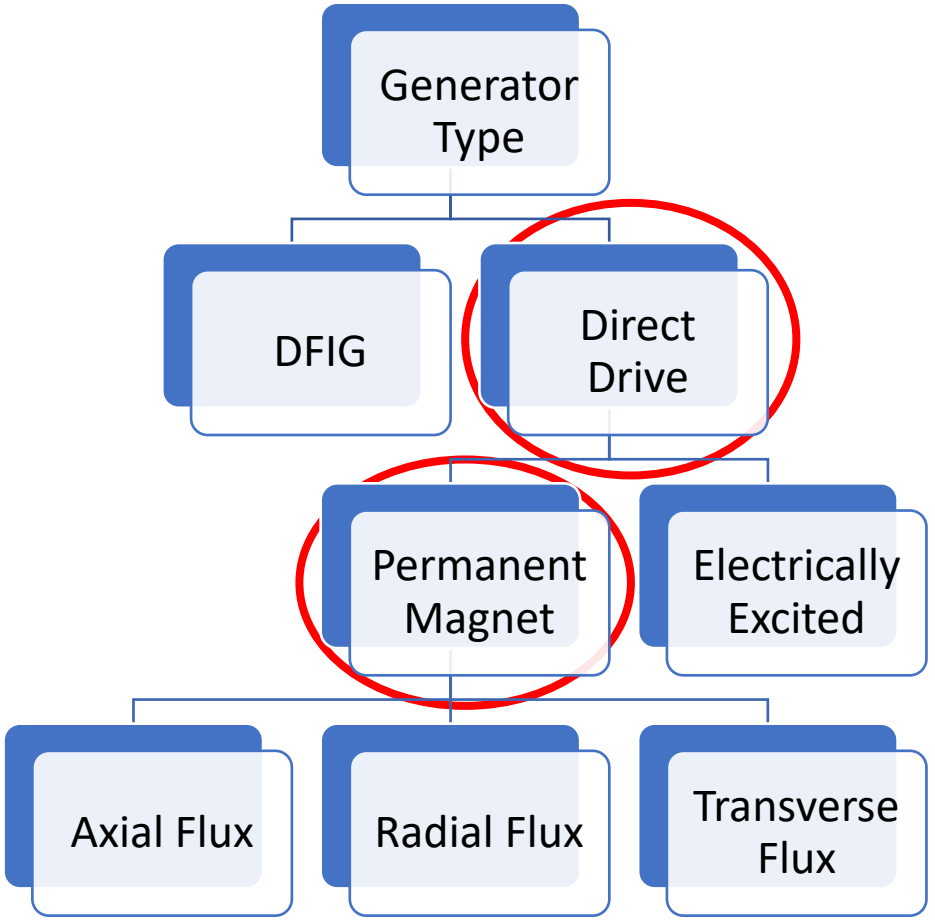


Photo Courtesy of:
http://shutthedoorhaveaseatblog.blogspot.com/2011/04/wind-turbines-direct-drive-vs-gearbox.html

BACKGROUND



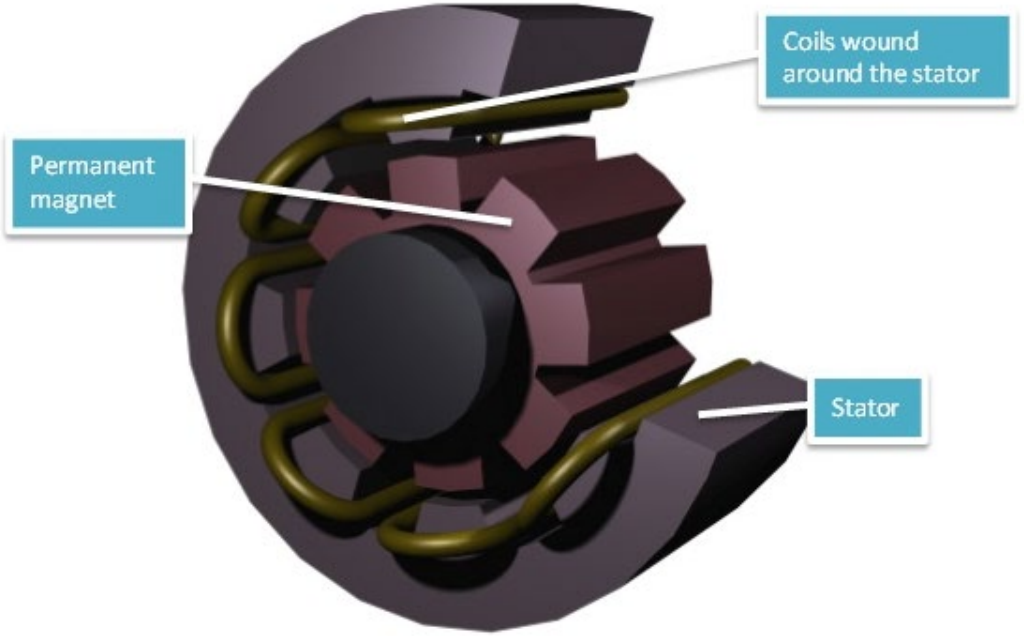
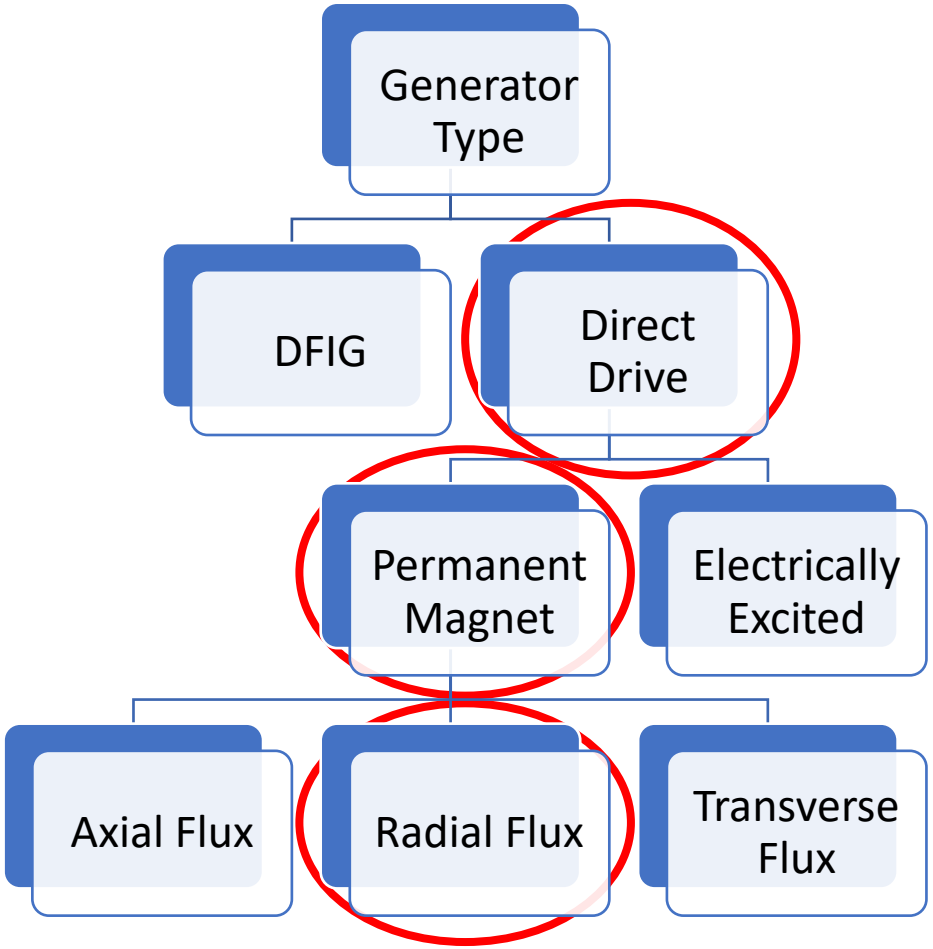


Photo Courtesy of:
https://www.comsol.com/blogs/simulating-permanent-magnet-generators/

BACKGROUND



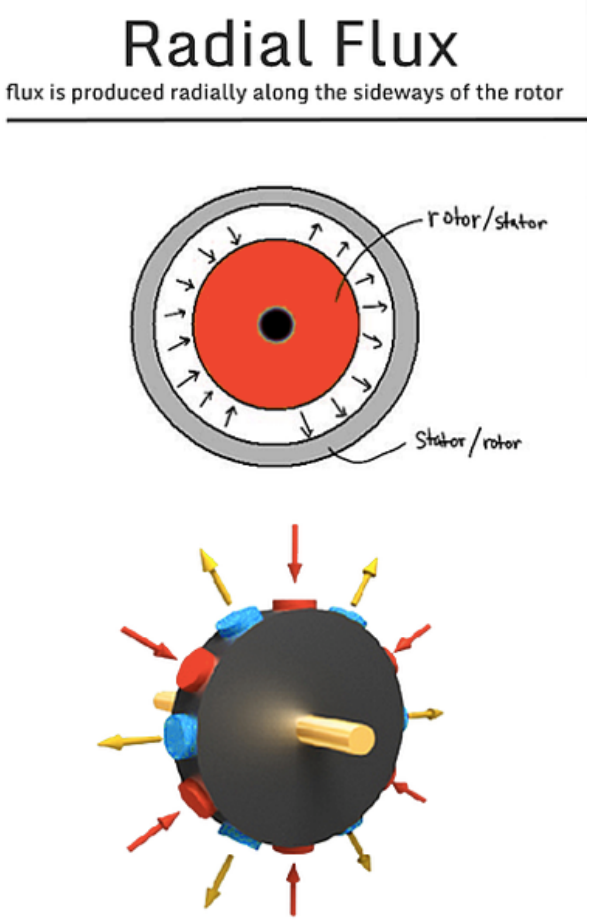


Photo Courtesy of:
https://www.magnax.com/magnax-blog/axial-flux-vs-radial-flux-for-direct-drive-generators

BACKGROUND

- Disadvantages:
  - Large and Heavy.
    - Equation 1:

$$P \uparrow = T \uparrow \omega \downarrow$$

    - Equation 2:

$$T \uparrow = 2\pi R^2 \uparrow \sigma l \uparrow$$

BACKGROUND

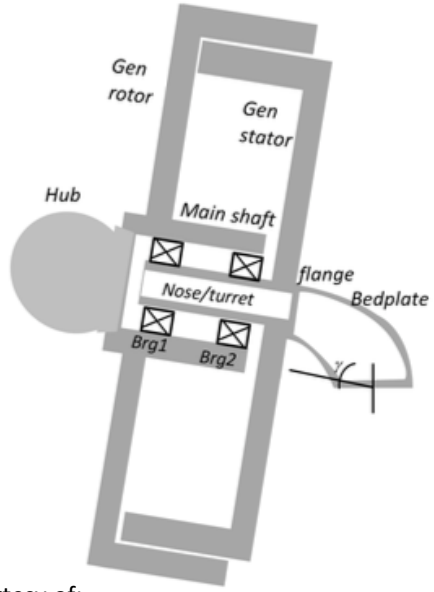
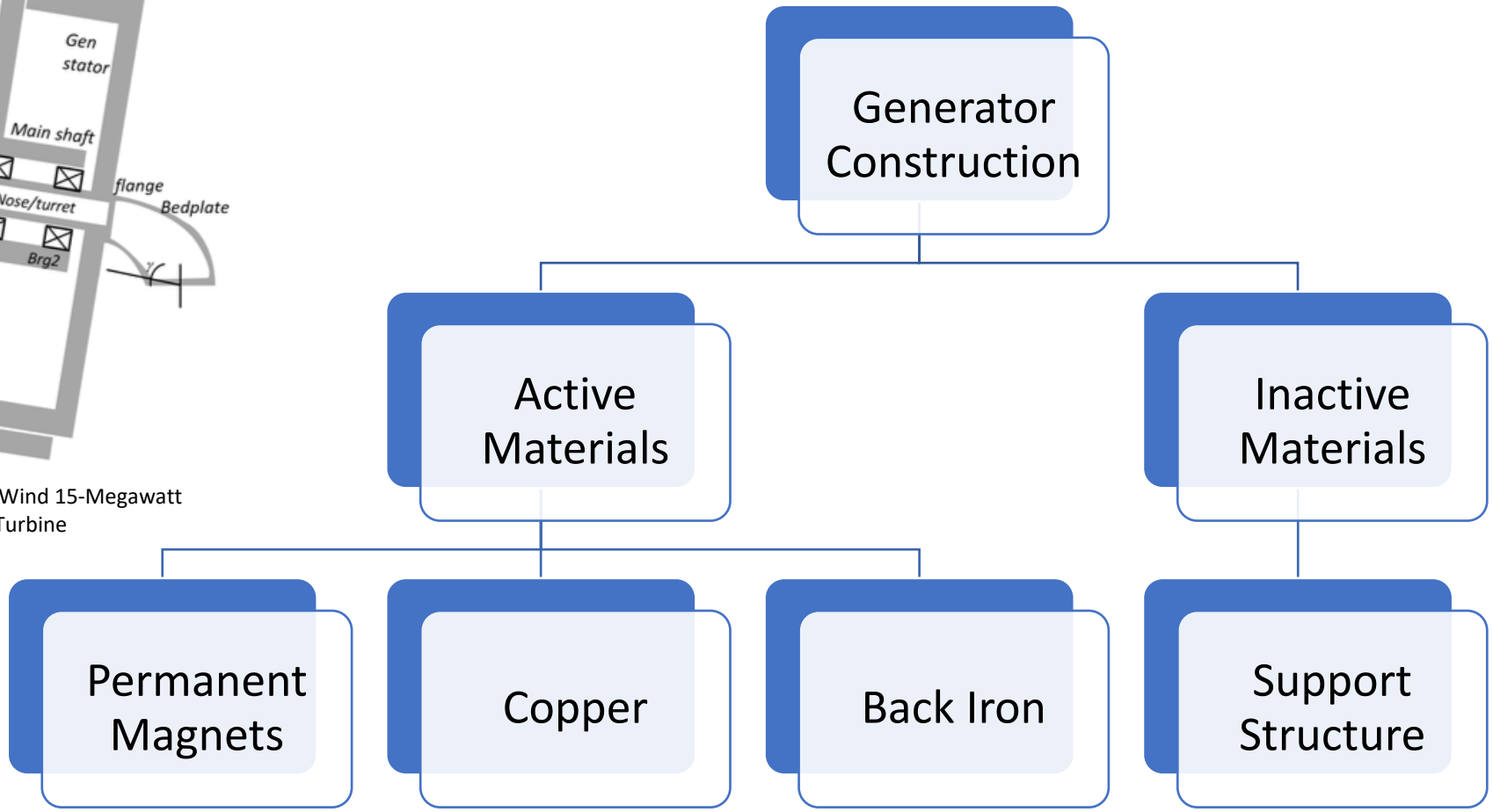


Photo Courtesy of:
NREL Definition of the IEA Wind 15-Megawatt Offshore Reference Wind Turbine



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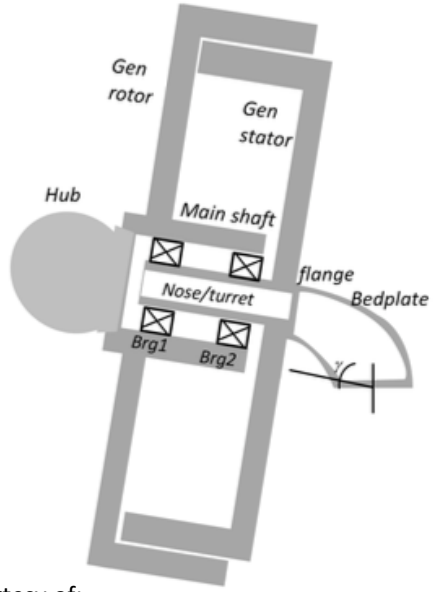

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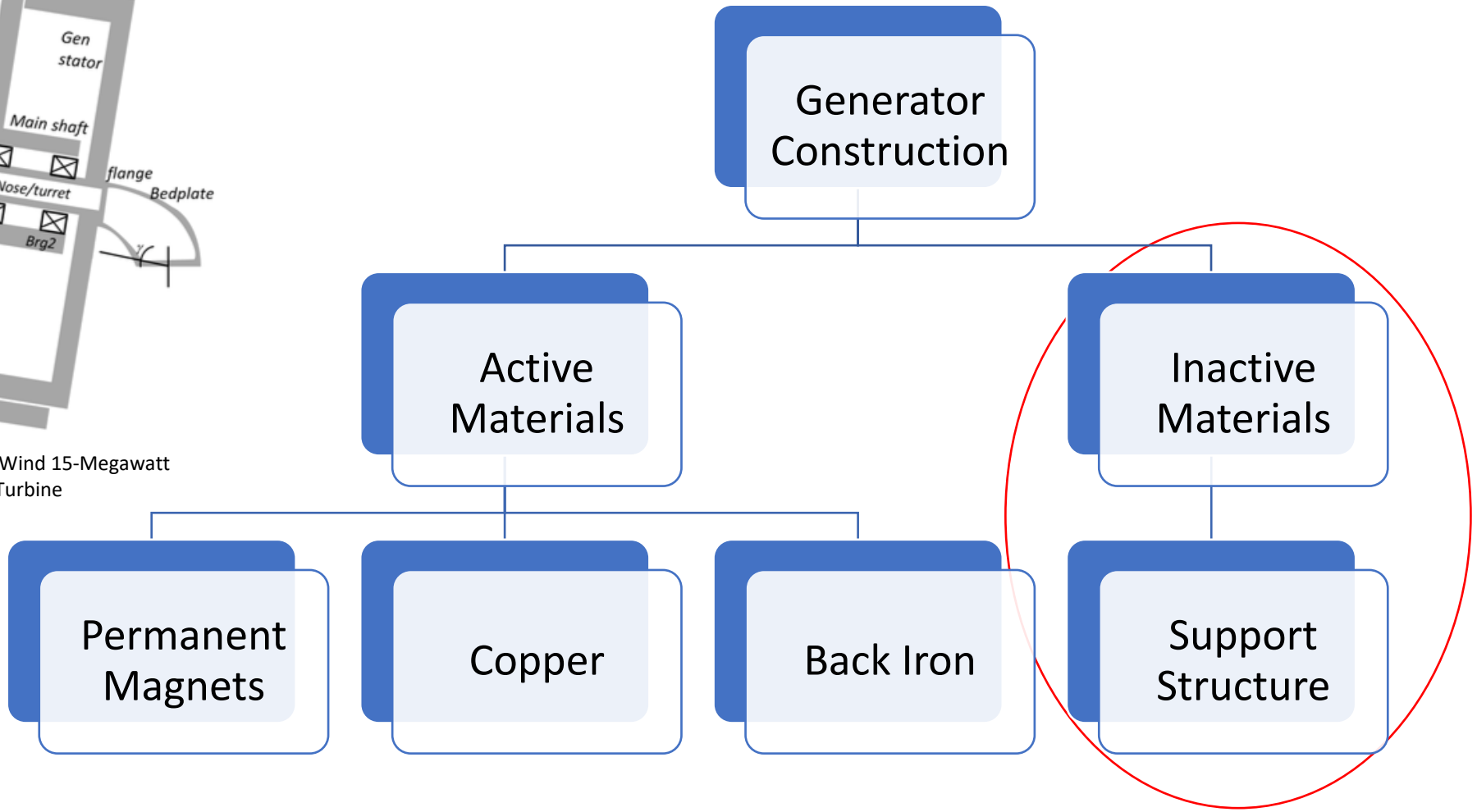


PROJECT AIM

- Aim of the Project:
  - Analyse the generator in the NREL 15MW reference wind turbine, specifically looking at the structural mass of the rotor structure.
  - Use Ansys to optimise the rotor structure by varying certain parameters in order to reduce the structural mass.
  - Review from both static and dynamic perspectives.
  - Ensure the radial deformation and equivalent stress stay within set limits (Static).
  - Ensure the natural frequencies of the structure avoid the operating region (Dynamic).

TURBINE - SPECIFICATION

- Turbine Specification:

PARAMETER	VALUE
POWER RATING	15 MW
HUB HEIGHT	150 m
ROTOR DIAMETER	240 m
DRIVETRAIN	Low Speed, Direct Drive
MINIMUM ROTOR SPEED	5 rpm
MAXIMUM ROTOR SPEED	7.56 rpm

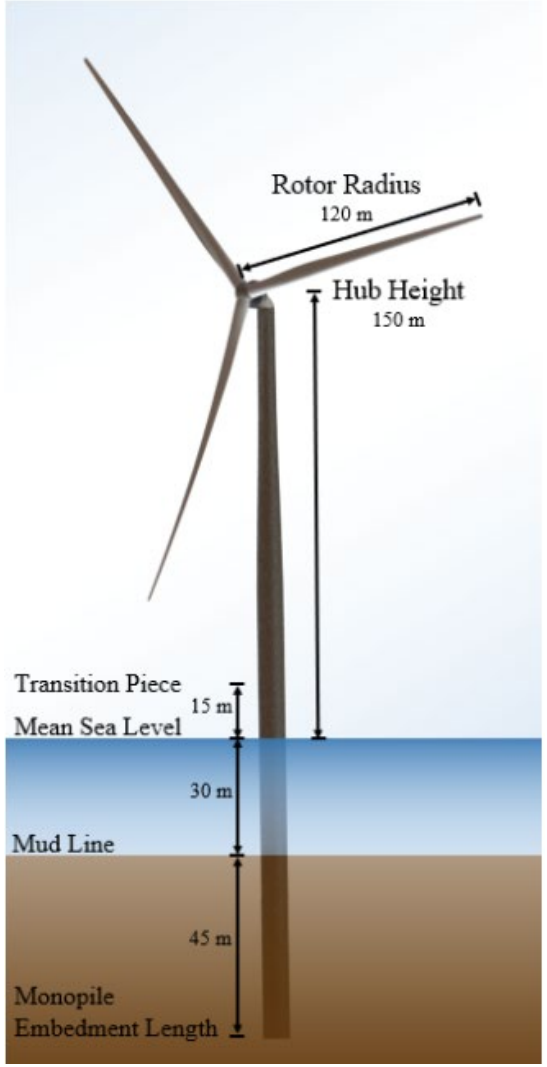


Photo Courtesy of:
NREL Definition of the IEA Wind 15-Megawatt Offshore Reference Wind Turbine

GENERATOR - SPECIFICATION

- Generator Specification:

PARAMETER	VALUE
RATED SPEED	0.792 rad/s
RATED TORQUE	21.03 MNm
AIR GAP RADIUS	5.08 m
CORE LENGTH	2.17 m
AIR GAP LENGTH	10.16 m
POLES	200
STATOR SLOTS	240
SHAFT TILT ANGLE	6 degrees

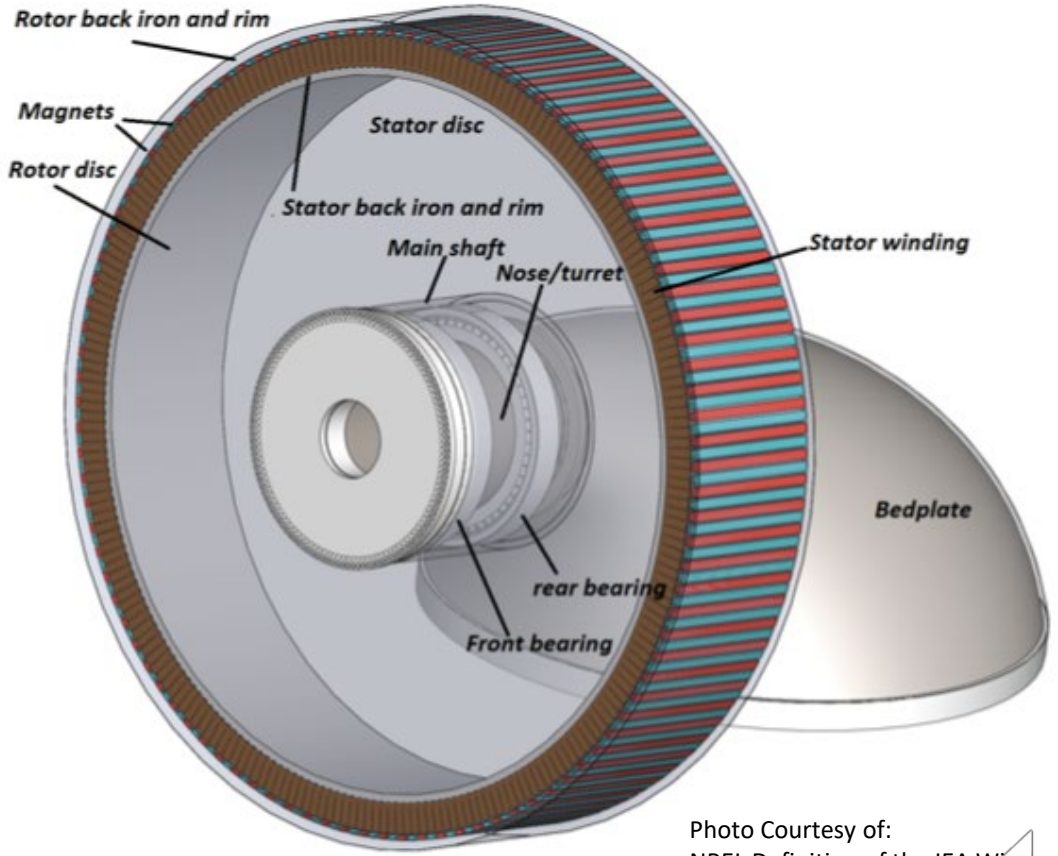


Photo Courtesy of:
NREL Definition of the IEA W
15-Megawatt Offshore Re ce
Wind Turbine

GENERATOR - SPECIFICATION

- Rotor Specification:

PARAMETER	VALUE
ROTOR RIM THICKNESS	63.69 m
ROTOR YOKE THICKNESS	63.62 m
MAGNET HEIGHT	58.39 m
ROTOR DISC THICKNESS	81.75 m

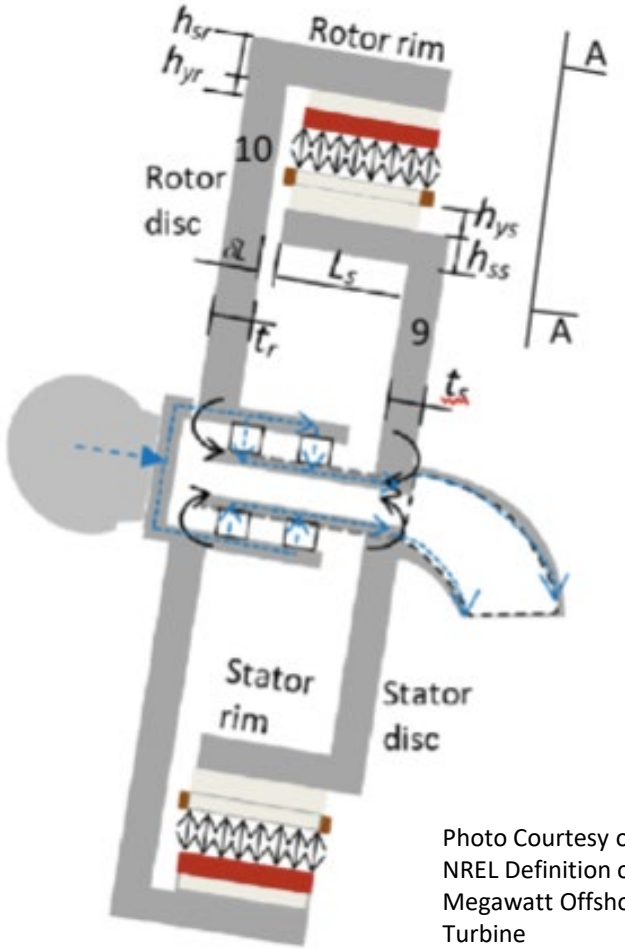
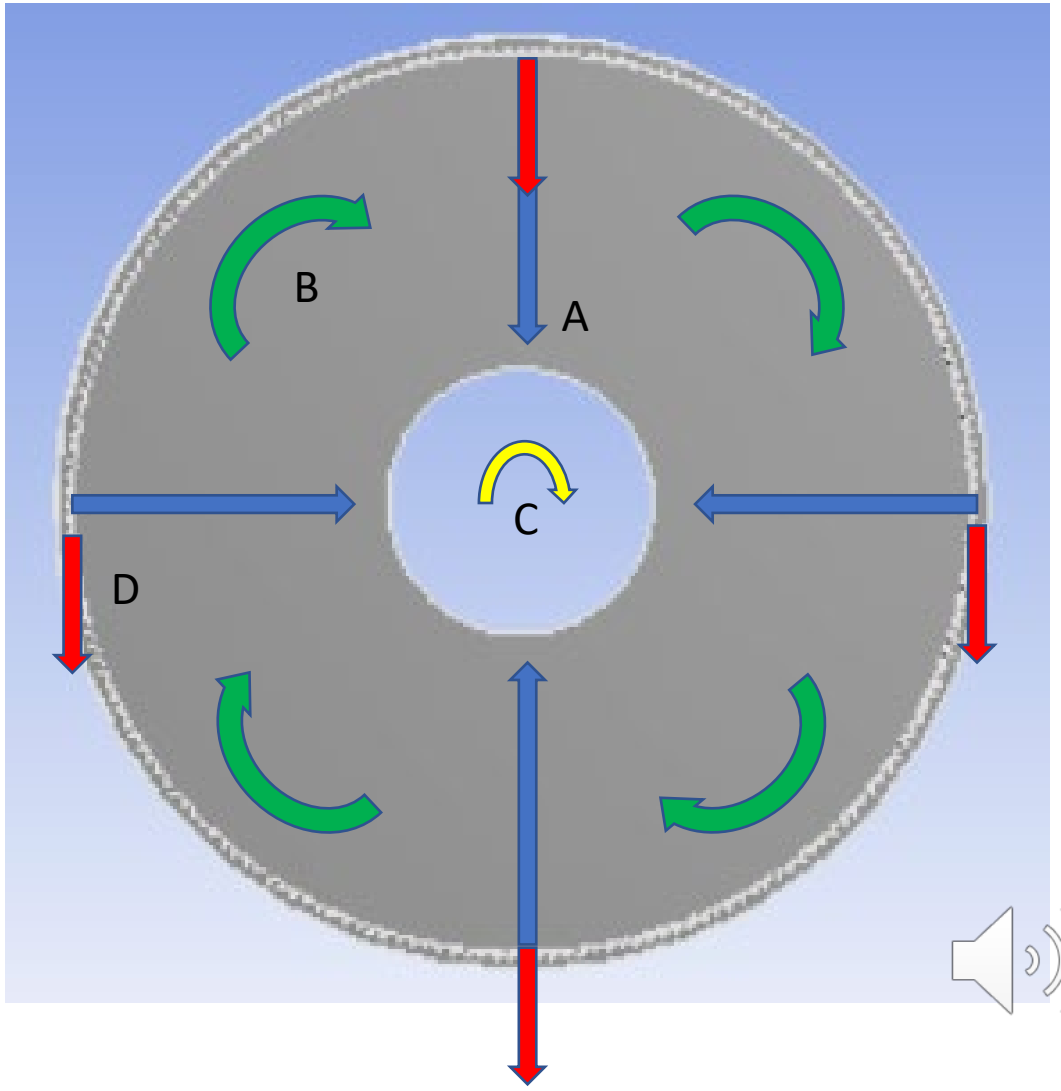


Photo Courtesy of:
NREL Definition of the IEA Wind 15-Megawatt Offshore Reference Wind Turbine

STATIC ANALYSIS

- Applied Forces/Loading:

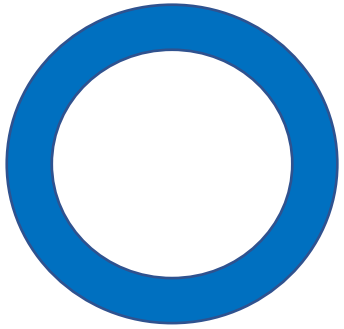
FORCE	VALUE
NORMAL STRESS (A)	447,066 Pa
TORQUE (B)	21.03 MNm
ROTATIONAL VELOCITY (C)	0.792 rad/s
GRAVITY (D)	$g\cos\theta = 9.416\ m/s^2$
DISTRIBUTED MASS (Rotor Yoke & Magnets)	46,021 kg

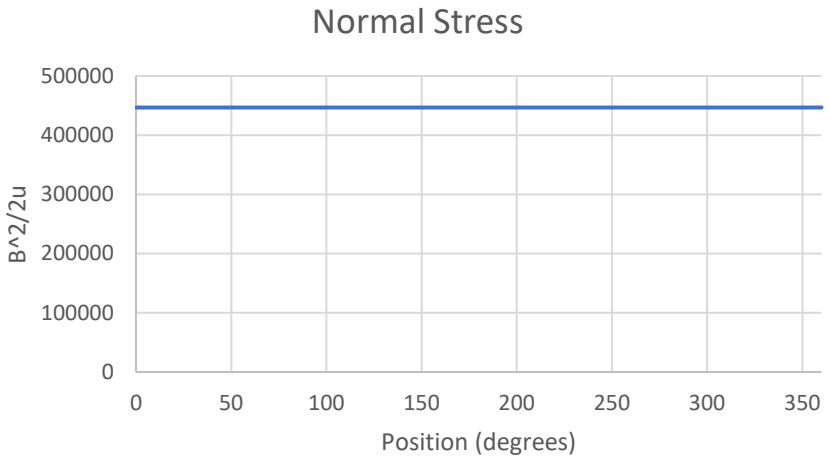


STATIC ANALYSIS – Normal Stress

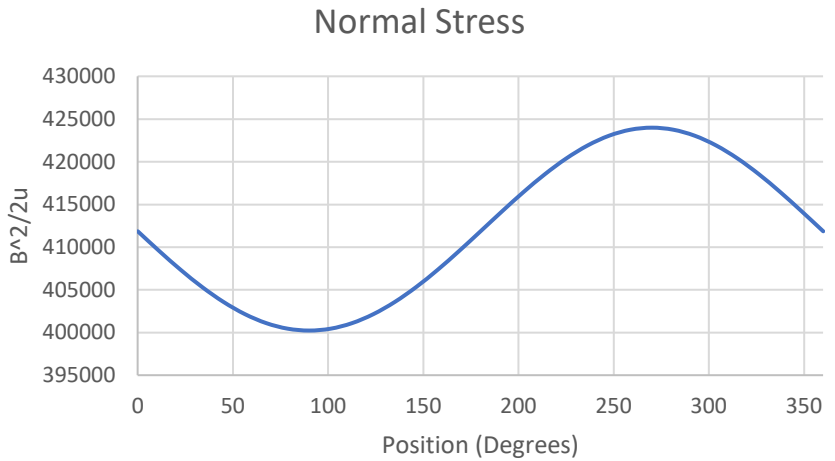
$$Normal\ Stress = \frac{Peak\ Airgap\ Flux\ Density^2}{2\ x\ Permeability\ of\ Free\ Space} = \frac{B^2}{2\mu_0}$$

- Uniform Loading (Mode 0):





- Non-Uniform Loading (Mode 1):

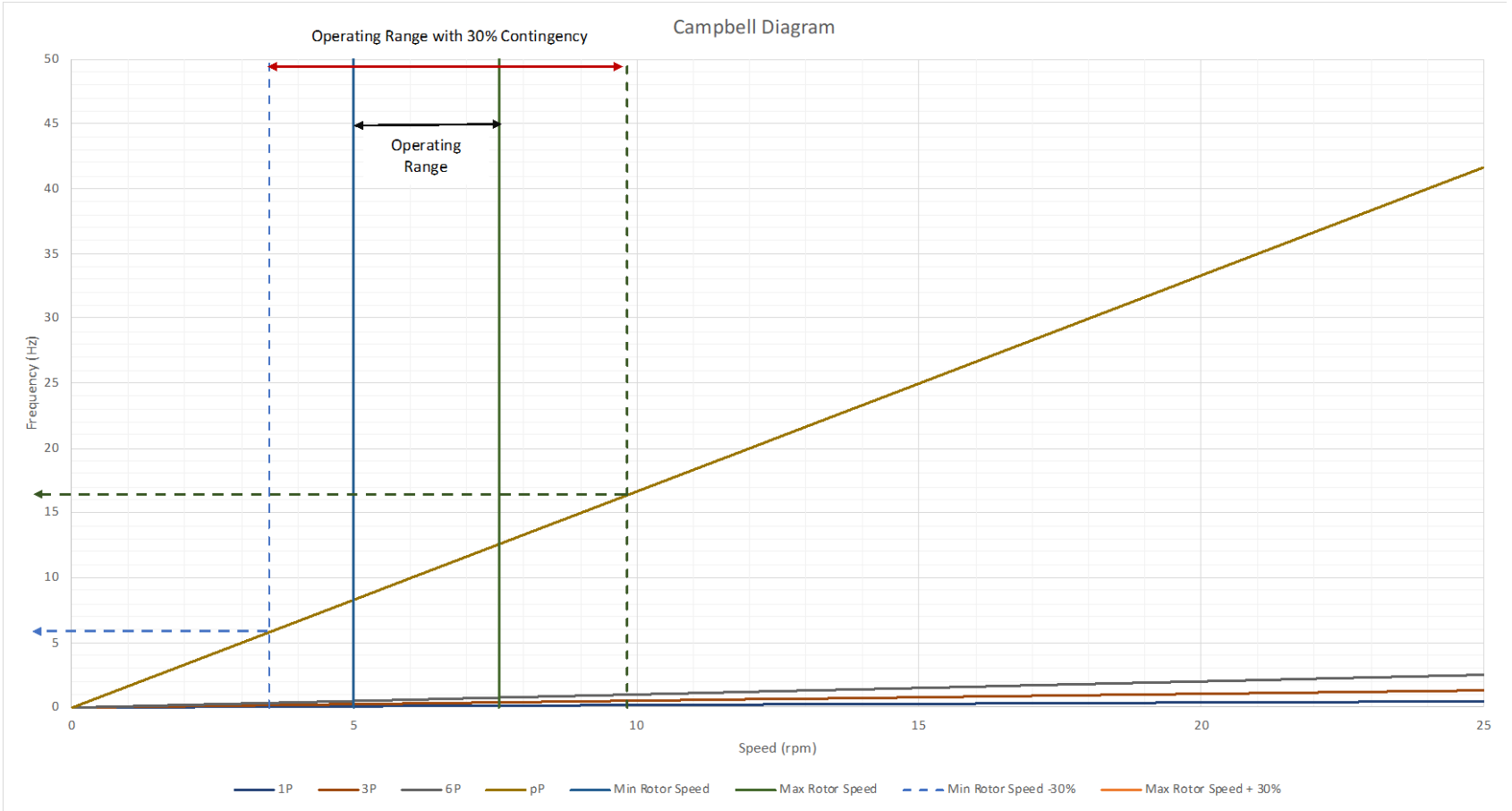


DYNAMIC ANALYSIS

- Purpose: Making the operating range clear, by avoidance of resonance.
- Campbell Diagram:

16 Hz

6 Hz



APPLIED OPTIMISATION CONSTRAINTS

OBJECTIVE	VALUE
MASS (ROTOR + MAIN SHAFT)	Minimize

CONSTRAINT	VALUE
VON MISES EQUIVALENT STRESS (Ultimate Limit State of Strength)	< 200 MPa
DEFORMATION IN RADIAL DIRECTION (Critical Deflection, 20% of Air Gap Length)	-2.032 < x < 2.032 mm
NATURAL FREQUENCIES (Avoidance of Resonance in Operation Speeds Range)	f < 6 Hz and f > 16 Hz

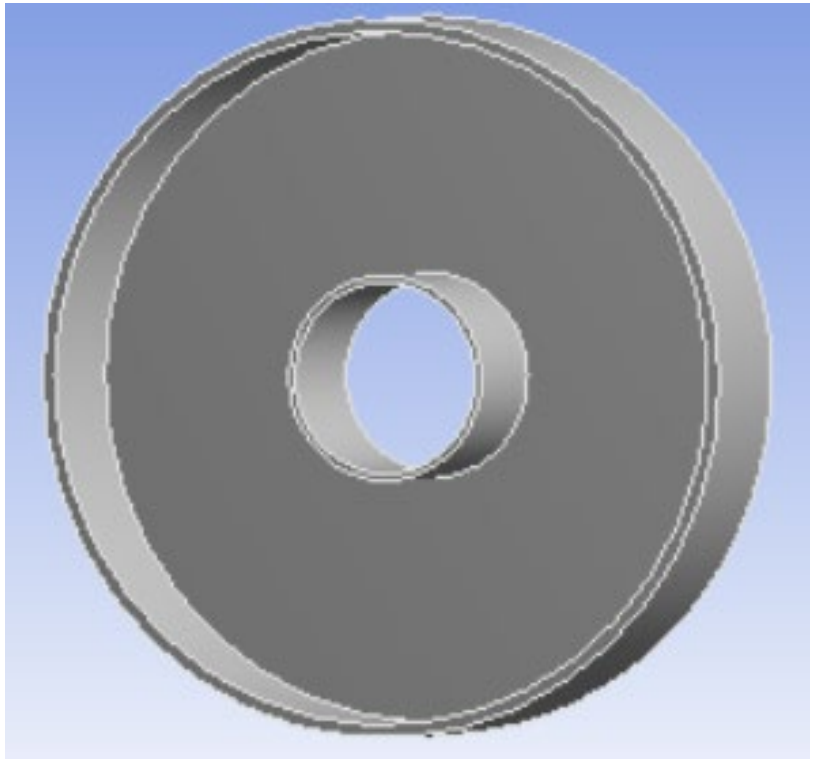
OPTIMISATION SCENARIOS

- 14 scenarios were investigated.

SCENARIO NUMBER	SCENARIO DESCRIPTION	PARAMETER DESCRIPTION	UNIFORM / NON-UNIFORM LOADING	
			STATIC ONLY	STATIC AND DYNAMIC
1	**BASE CASE**	Design Variables	Rim and Disc Thicknesses	Rim and Disc Thicknesses
		Constraints	Stress/Deformation	Stress/Deformation/Natural Frequencies
2	**MASS REMOVAL ADDITION OF HOLES**	Design Variables	Rim and Disc Thicknesses and Holes Diameter	Rim and Disc Thicknesses and Holes Diameter
		Constraints	Stress/Deformation	Stress/Deformation/Natural Frequencies

SCENARIO 1a

- BASE CASE (UNIFORM LOADING):

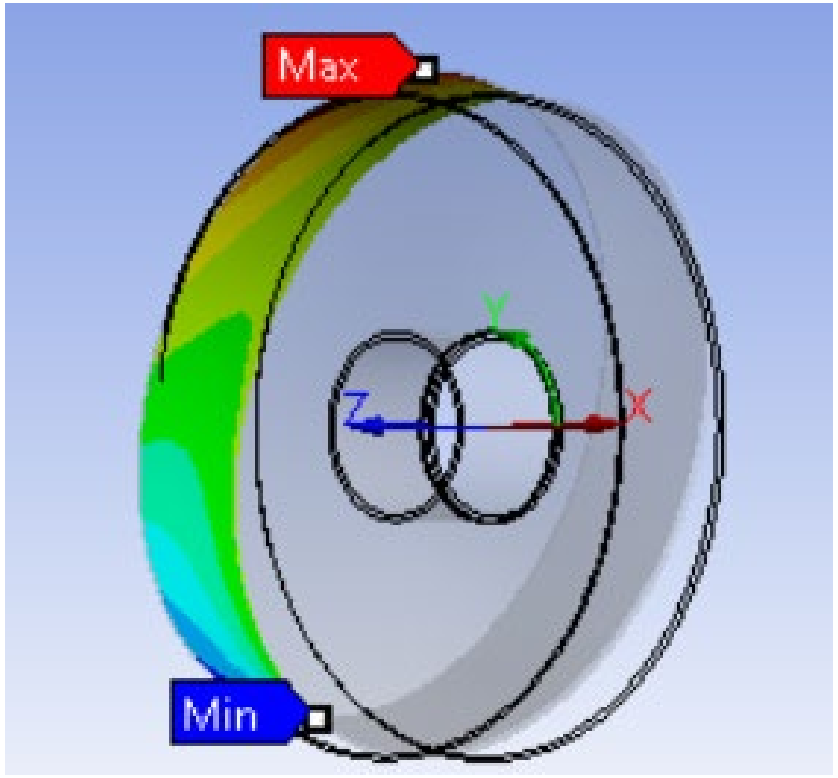


PARAMETER	VALUE
ROTOR RIM THICKNESS	63.69 mm
RIM LENGTH	2.17 m
ROTOR DISC DIAMETER	10.53 m
ROTOR DISC THICKNESS	81.75 mm
SHAFT OUTER DIAMETER	3 m
SHAFT INNER DIAMETER	2.8 m

SCENARIO 1a - RESULTS

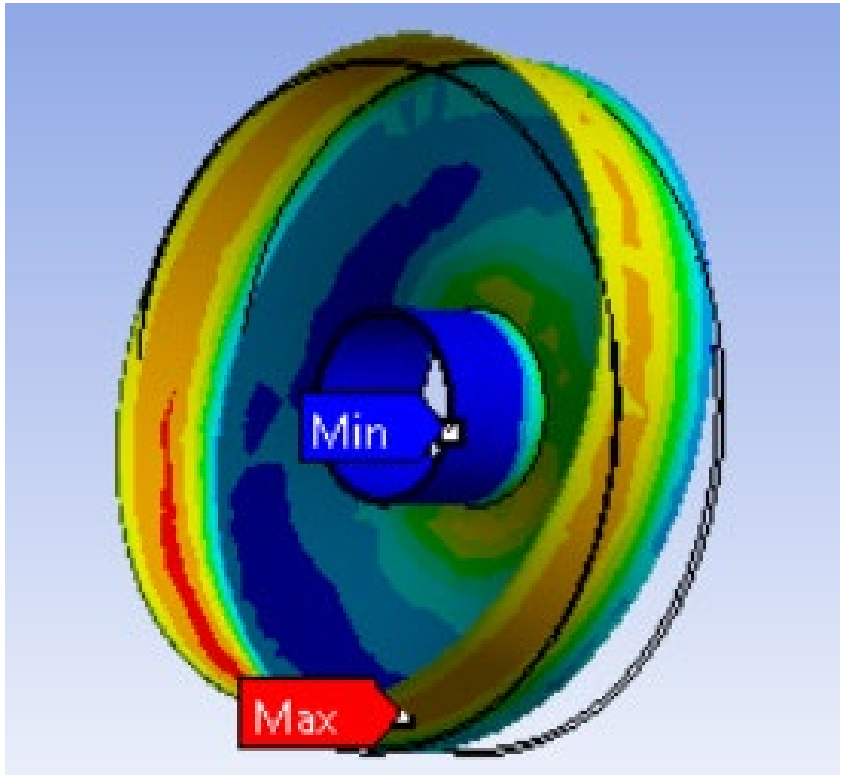
- BASE CASE – RESULTS – STATIC – UNIFORM LOADING:

Deformation



Max. = 3.8 mm
Min. = -5.4 mm

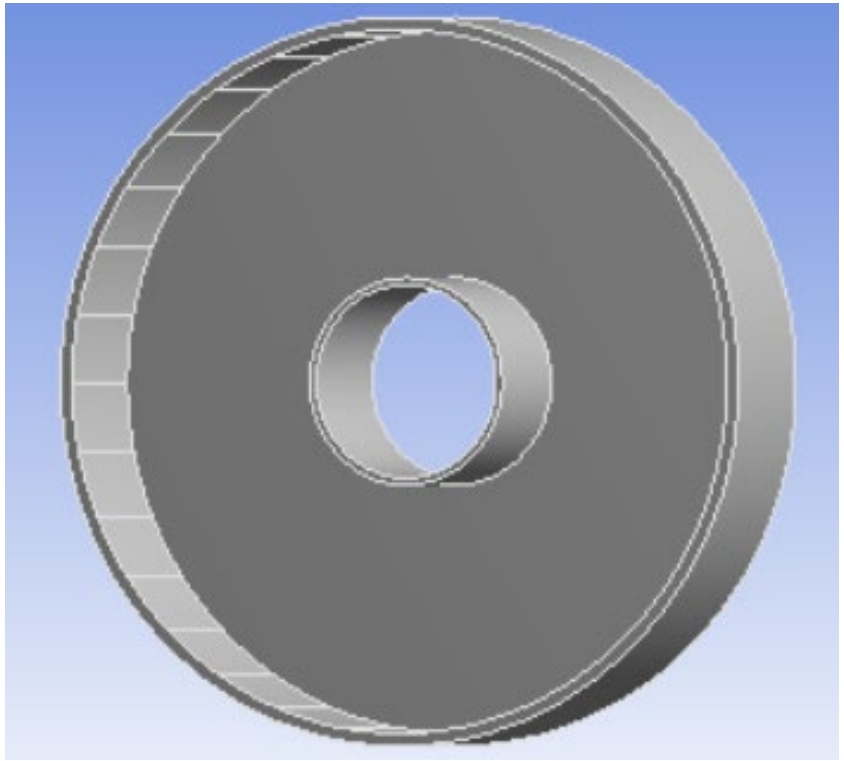
Equivalent Stress

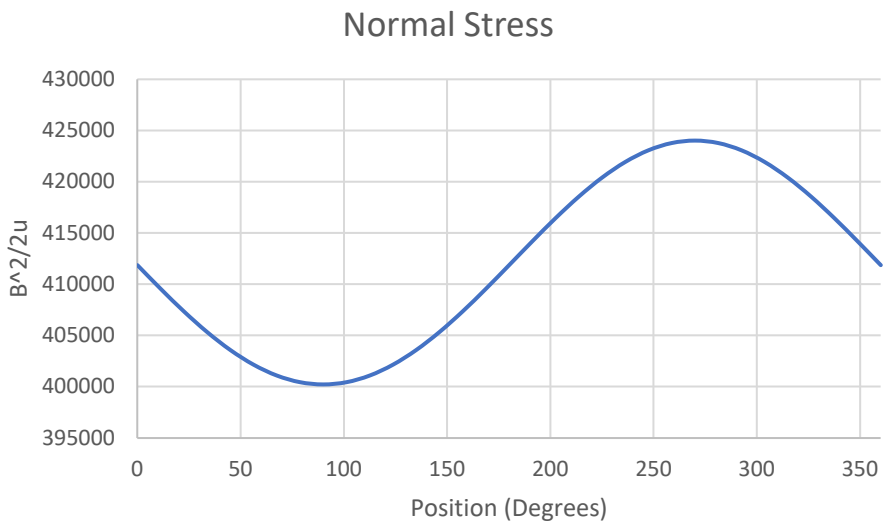


Max. = 48.8 MPa

SCENARIO 1b

- BASE CASE (NON-UNIFORM LOADING):

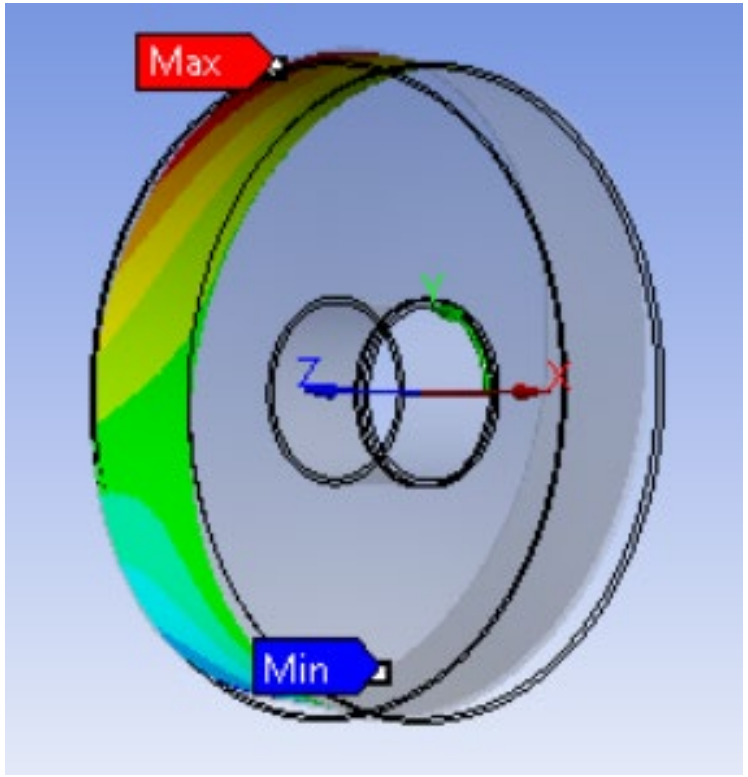




SCENARIO 1b - RESULTS

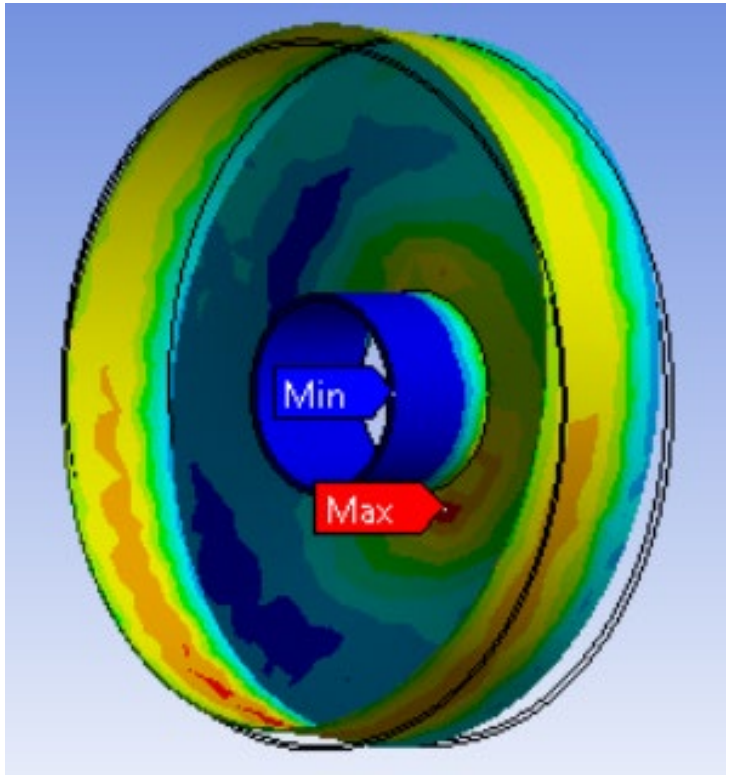
- BASE CASE – RESULTS – STATIC – NON-UNIFORM LOADING:

Deformation



Max. = 6.1 mm
Min. = -7.4 mm

Equivalent Stress

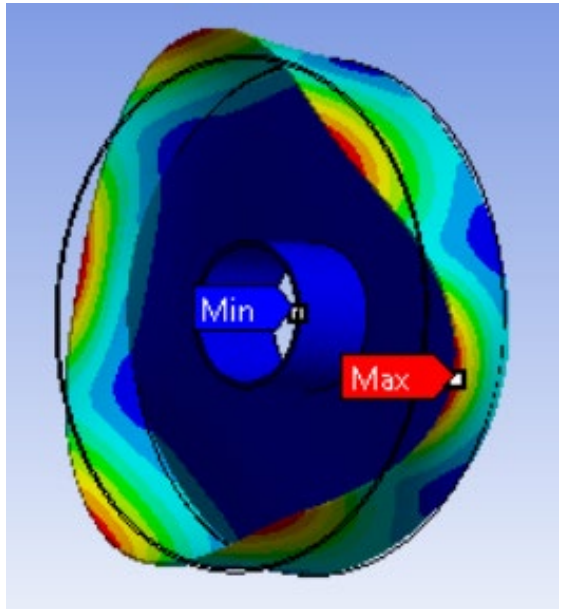


Max. = 49.3 MPa

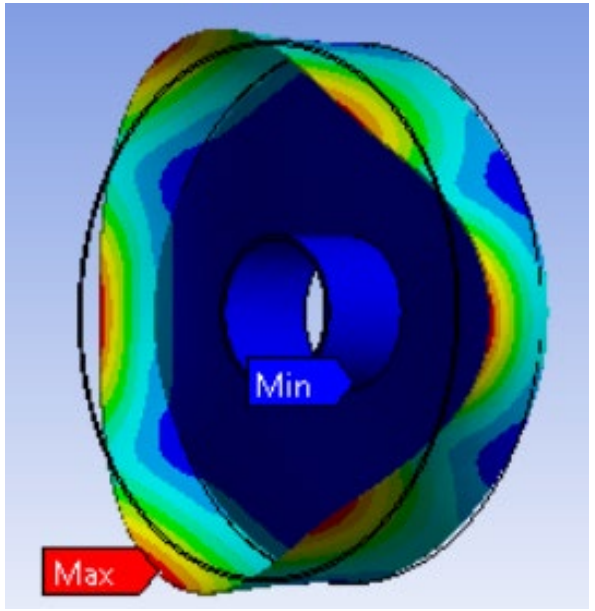
SCENARIO 1 - RESULTS

- BASE CASE – RESULTS – DYNAMIC:

Mode 6

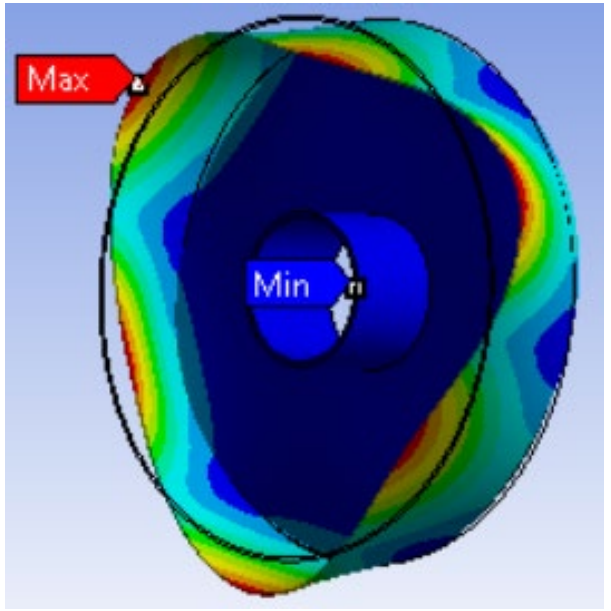


Uniform Loading
f = 9.7 Hz

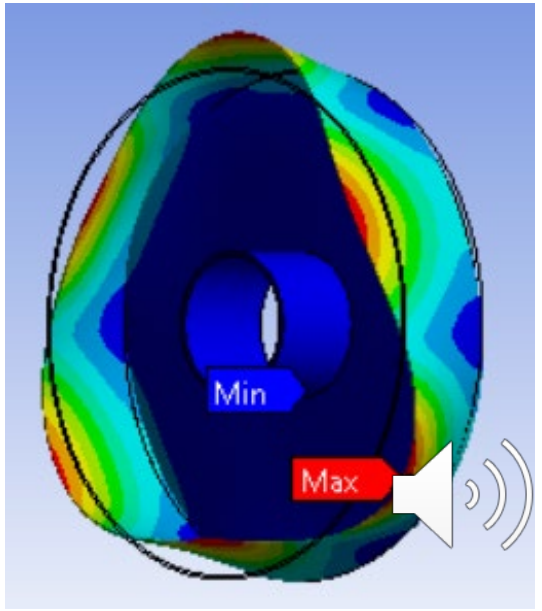


Non-Uniform Loading
f = 9.8 Hz

Mode 7



Uniform Loading
f = 9.8 Hz



Non-Uniform Loading
f = 10.1 Hz

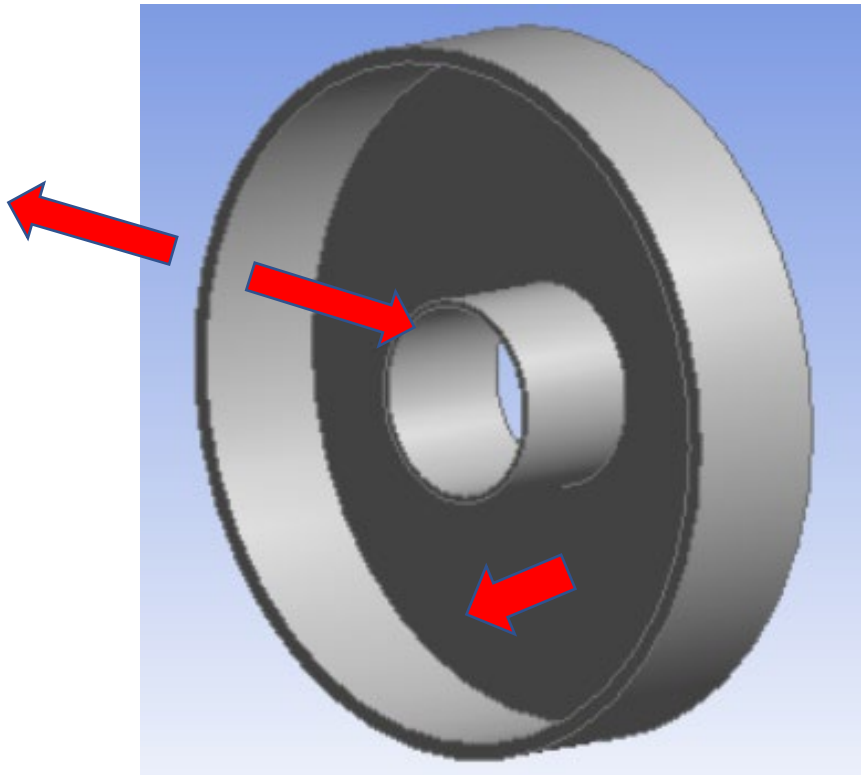
SCENARIO 1 - RESULTS

- BASE CASE (UNIFORM vs. NON-UNIFORM LOADING):

PARAMETER	UNIFORM LOADING		NON-UNIFORM LOADING	
	STATIC ONLY	STATIC AND DYNAMIC	STATIC ONLY	STATIC AND DYNAMIC
MASS (kg)	2.58×10^5	2.58×10^5	-	-
EQUIVALENT STRESS (MPa)	111.11	111.11	-	-
DEFORMATION (Radial) (mm)	-2.03	-2.03	-	-
FREQUENCY (MODE 6) (Hz)	N/A	18.9	N/A	-
FREQUENCY (MODE 7) (Hz)	N/A	19.1	N/A	-

SCENARIO 1 - RESULTS

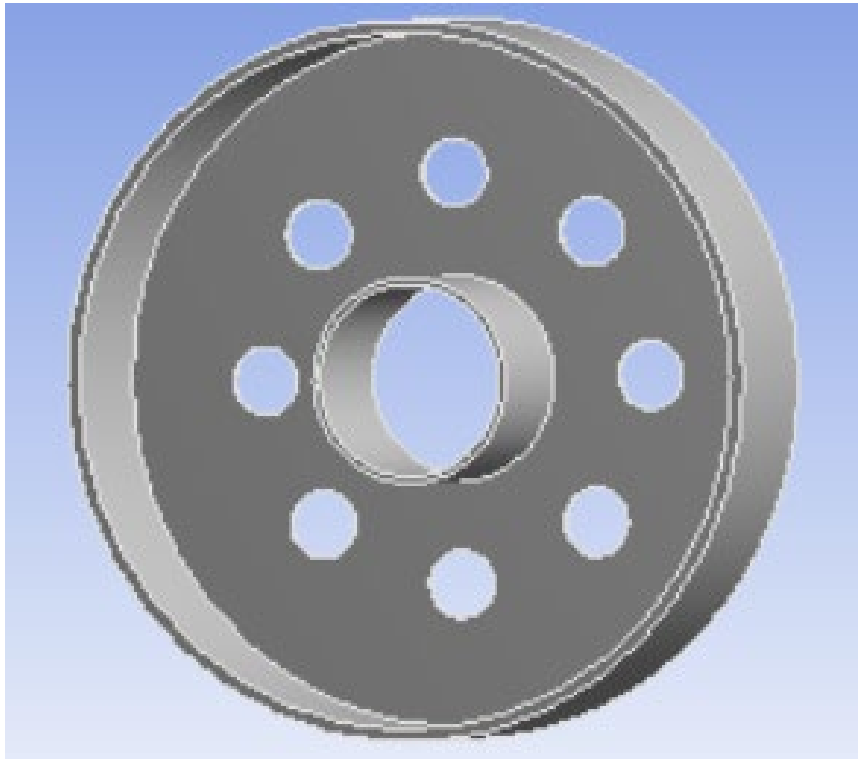
- FINAL RESULT (UNIFORM LOADING):



PARAMETER	ORIGINAL VALUE	OPTIMISED VALUE
ROTOR RIM THICKNESS	63.69 mm	244.7 mmm
ROTOR DISC THICKNESS	81.75 mm	108.39 mm

SCENARIO 2a

- ADDITION OF HOLES (UNIFORM LOADING):



PARAMETER	VALUE
ROTOR RIM THICKNESS	63.69 m
RIM LENGTH	2.17 m
ROTOR DISC DIAMETER	10.53 m
ROTOR DISC THICKNESS	81.75 m
SHAFT OUTER DIAMETER	3 m
SHAFT INNER DIAMETER	2.8 m
HOLE DIAMETERS	1 m

SCENARIO 2a - COMBINATIONS

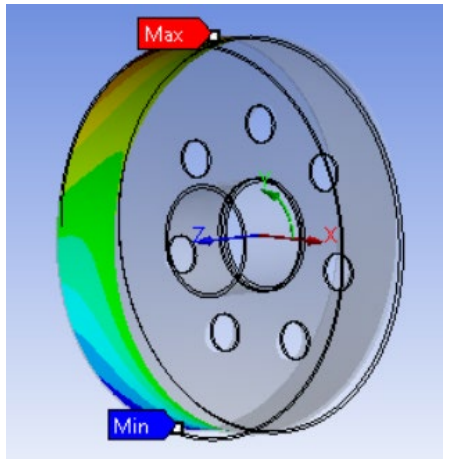
- DIFFERENT COMBINATIONS ANALYSED:

HOLES / RADIUS	7	8	9
3 m	✓	✓	✓
3.5 m	✓	✓	✓

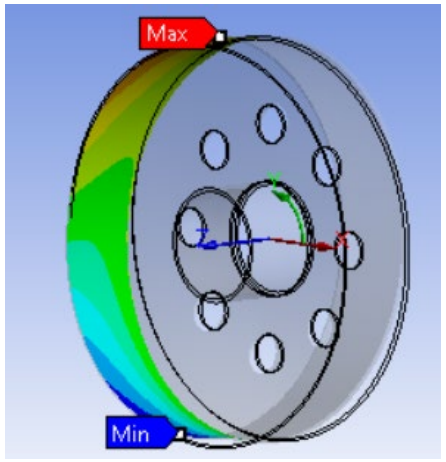
SCENARIO 2a - RESULTS

- ADDITION OF HOLES – RESULTS – STATIC – UNIFORM LOADING:

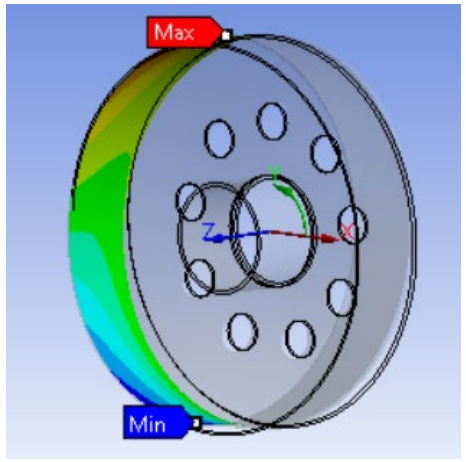
Deformation



7 Holes



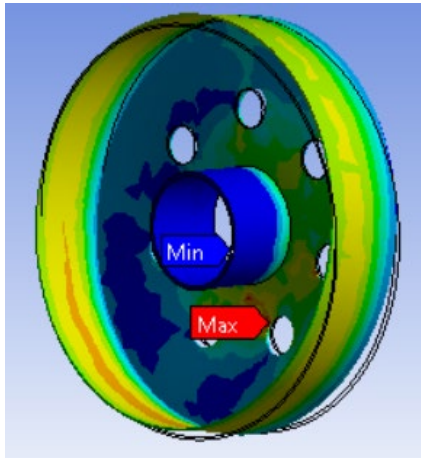
8 Holes

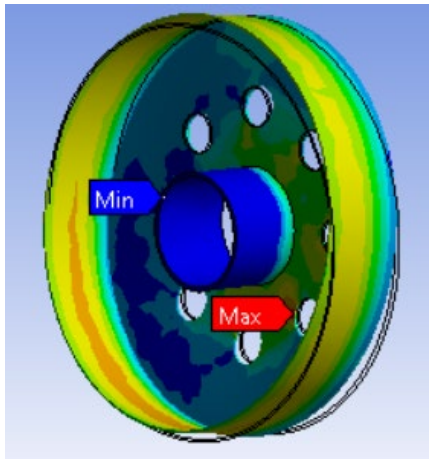


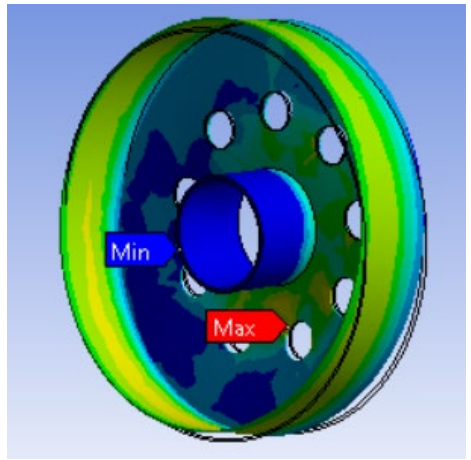
9 Holes

Distance Between Holes - 6m

Equivalent Stress



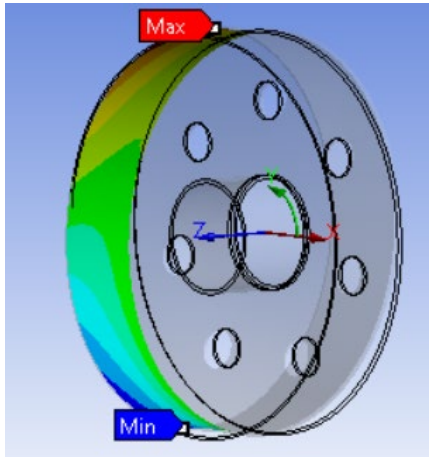




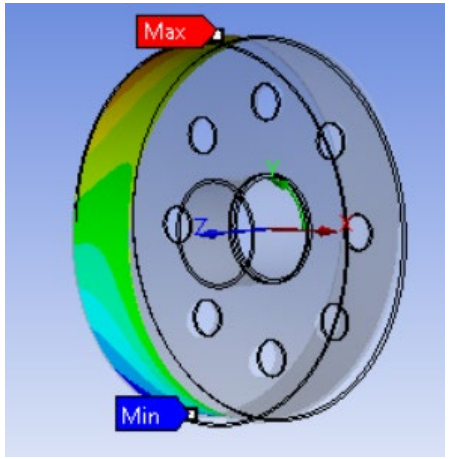
SCENARIO 2a - RESULTS

- ADDITION OF HOLES – RESULTS – STATIC – UNIFORM LOADING:

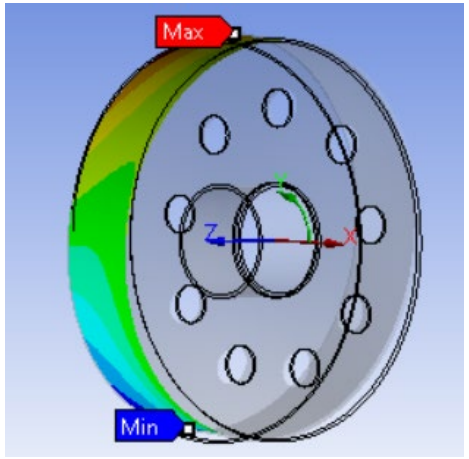
Deformation



7 Holes



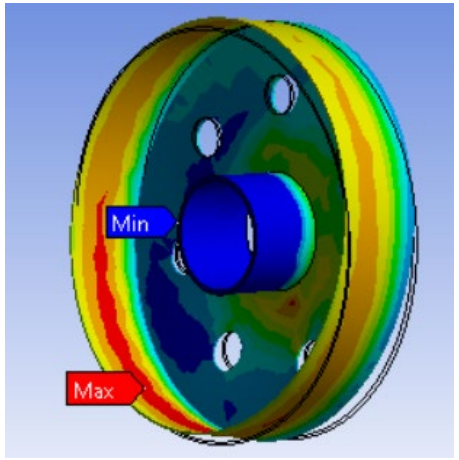
8 Holes

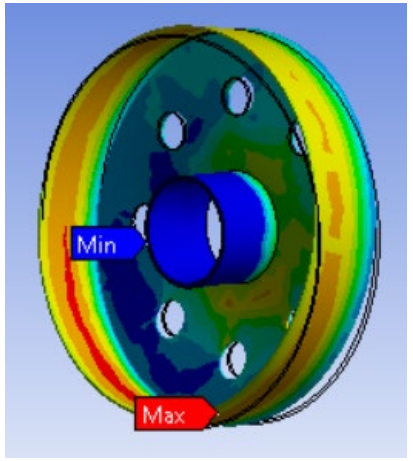


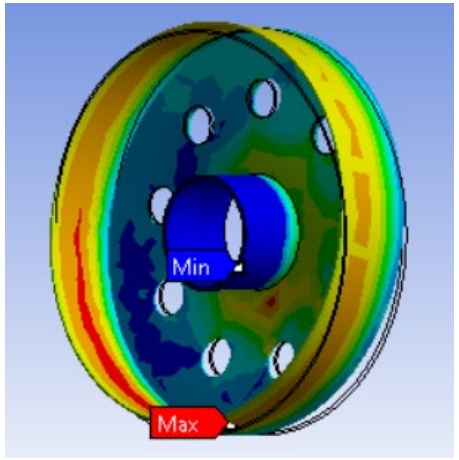
9 Holes

Distance Between Holes - 7m

Equivalent Stress



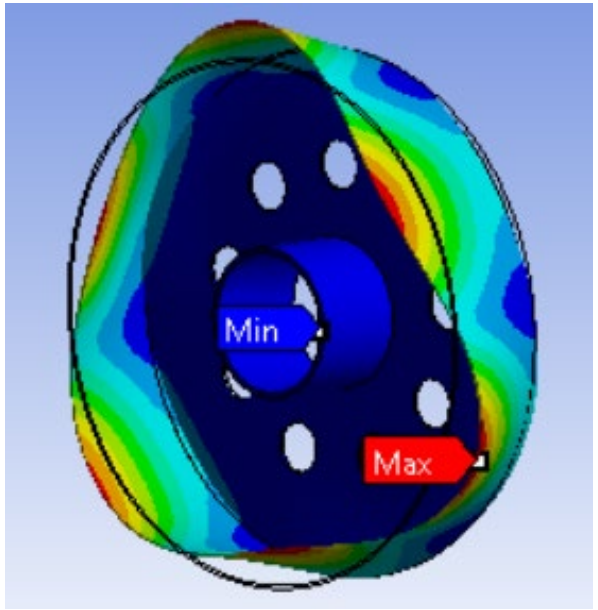




SCENARIO 2a - RESULTS

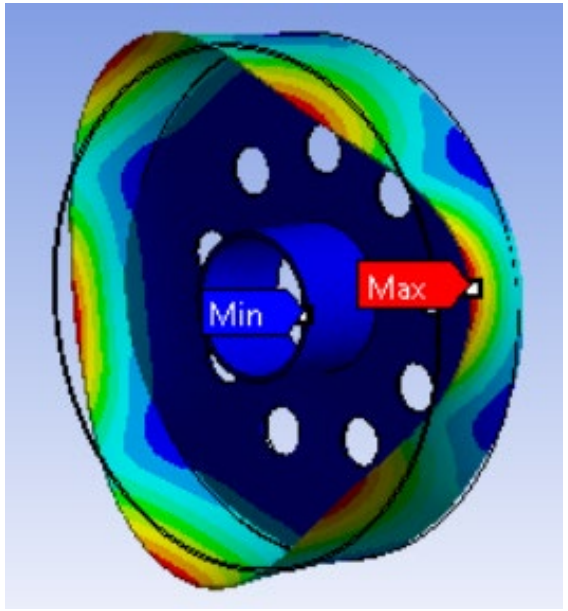
- ADDITION OF HOLES – RESULTS – DYNAMIC:

Mode 6



NUMBER OF HOLES	FREQUENCY (Hz)
7 Holes @ 3m	9.34
7 Holes @ 3.5m	9.34
8 Holes @ 3m	9.36
8 Holes @ 3.5m	9.19
9 Holes @ 3m	9.20
9 Holes @ 3.5m	9.30

Mode 7

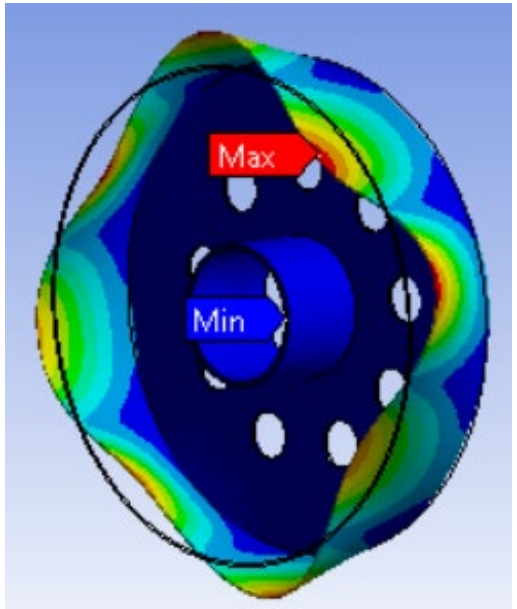


NUMBER OF HOLES	FREQUENCY (Hz)
7 Holes @ 3m	9.49
7 Holes @ 3.5m	9.36
8 Holes @ 3m	9.48
8 Holes @ 3.5m	9.31
9 Holes @ 3m	9.48
9 Holes @ 3.5m	9.32

SCENARIO 2a - RESULTS

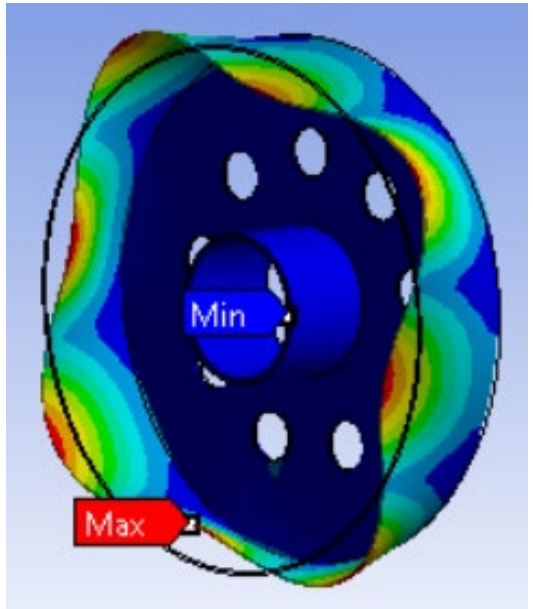
- ADDITION OF HOLES – RESULTS – DYNAMIC:

Mode 8



NUMBER OF HOLES	FREQUENCY (Hz)
7 Holes @ 3m	15.62
7 Holes @ 3.5m	15.60
8 Holes @ 3m	15.69
8 Holes @ 3.5m	15.38
9 Holes @ 3m	15.62
9 Holes @ 3.5m	15.40

Mode 9



NUMBER OF HOLES	FREQUENCY (Hz)
7 Holes @ 3m	15.77
7 Holes @ 3.5m	15.95
8 Holes @ 3m	15.78
8 Holes @ 3.5m	15.57
9 Holes @ 3m	15.73
9 Holes @ 3.5m	15.59

SCENARIO 2a - RESULTS

- ADDITION OF HOLES – RESULTS – UNIFORM LOADING:

PARAMETER	7 HOLES @ 3m		8 HOLES @ 3m		9 HOLES @ 3m	
	STATIC ONLY	STATIC AND DYNAMIC	STATIC ONLY	STATIC AND DYNAMIC	STATIC ONLY	STATIC AND DYNAMIC
MASS (kg)	1.30×10^5	2.01×10^5	1.59×10^5	1.99×10^5	51336	1.85×10^5
EQUIVALENT STRESS (MPa)	199.2	98.39	59.27	58.55	-21.91	36.63
DEFORMATION (Radial) (mm)	-1.12	-1.95	-2.03	-1.92	-1.95	-0.68
FREQUENCY (M6) (Hz)	N/A	16	N/A	16	N/A	16.03
FREQUENCY (M7) (Hz)	N/A	17.25	N/A	16.12	N/A	21.63
FREQUENCY (M8) (Hz)	N/A	18.53	N/A	24.41	N/A	23.75
FREQUENCY (M9) (Hz)	N/A	25.35	N/A	24.77	N/A	25.98

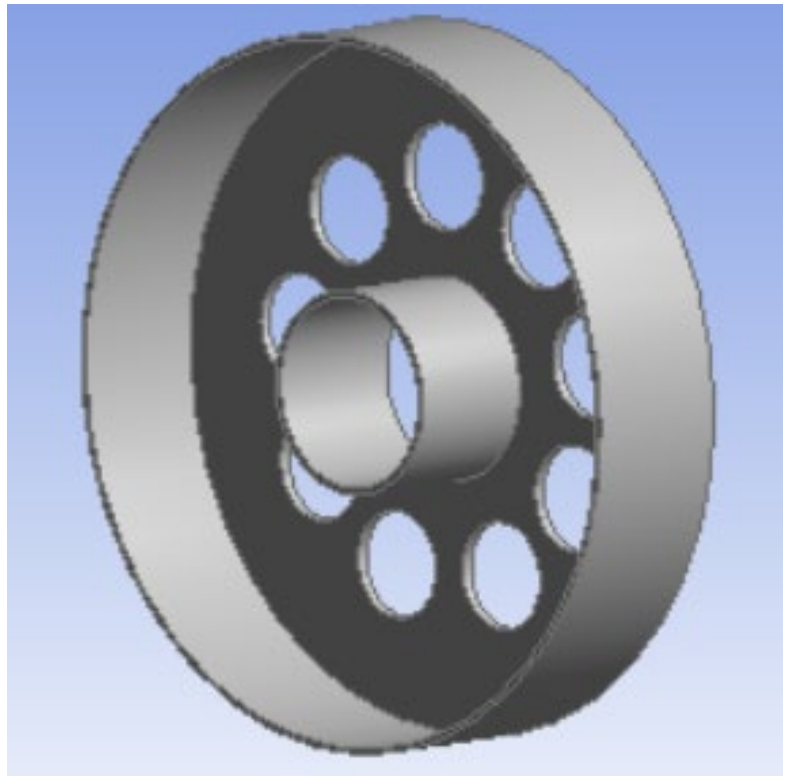
SCENARIO 2a - RESULTS

- ADDITION OF HOLES – RESULTS – UNIFORM LOADING:

PARAMETER	7 HOLES @ 3.5m		8 HOLES @ 3.5m		9 HOLES @ 3.5m	
	STATIC ONLY	STATIC AND DYNAMIC	STATIC ONLY	STATIC AND DYNAMIC	STATIC ONLY	STATIC AND DYNAMIC
MASS (kg)	1.25×10^5	2.11×10^5	1.3×10^5	2.01×10^5	1.81×10^5	2.04×10^5
EQUIVALENT STRESS (MPa)	109.28	36.76	103.68	55.39	58.14	36.12
DEFORMATION (Radial) (mm)	-0.37	-1.91	-2.01	-1.84	-2.03	-1.67
FREQUENCY (M6) (Hz)	N/A	16.04	N/A	16.02	N/A	16.00
FREQUENCY (M7) (Hz)	N/A	18.89	N/A	18.18	N/A	16.00
FREQUENCY (M8) (Hz)	N/A	24.15	N/A	24.16	N/A	23.60
FREQUENCY (M9) (Hz)	N/A	27.25	N/A	25.79	N/A	24.55

SCENARIO 2a - RESULTS

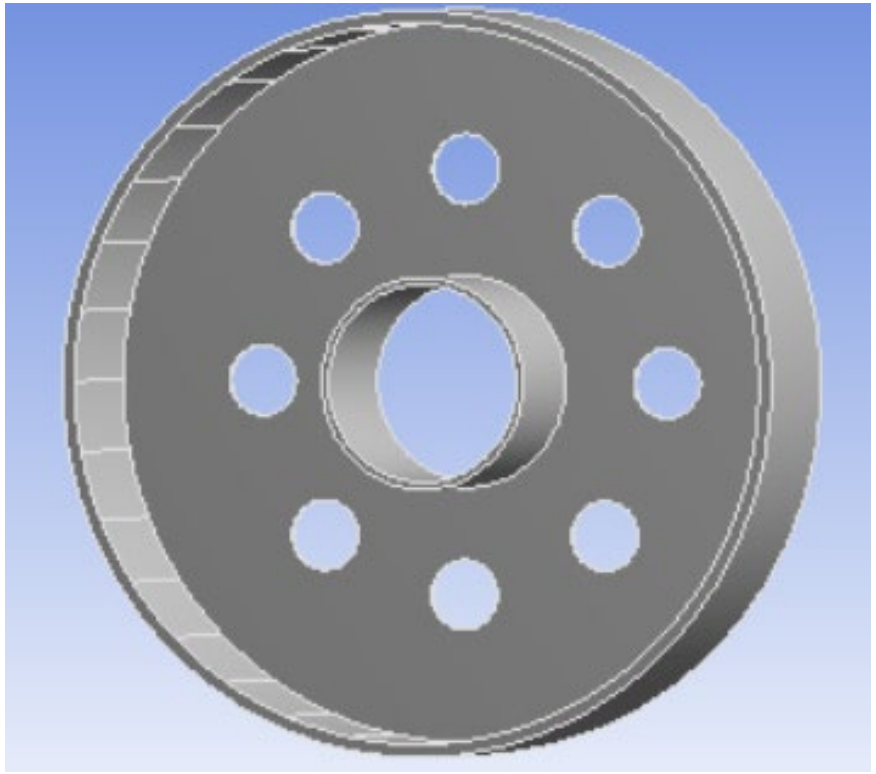
- ADDITION OF HOLES – OPTIMISED DESIGN:
  - 9 Holes @ 3m Radius

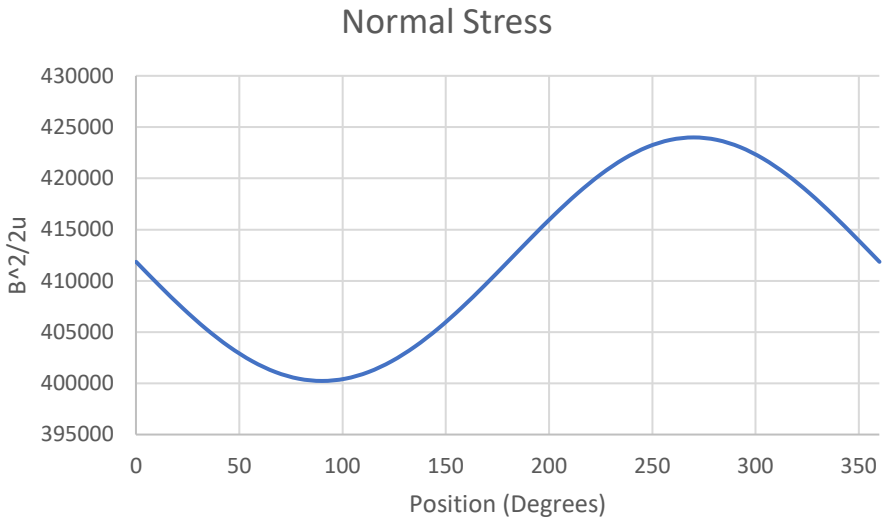


PARAMETER	OPTIMISED BASE CASE	OPTIMISED CASE	DIFFERENCE
RIM THICKNESS (mm)	244.7	83.7	-65.8% ↓
DISC THICKNESS (mm)	108.39	178.67	64.8% ↑
MASS (kg)	2.58×10^5	1.85×10^5	-28.3% ↓
EQUIVALENT STRESS (MPa)	111.11	36.63	-67.0% ↓
DEFORMATION (Radial) (mm)	-2.03	- 0.678	-66.6% ↓

SCENARIO 2b

- ADDITION OF HOLES (NON-UNIFORM LOADING):

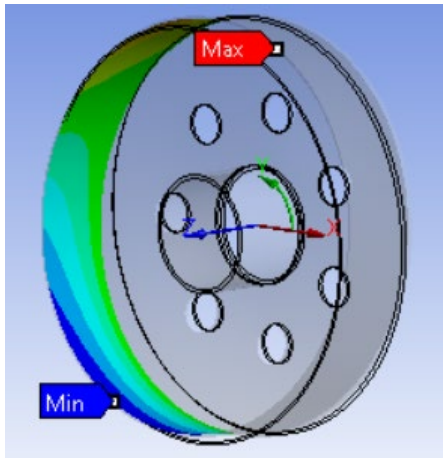




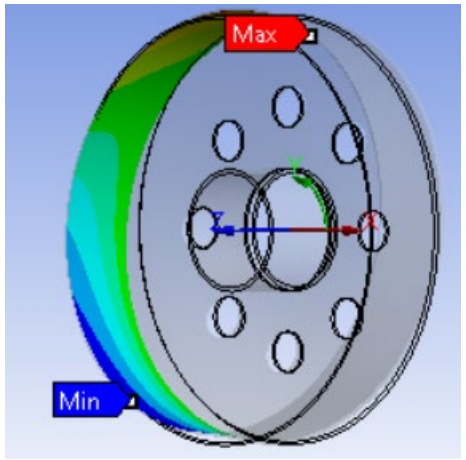
SCENARIO 2b - RESULTS

- ADDITION OF HOLES – RESULTS – STATIC – NON-UNIFORM LOADING:

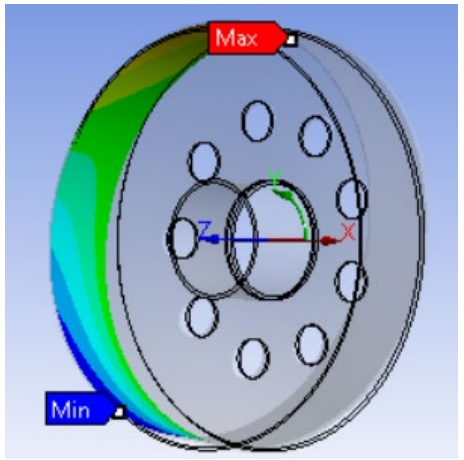
Deformation



7 Holes



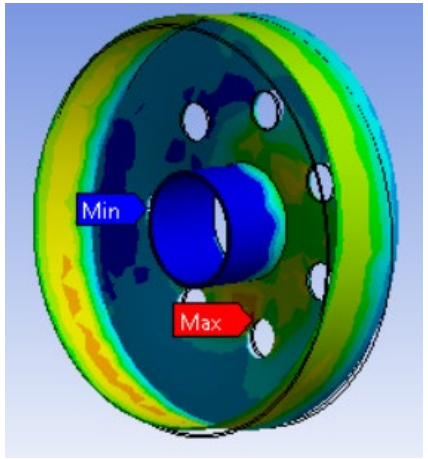
8 Holes

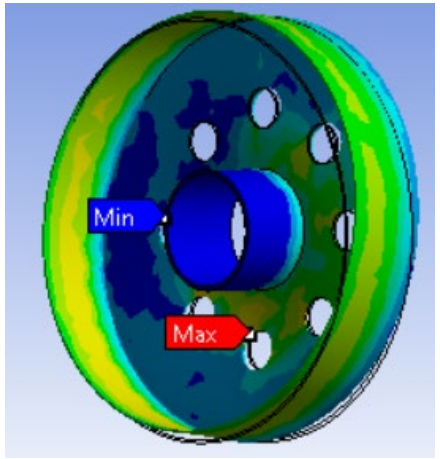


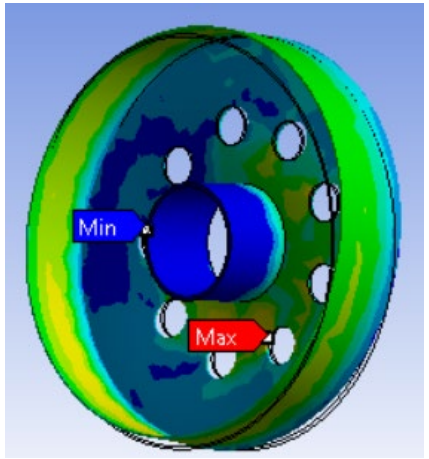
9 Holes

Distance Between Holes - 6m

Equivalent Stress



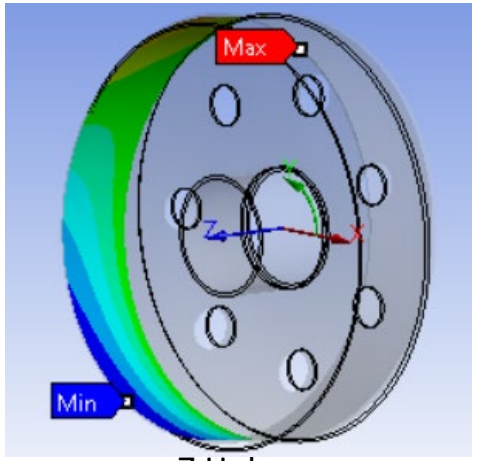




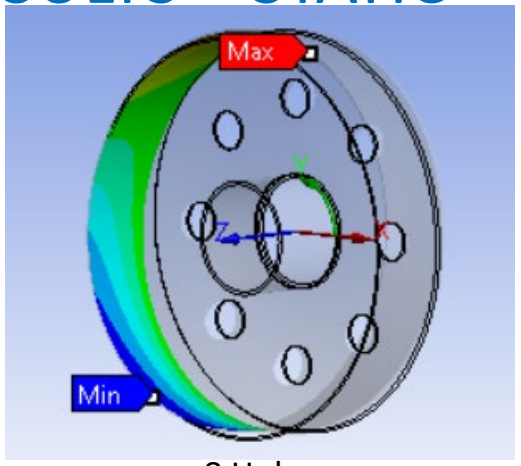
SCENARIO 2b - RESULTS

- ADDITION OF HOLES – RESULTS – STATIC – NON-UNIFORM LOADING:

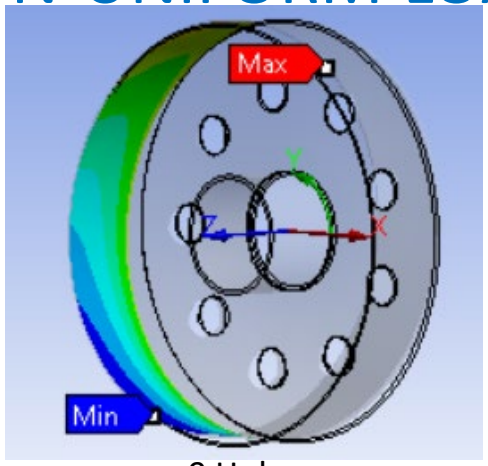
Deformation



7 Holes



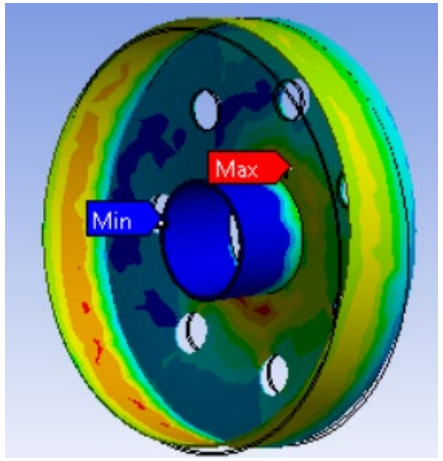
8 Holes

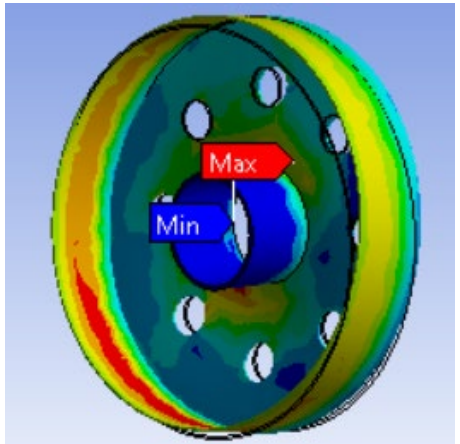


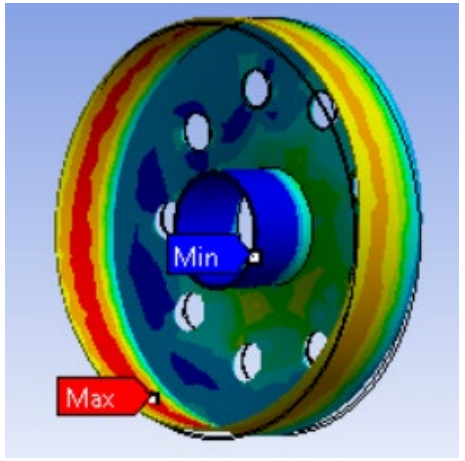
9 Holes

Distance Between Holes - 7m

Equivalent Stress



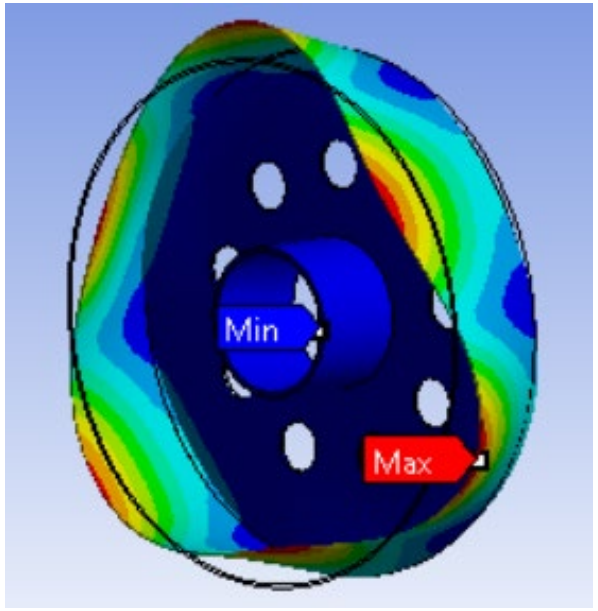




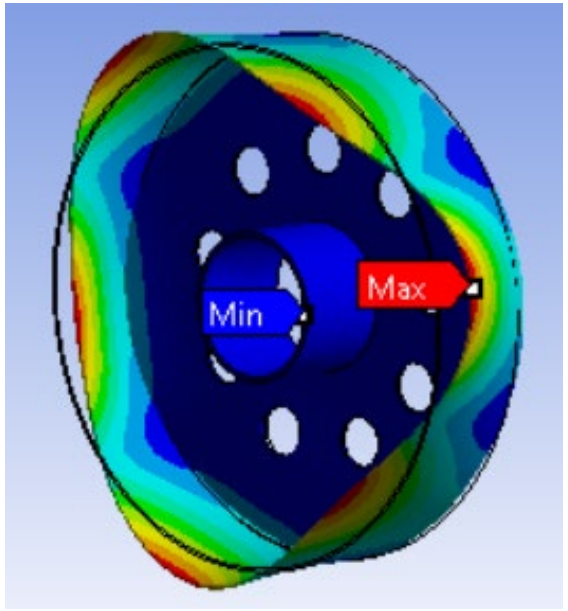
SCENARIO 2b - RESULTS

- ADDITION OF HOLES – RESULTS – DYNAMIC:

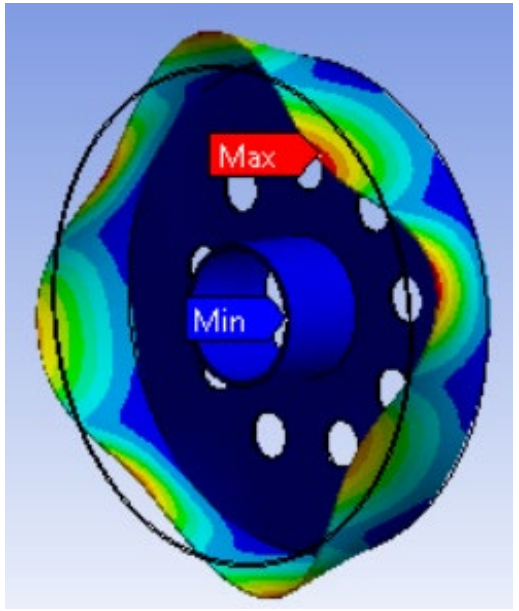
Mode 6



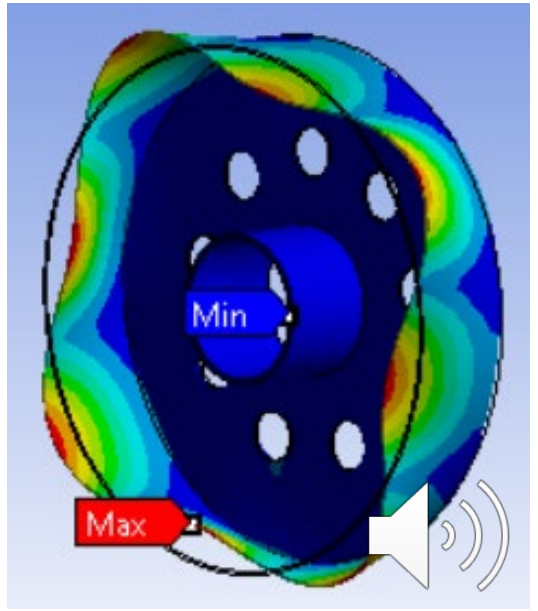
Mode 7



Mode 8



Mode 9



SCENARIO 2b - RESULTS

- ADDITION OF HOLES – RESULTS – NON-UNIFORM LOADING:

PARAMETER	7 HOLES @ 3m		8 HOLES @ 3m		9 HOLES @ 3m	
	STATIC ONLY	STATIC AND DYNAMIC	STATIC ONLY	STATIC AND DYNAMIC	STATIC ONLY	STATIC AND DYNAMIC
MASS (kg)	-	-	1.53×10^5	1.8×10^5	-	-
EQUIVALENT STRESS (MPa)	-	-	93.98	94.53	-	-
DEFORMATION (Radial) (mm)	-	-	-2.03	-1.97	-	-
FREQUENCY (M6) (Hz)	N/A	-	N/A	16.04	N/A	-
FREQUENCY (M7) (Hz)	N/A	-	N/A	16.01	N/A	-

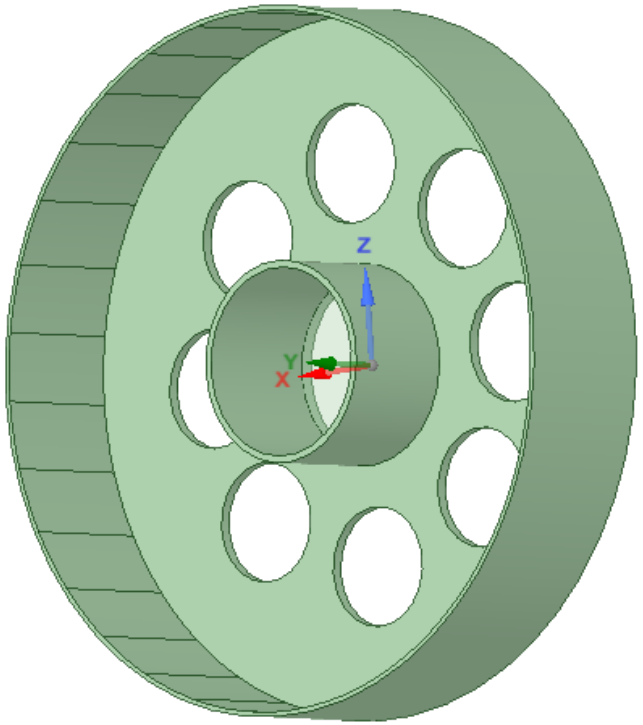
SCENARIO 2b - RESULTS

- ADDITION OF HOLES – RESULTS – NON-UNIFORM LOADING:

PARAMETER	7 HOLES @ 3.5m		8 HOLES @ 3.5m		9 HOLES @ 3.5m	
	STATIC ONLY	STATIC AND DYNAMIC	STATIC ONLY	STATIC AND DYNAMIC	STATIC ONLY	STATIC AND DYNAMIC
MASS (kg)	-	-	-	-	-	-
EQUIVALENT STRESS (MPa)	-	-	-	-	-	-
DEFORMATION (Radial) (mm)	-	-	-	-	-	-
FREQUENCY (M6) (Hz)	N/A	-	N/A	-	N/A	-
FREQUENCY (M7) (Hz)	N/A	-	N/A	-	N/A	-

SCENARIO 2b - RESULTS

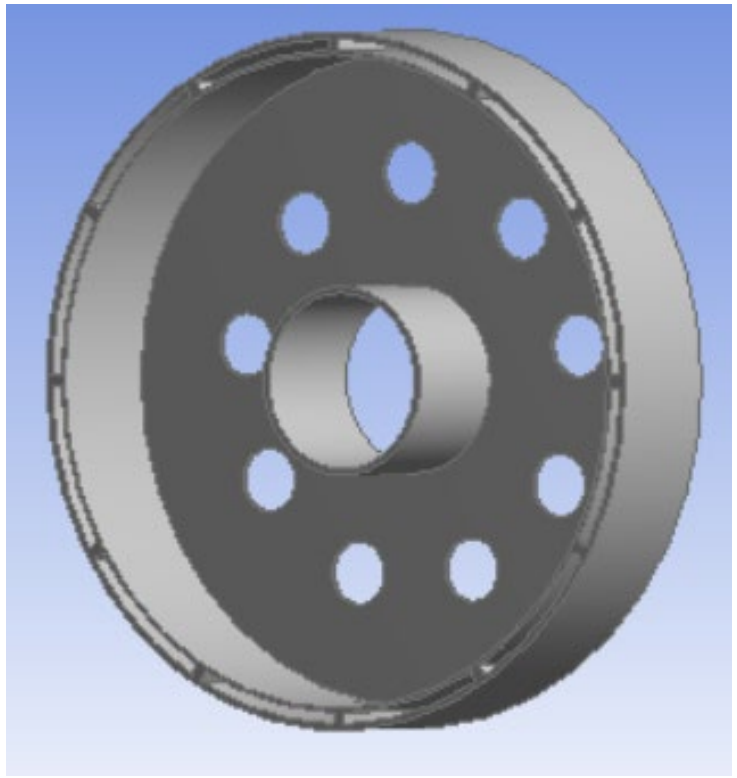
- ADDITION OF HOLES – OPTIMISED DESIGN:
  - 8 Holes @ 3 m Radius



PARAMETER	OPTIMISED BASE CASE	OPTIMISED CASE	DIFFERENCE
RIM THICKNESS (mm)	-	71.5	-
DISC THICKNESS (mm)	-	168.24	-
MASS (kg)	-	1.8×10^5	-
EQUIVALENT STRESS (MPa)	-	94.53	-
DEFORMATION (Radial) (mm)	-	-1.97	-

SCENARIO 3

- ADDITION OF HOLES AND RIM STIFFENERS (UNIFORM LOADING):



PARAMETER	VALUE
ROTOR RIM THICKNESS	63.69 m
RIM LENGTH	2.17 m
ROTOR DISC DIAMETER	10.53 m
ROTOR DISC THICKNESS	81.75 m
SHAFT OUTER DIAMETER	3 m
SHAFT INNER DIAMETER	2.8 m
HOLE DIAMETERS	1 m
STIFFENER WIDTH	0.2 m
OUTER RIM THICKNESS	0.1 m

CONCLUSION

- To conclude:
  - Baseline NREL design doesn’t address the resonance with operating range.
  - Consideration of dynamic constraints, increases the mass of the structure.
  - No further mass reduction when just disc and rim thicknesses are the variables.
  - Introduction of holes, reduces mass, even in combined static-dynamic case.
  - Biggest reduction of mass came from the addition of 9 holes in the disc at a distance of 3m from the centre for uniform loading and 8 holes at a 3m radius for non-uniform loading.
  - Results suggest that the new design with 8 holes at 3m radial distance is a design option that addresses static and dynamic aspects under both uniform and non-uniform loading cases.

FUTURE WORK

- Proposed Future Work:
  - Reduction of radial deformation by the addition of stiffeners (Mode 1 cases).
  - Investigation of different rotor shapes.
  - Optimisation of stator's support structure.
  - Optimisation of direct-drive generator as a whole.

University of Strathclyde Glasgow