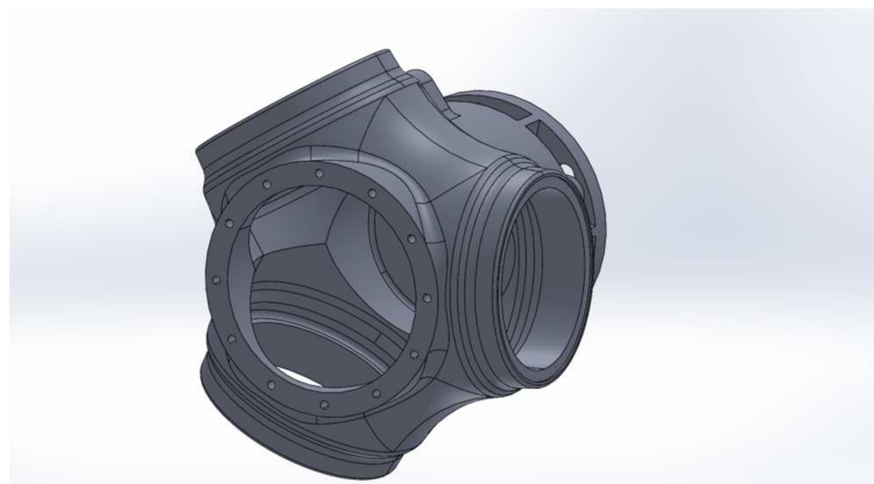
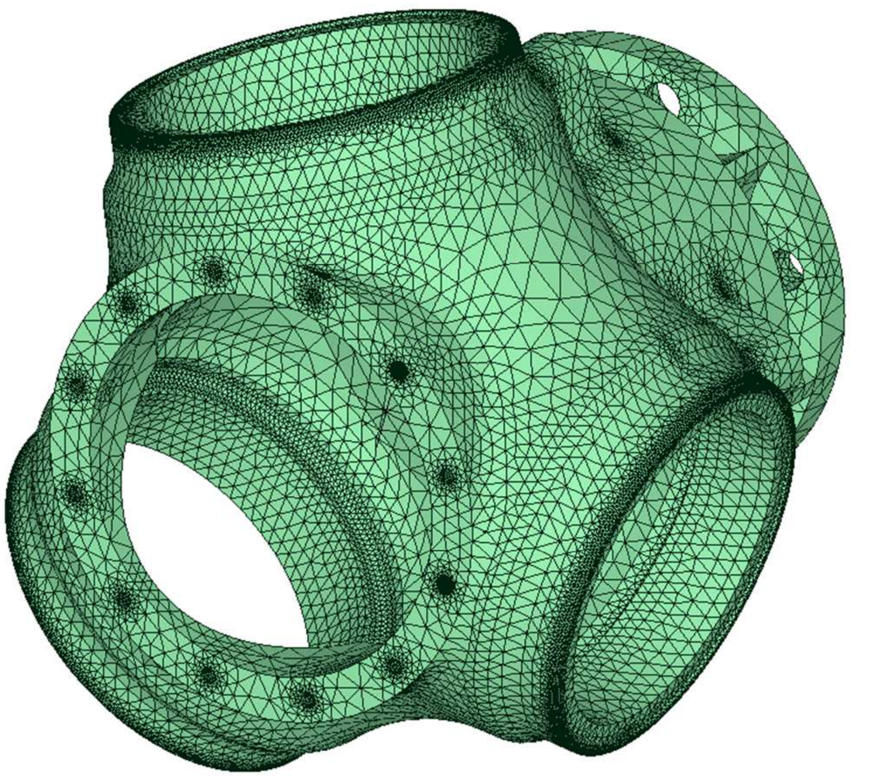
Whirlwind
300-72-3B
Hub Analysis

S. Melton

April 2019



FE Model



Supplied Boundary Conditions

Whirlwind Analysis 3B CS

Hub
Aluminum: 6061 (Hub, Ferrule, Cap)
Bearing Races: 440 C Stainless
Internal Oil Pressure: 400 psi max

Engine
RPM: 2700
Horsepower: 186.8
Peak Torque: 1335.5 ft*lb

Blade
Weight: ~5.4 lb
CG Station: ~9.4”

Analysis Boundary Conditions

Whirlwind Analysis 3B CS

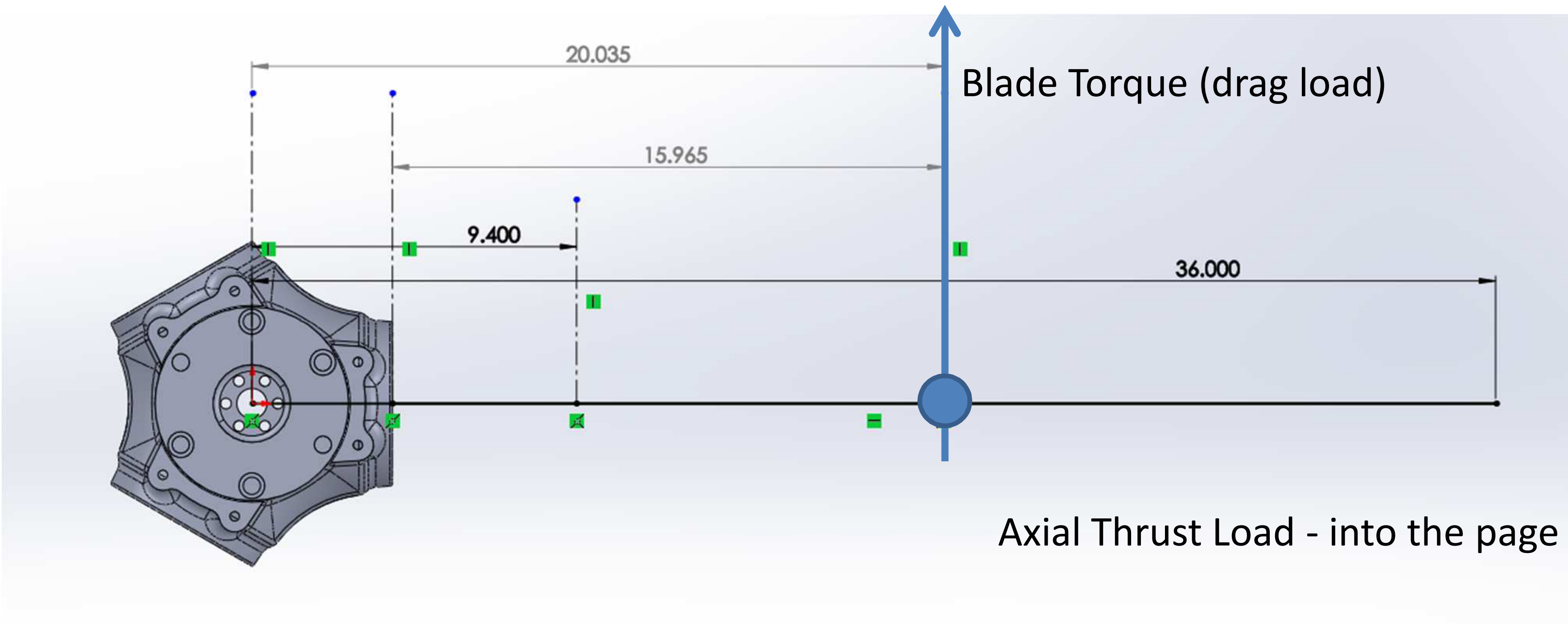
Hub
Aluminum: 6061 (Hub, Ferrule, Cap)
Bearing Races: 440 C Stainless
Internal Oil Pressure: 400 psi max

Engine
RPM: ~~2700~~ 2835 (+5%) (Melton - consider as redline design speed)
Horsepower: 186.8
Peak Torque: 1335.5 ft*lb (must be due to fast accel and crank position?)

Blade
Weight: ~5.4 lb
CG Station: ~9.4”

Total Thrust = 740lb (Melton - consider as redline design thrust)

Assume Blade Center of Pressure at 50% span



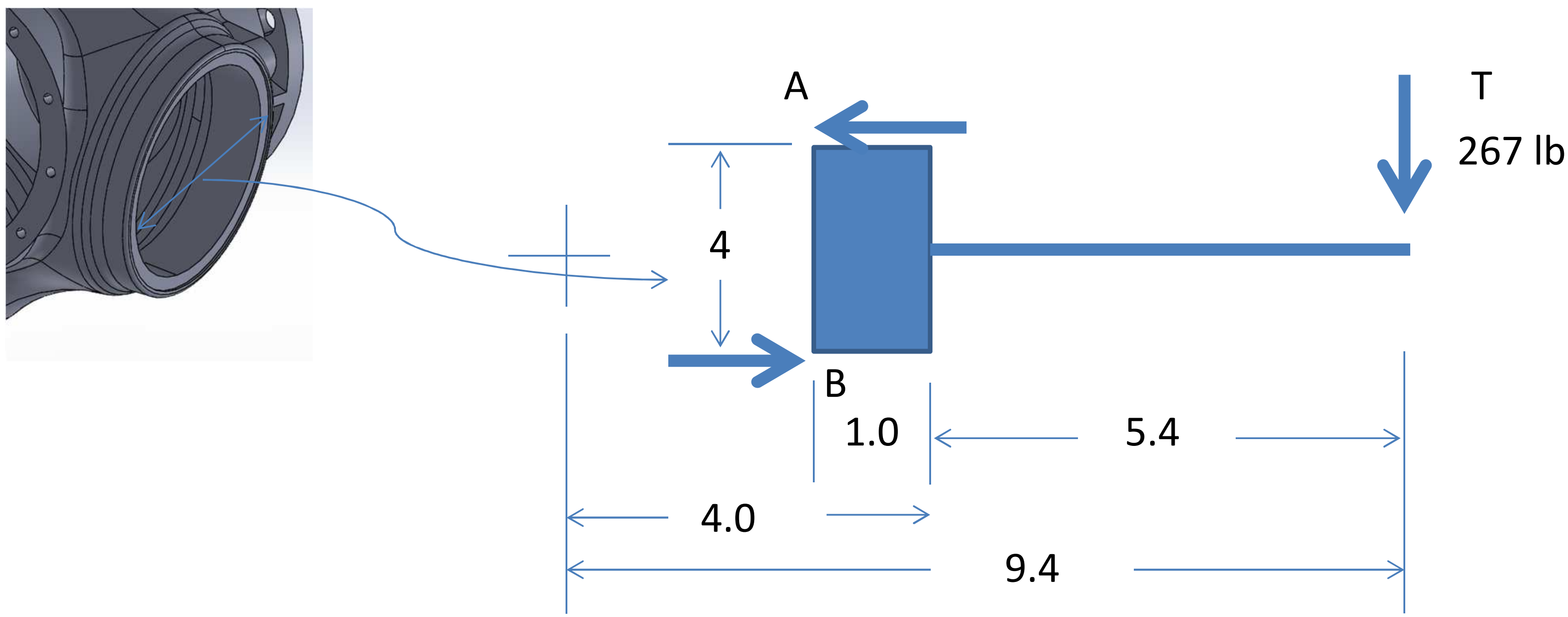
Calculated Loads

CF Blade Load						
Phase	Blade weight (lb)	Blade CG (inch from CL)	RPM	Blade mass (slinch)	rad/s	CF load each blade (lb)
Takeoff	5.4	9.4	2835	0.01398	297	11578
Idle	5.4	9.4	500	0.01398	52	360

Torque						
Phase	ft-lb	in-lb	center of pressure distace from CL	total torque force (lb)	places	drag force each blade (lb)
Fast accel	1335	16020	20	801.00000	3	267
Max Nominal	370	4440	20	222.00000	3	74

Axial Thrust Static (200 HP)						
Phase	Total axial thrust (lb)		center of pressure distace from CL		places	lift force each blade (lb)
Takeoff	740		20		3	247

Blade Peak Torque Load Component
(Assumes torque load is located at blade CG)



Sum X forces = 0 = B – A

B = A

B = 427 lb

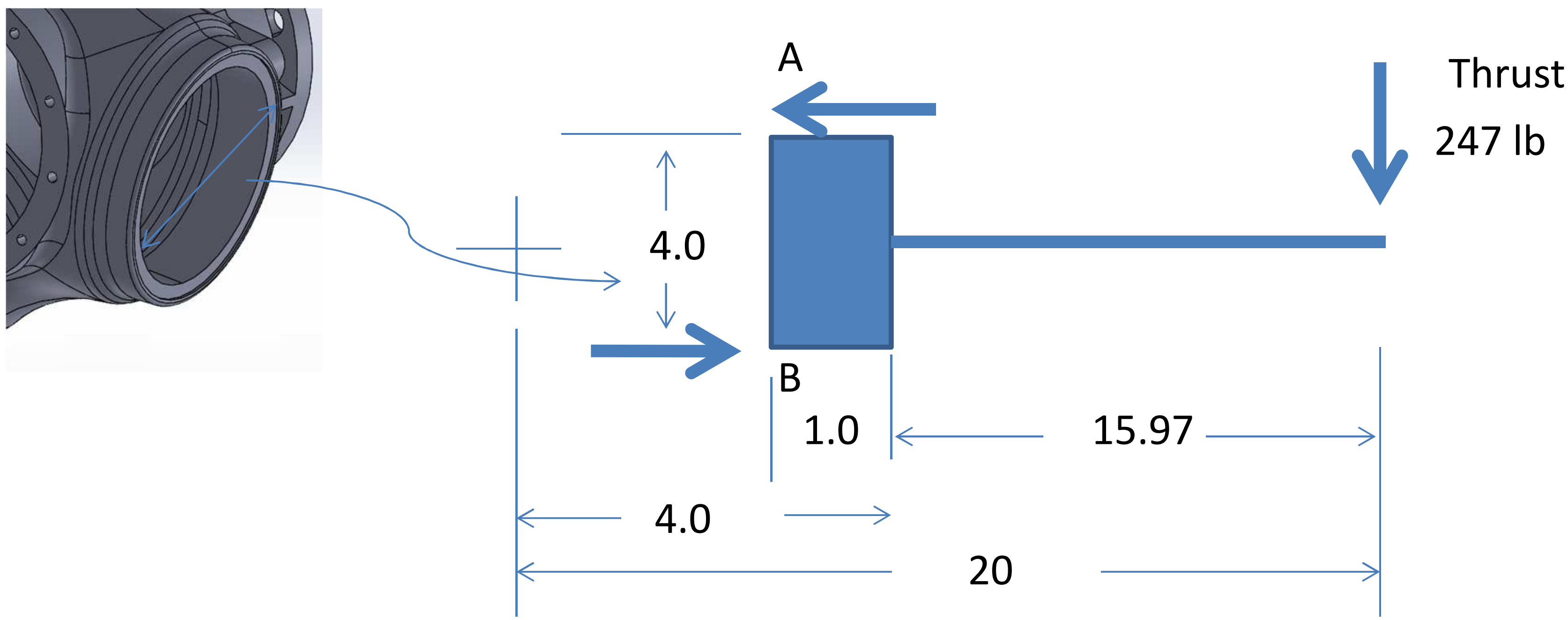
Sum Moments about B = 0 = (4) A – (5.4+1) T

A = (5.4+1) T/4

A = (6.4) 267/4

A = 427 lb

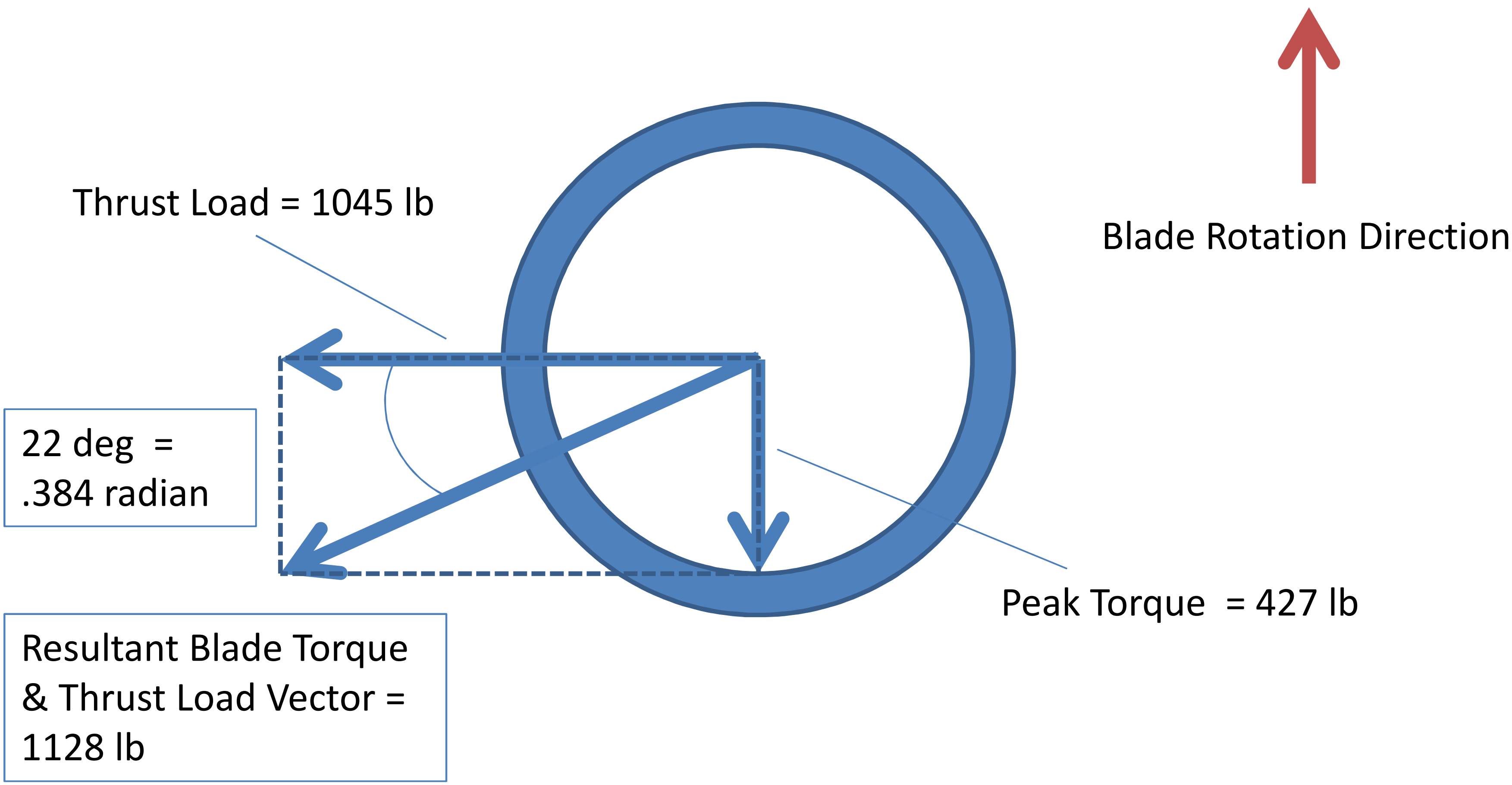
Blade Thrust Component (2835 rpm)
(Assumes thrust is located at 50% blade span)



Sum Y forces = 0 = B –A
B = A
B = 1045

Sum Moments about B = 0 = (4) A – (15.97+1) T
A = (15.97+1) T/4
A = (15.97+1) 247/4
A = 1045 lb

Resultant Blade Torque & Thrust Load Vector (fast accel to 2835 rpm)



Peak Torque vs Idle (interesting note)

CF Blade Load						
Phase	Blade weight (lb)	Blade CG (inch from CL)	RPM	Blade mass (slinch)	rad/s	CF load each blade (lb)
Takeoff	5.4	9.4	2835	0.01398	297	11578
Idle	5.4	9.4	500	0.01398	52	360

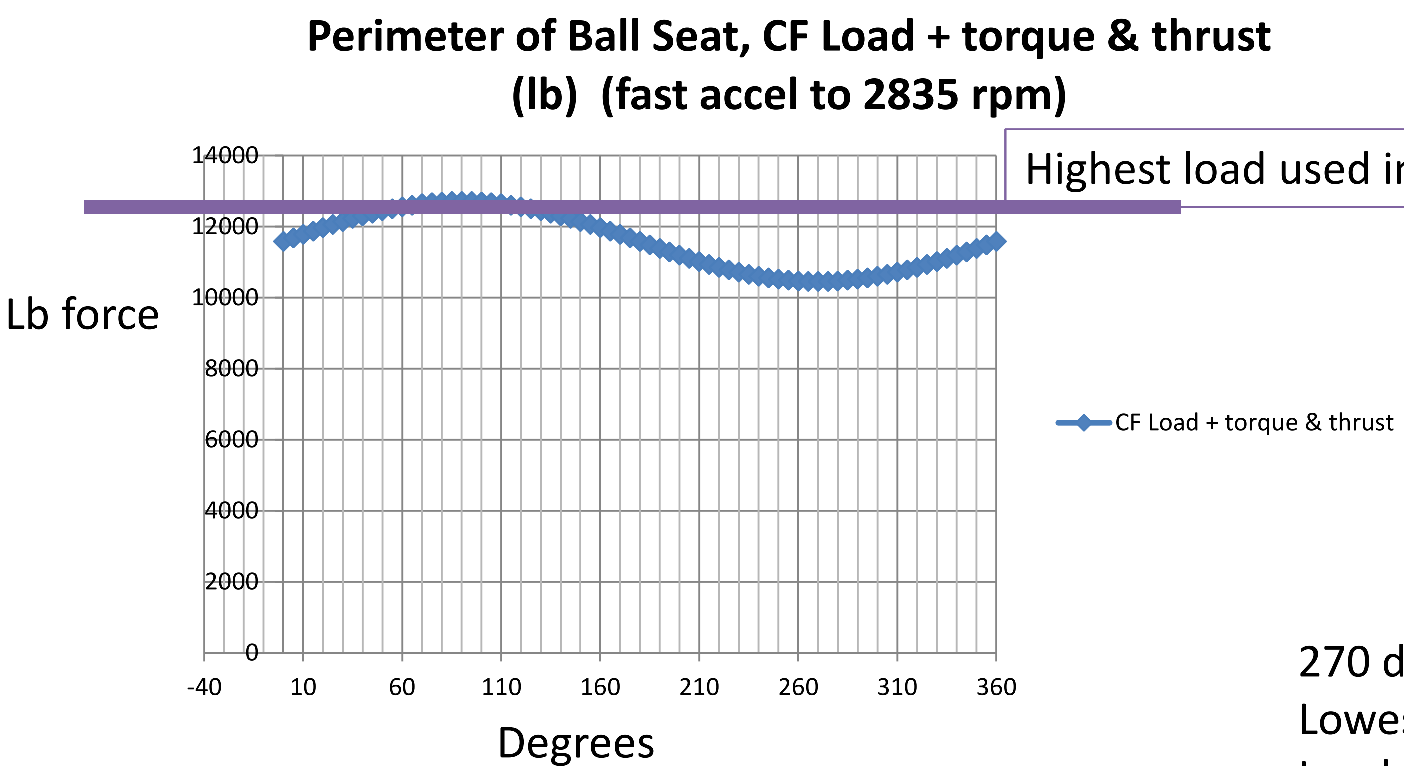
Torque load for fast accel = 427 lb

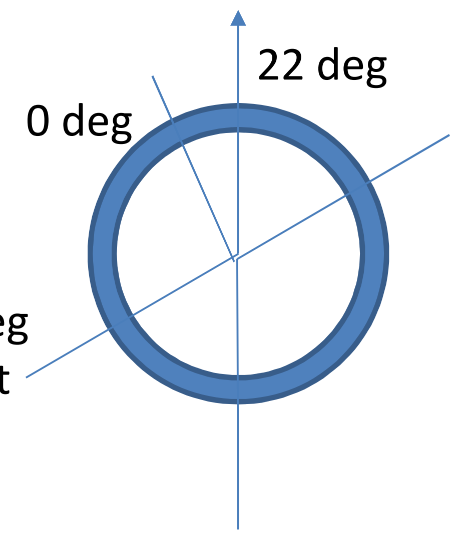
Centrifugal force / peak toque load = 360/427 = .843 factor
For blade lifting from bearing seat

For a step function fast accel from 500 rpm the blade could momentarily lift from bearing. The blade would seat at 600 rpm barring any other adverse torque ripple. Note to self: a good reason not to slow idle.

Reaction Loading Around ball perimeter
Perimeter of Ball Seat, CF Load + torque & thrust (lb) (fast accel to 2835 rpm)

Blade centrifugal (CF) load dominates the hub maximum loading.
The FE model uses the highest perimeter load around the entire perimeter to be for ease and is conservative. For further study the load could be mapped to the actual profile. The blade load variation around the perimeter = +/- 10% to the average.

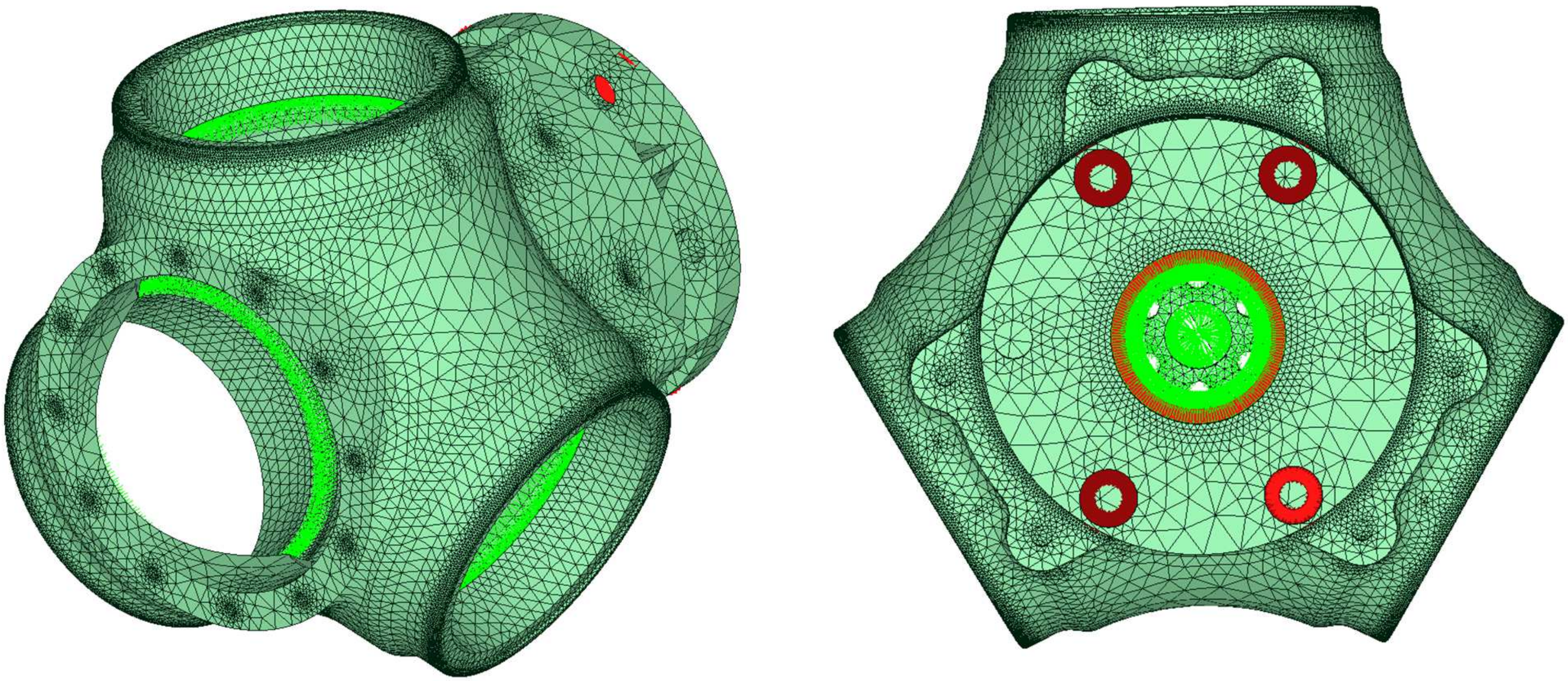




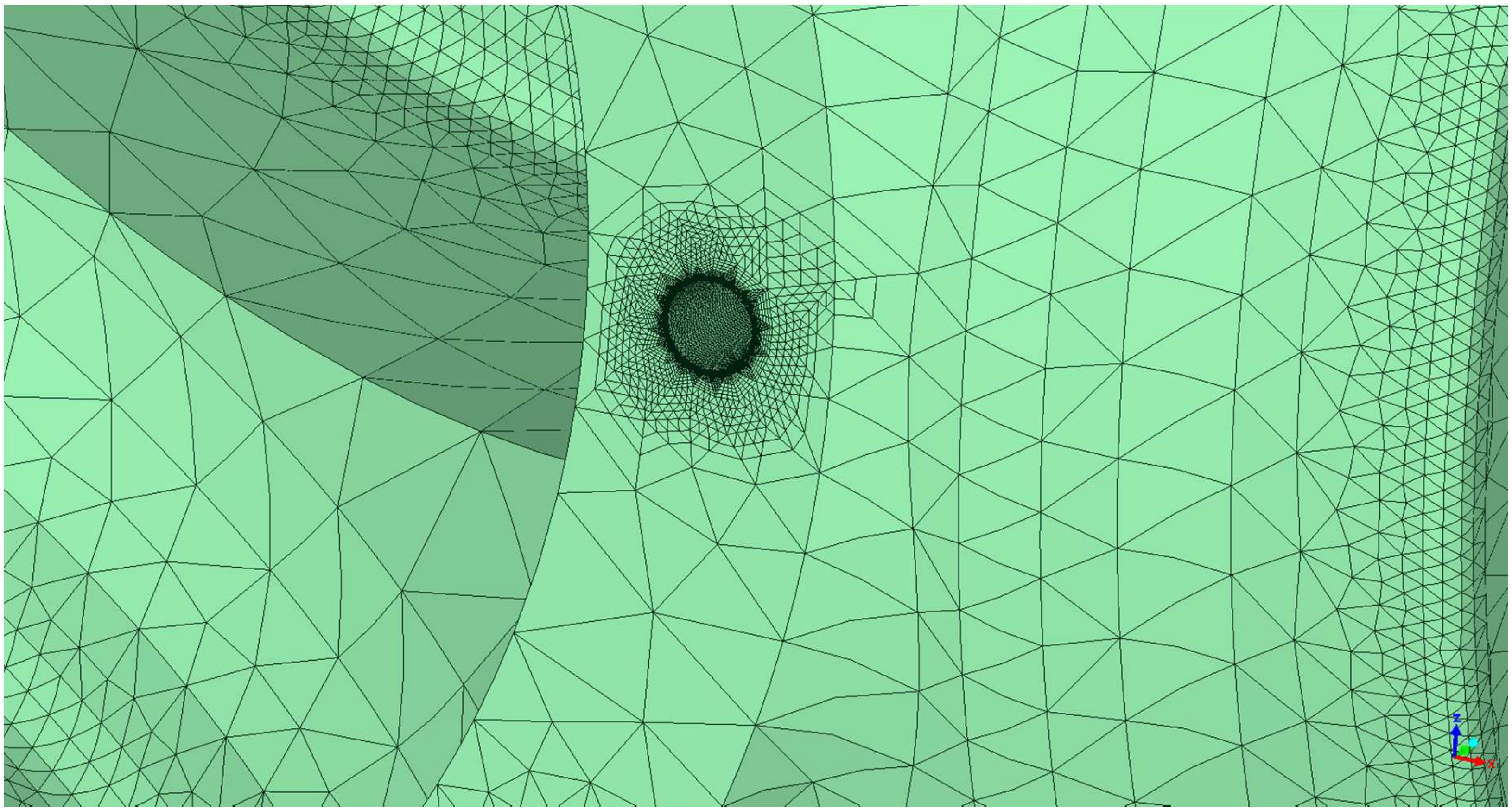
6061-T6 Allowable Stress

Low Cycle Fatigue Properties
95/99 data curve
$K_t = 1.5$ to allow for scratches
10K Cycles = 26 ksi
100K Cycles = 20 ksi

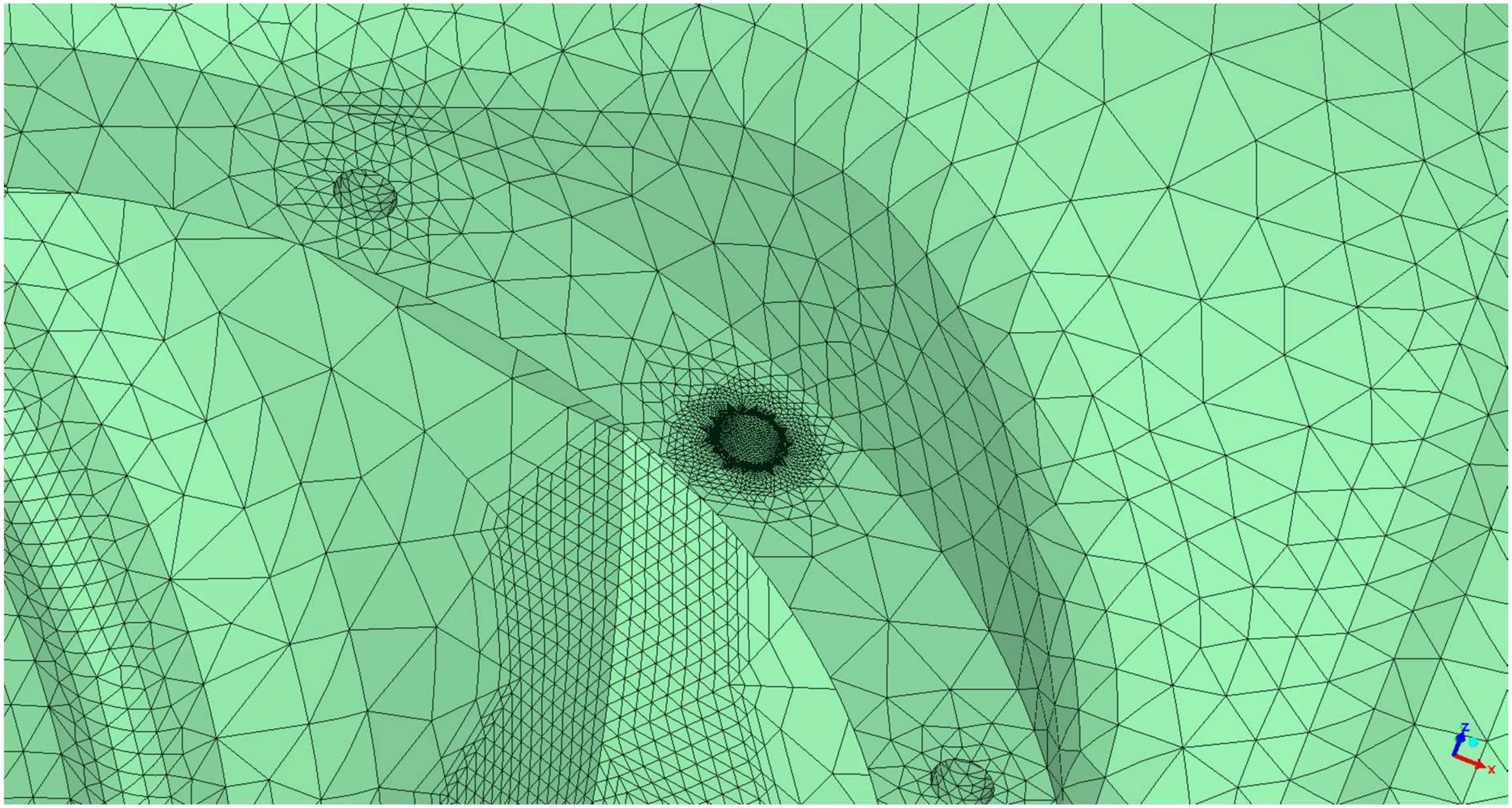
Hub V1 Boundary Conditions, no Cap
Mounting Bolts, Blade Load and Hydraulic Pressure



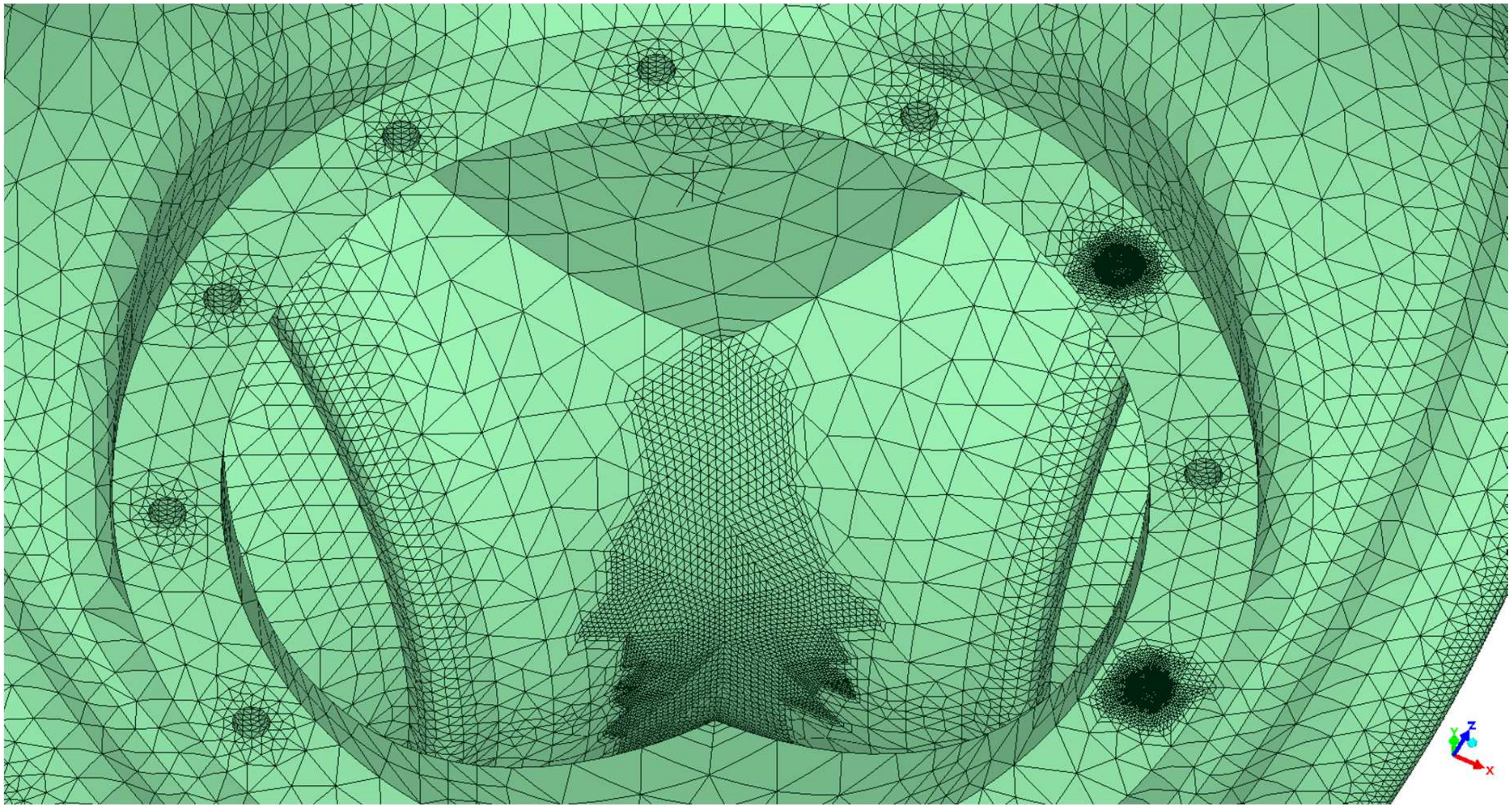
Refined Mesh at Hole, no Cap



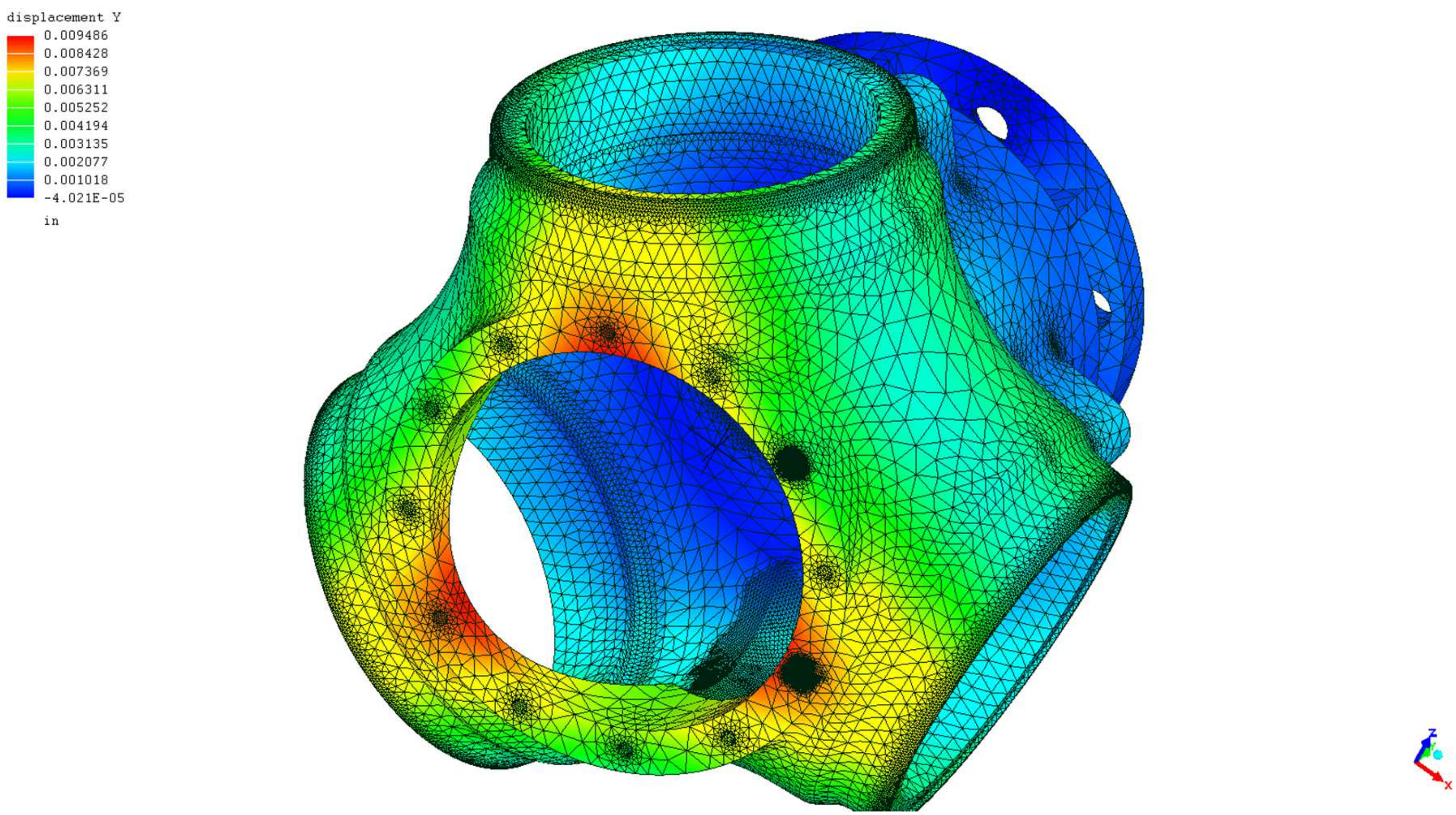
Refined Mesh at Hole, no Cap



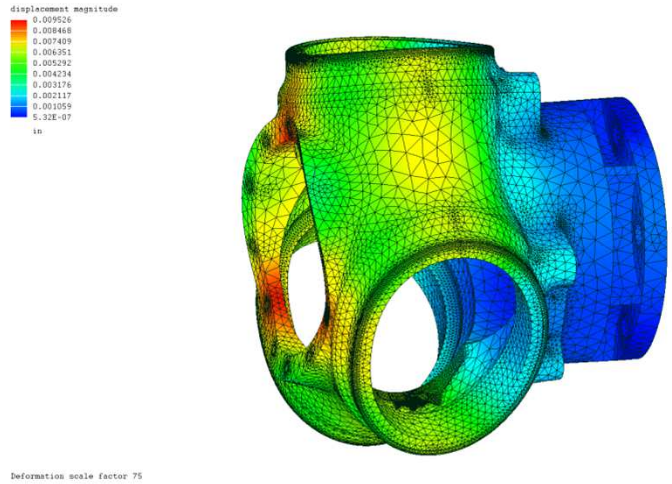
Refined Mesh at Inner Edge, no Cap

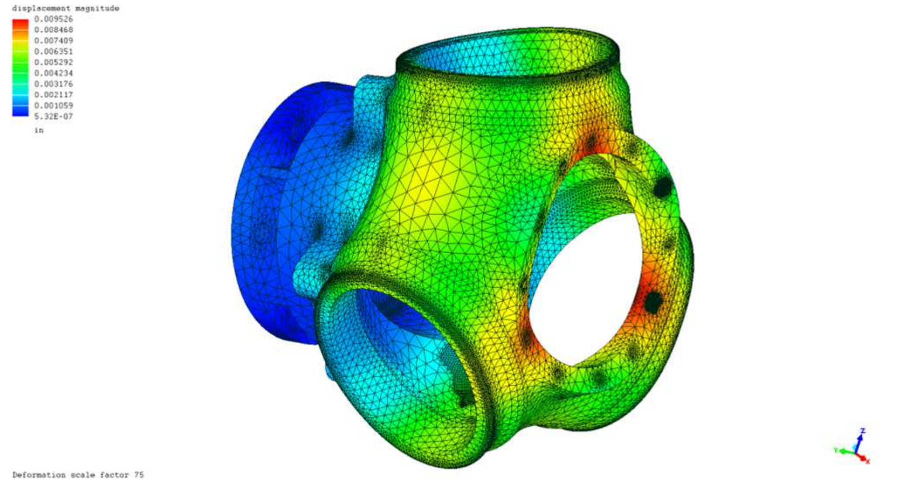


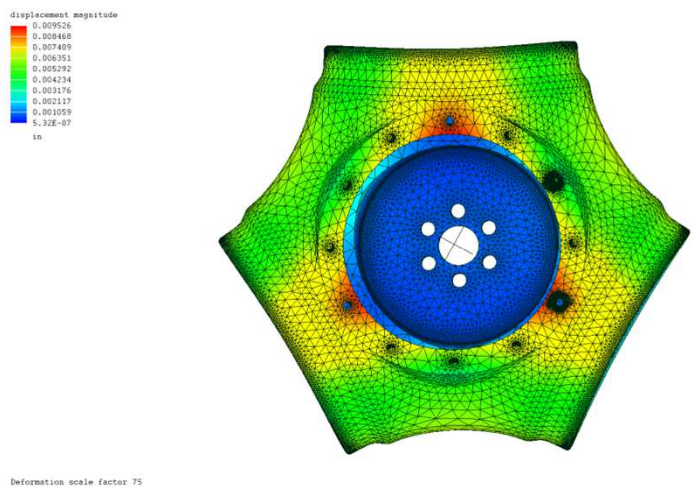
Axial Displacement (inch) (crankshaft direction)
.005 - .009 inch = .004 inch axial displacement variation
at cap face, no Cap

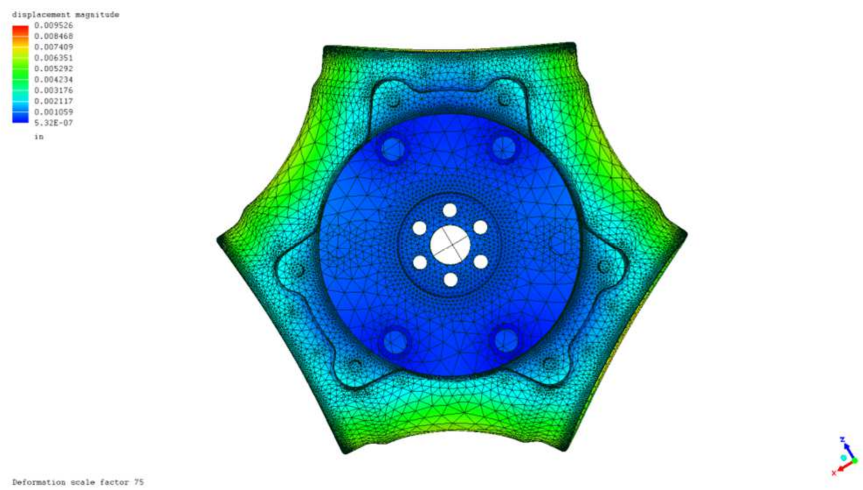


Magnified Deformed Shape, no Cap

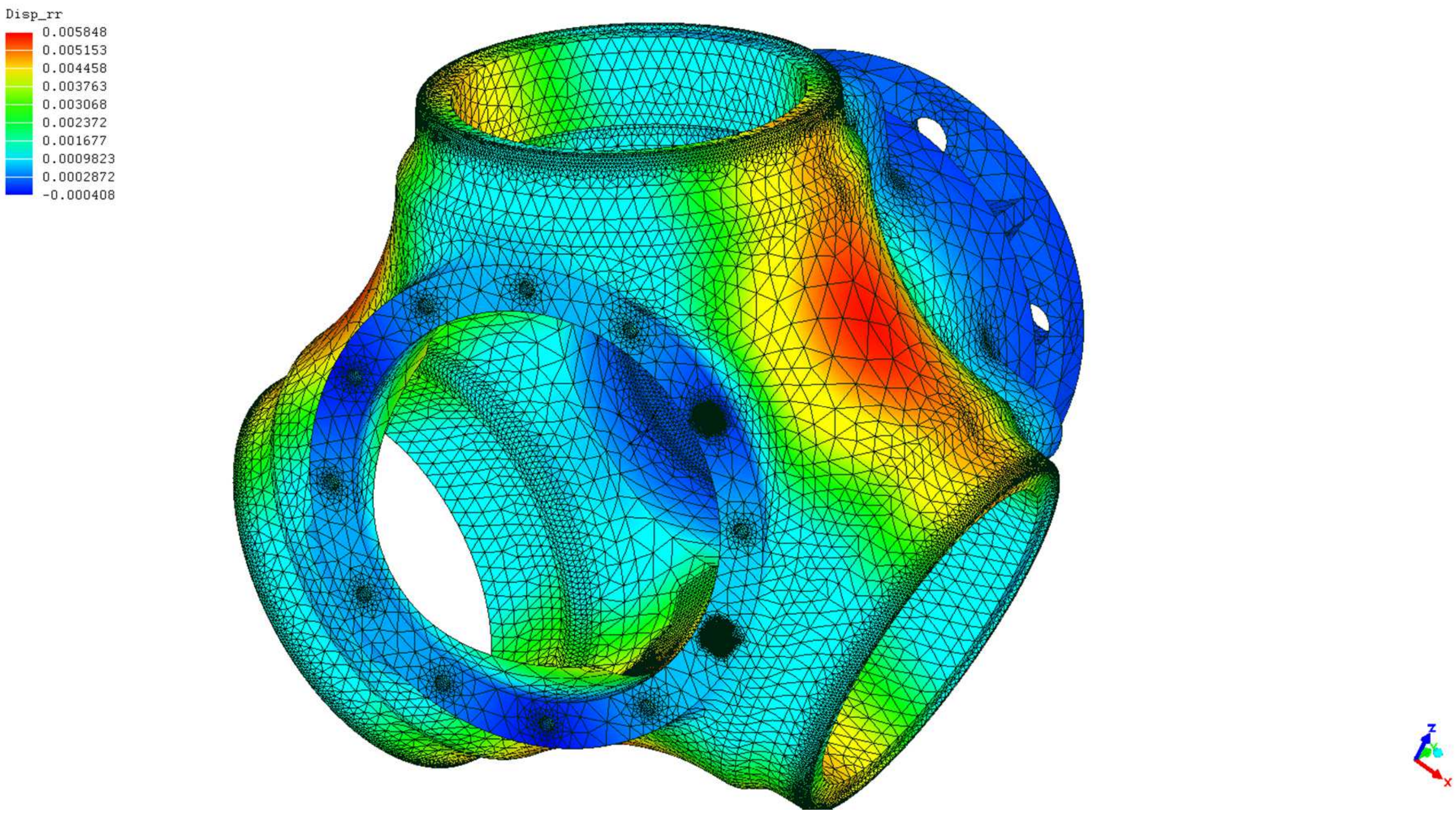




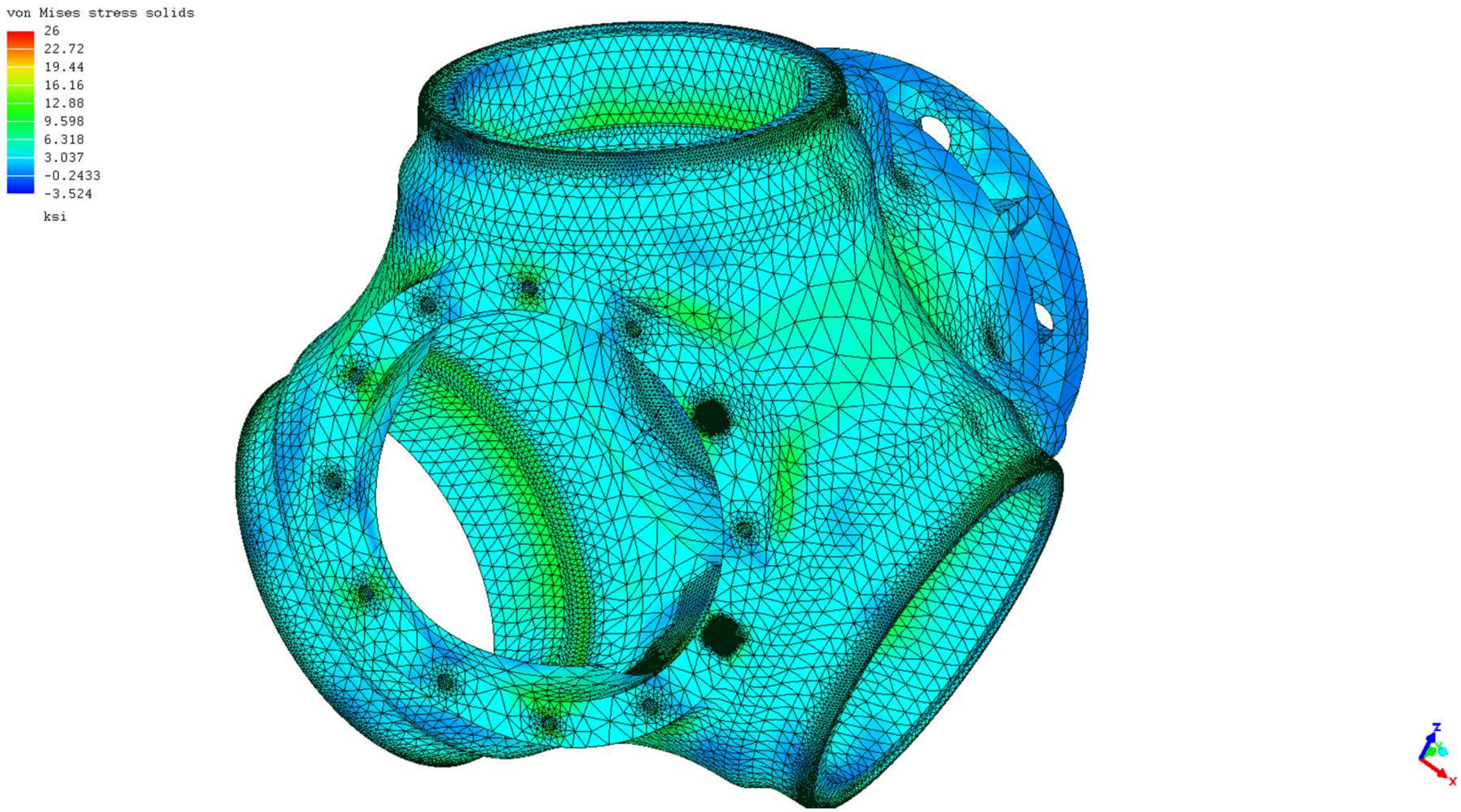




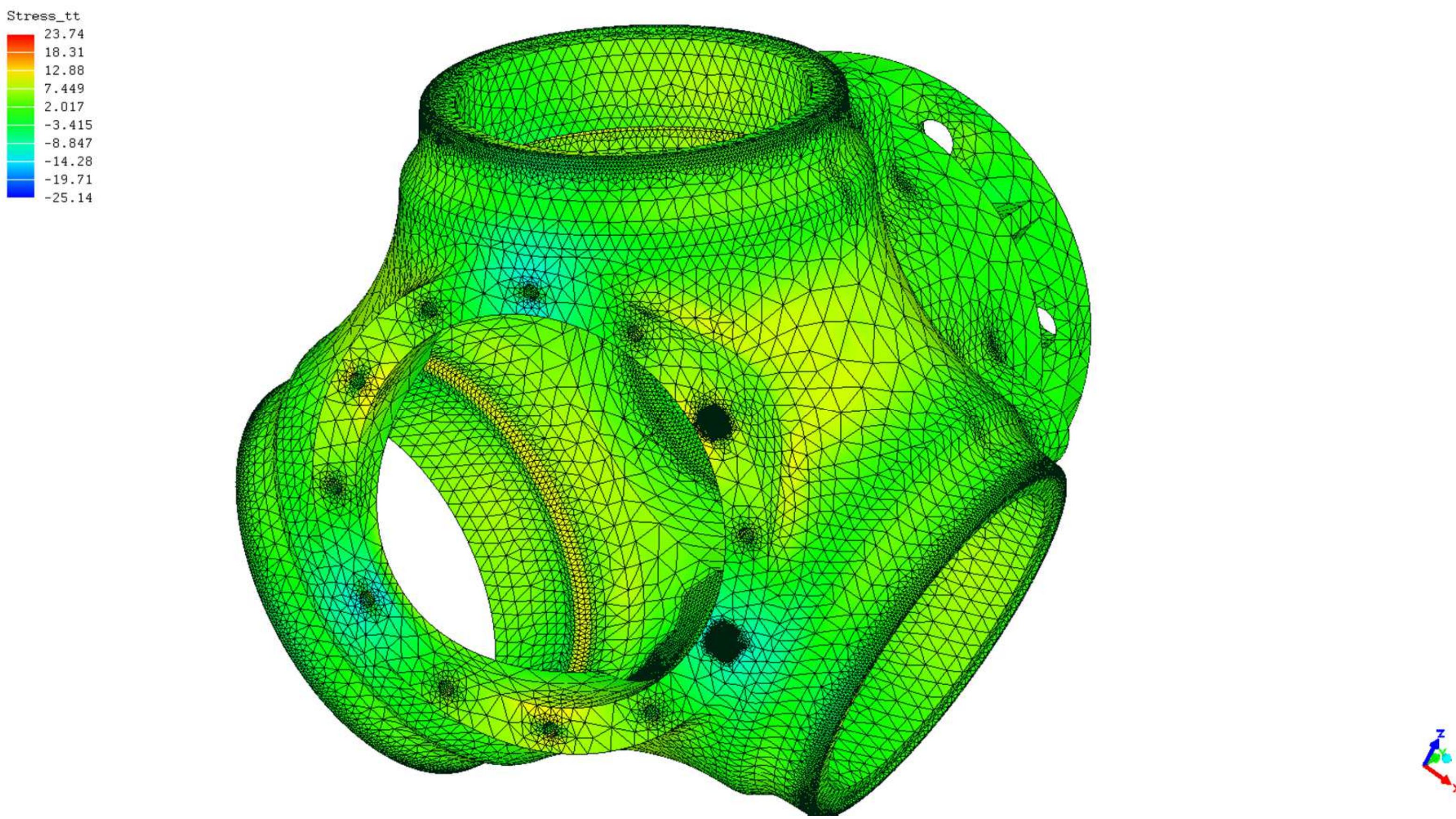
Radial Displacement (inch) , no Cap



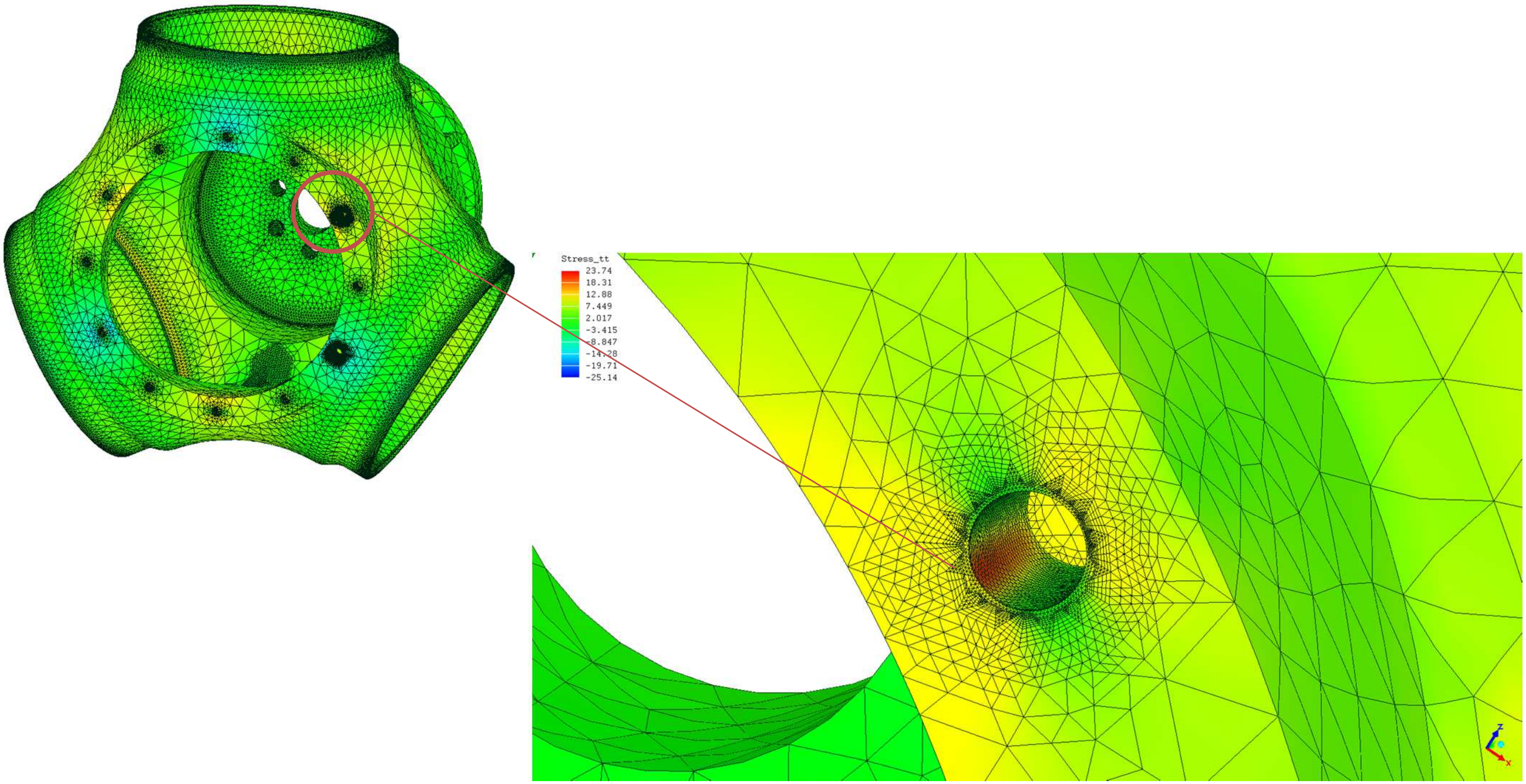
Von Mises Stress (ksi) , no Cap



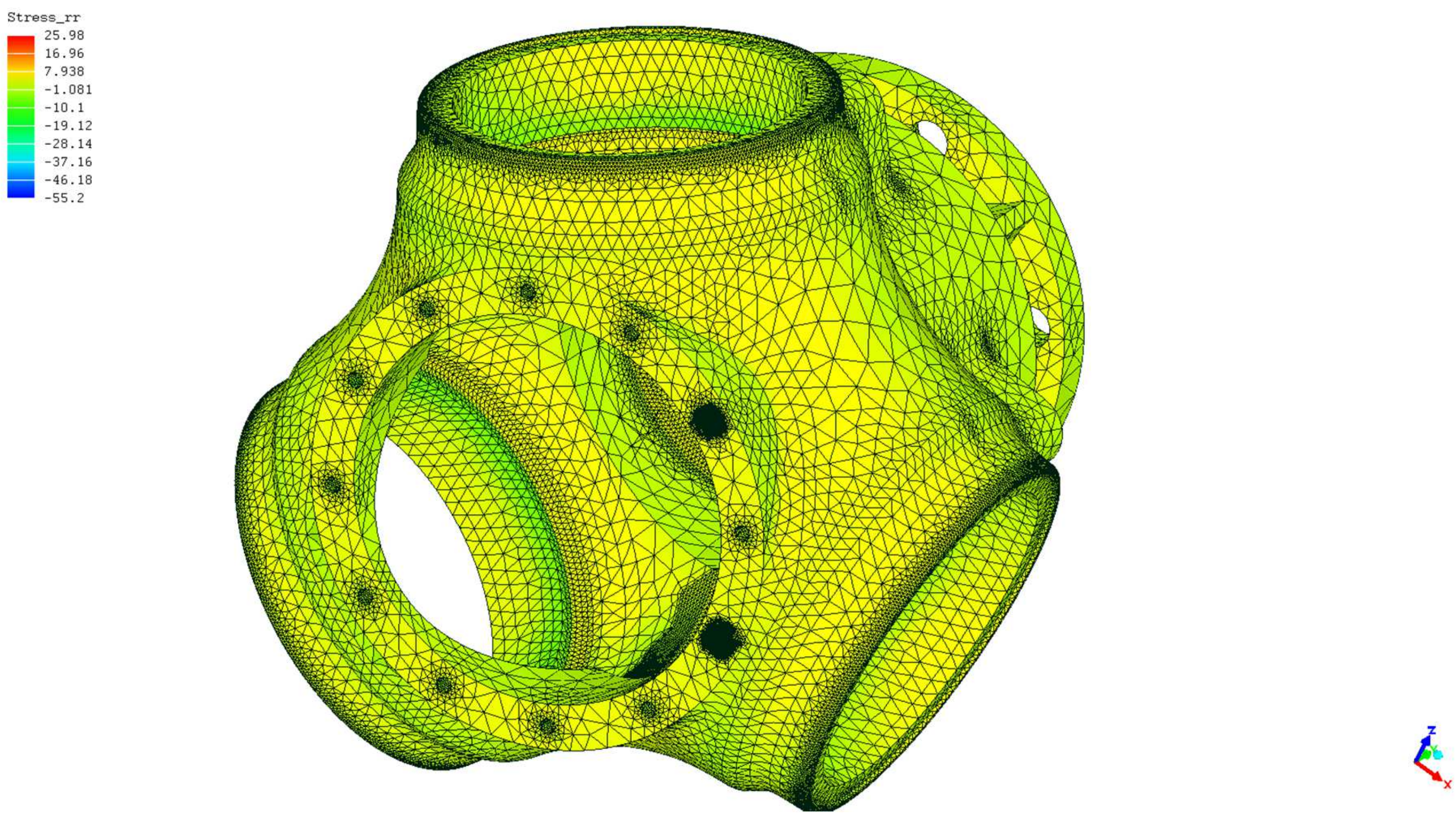
Hoop Stress (ksi) , no Cap



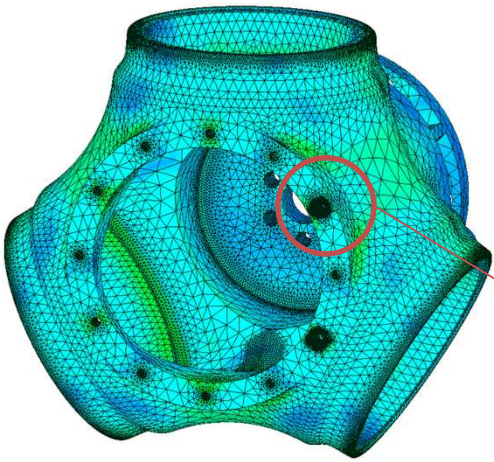
Hoop Stress (ksi) , no Cap

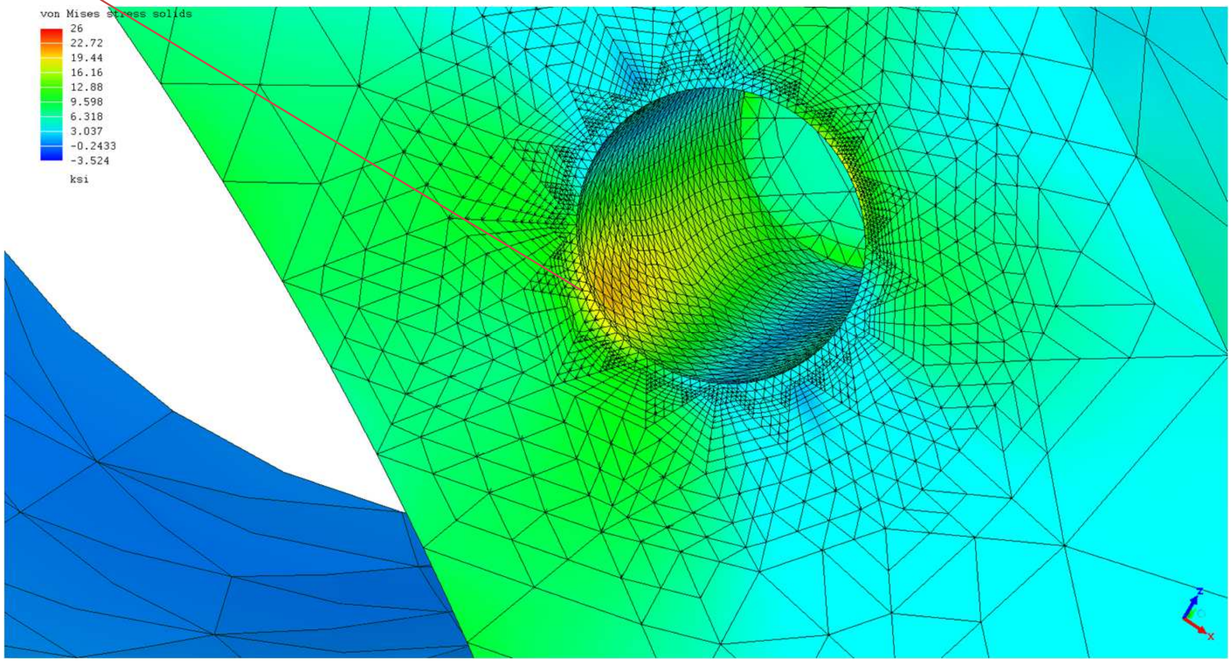


Radial Stress (ksi), no Cap



no Cap, von Mises Stress =20 ksi, smooth bore hole no threaded insert, locking tab threaded insert Kt = 3 but area is small and will locally yield and should not present a problem





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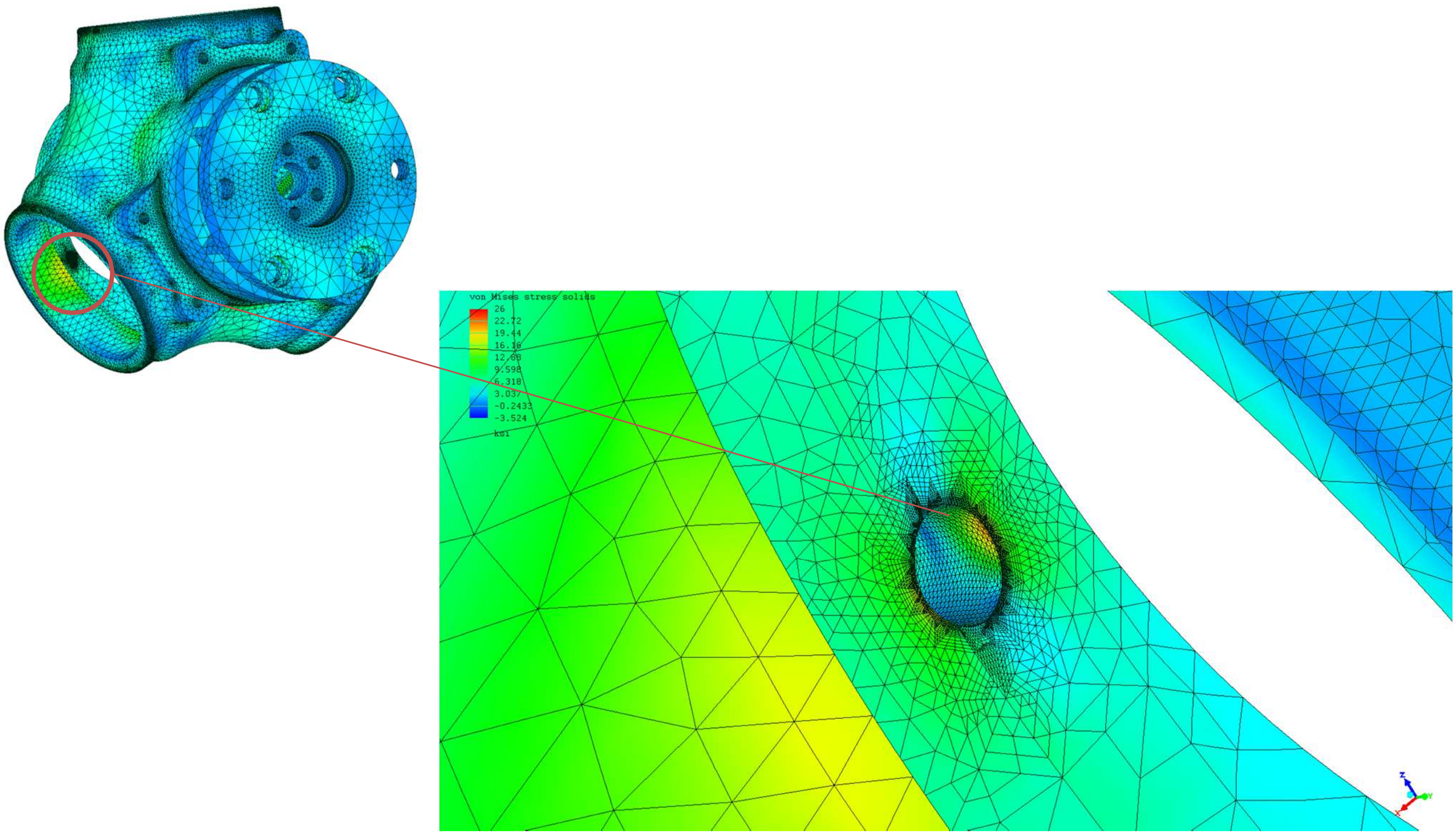
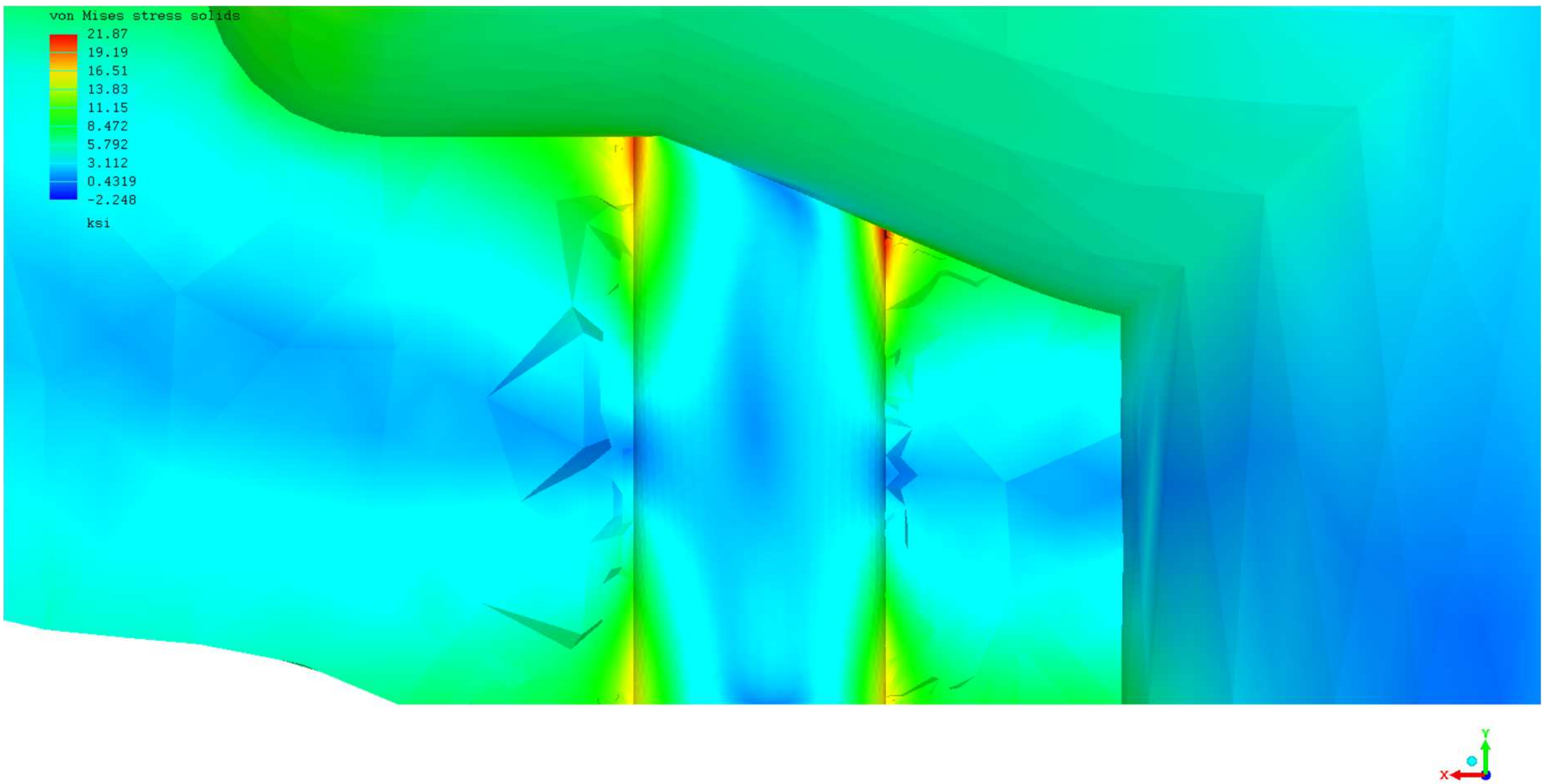
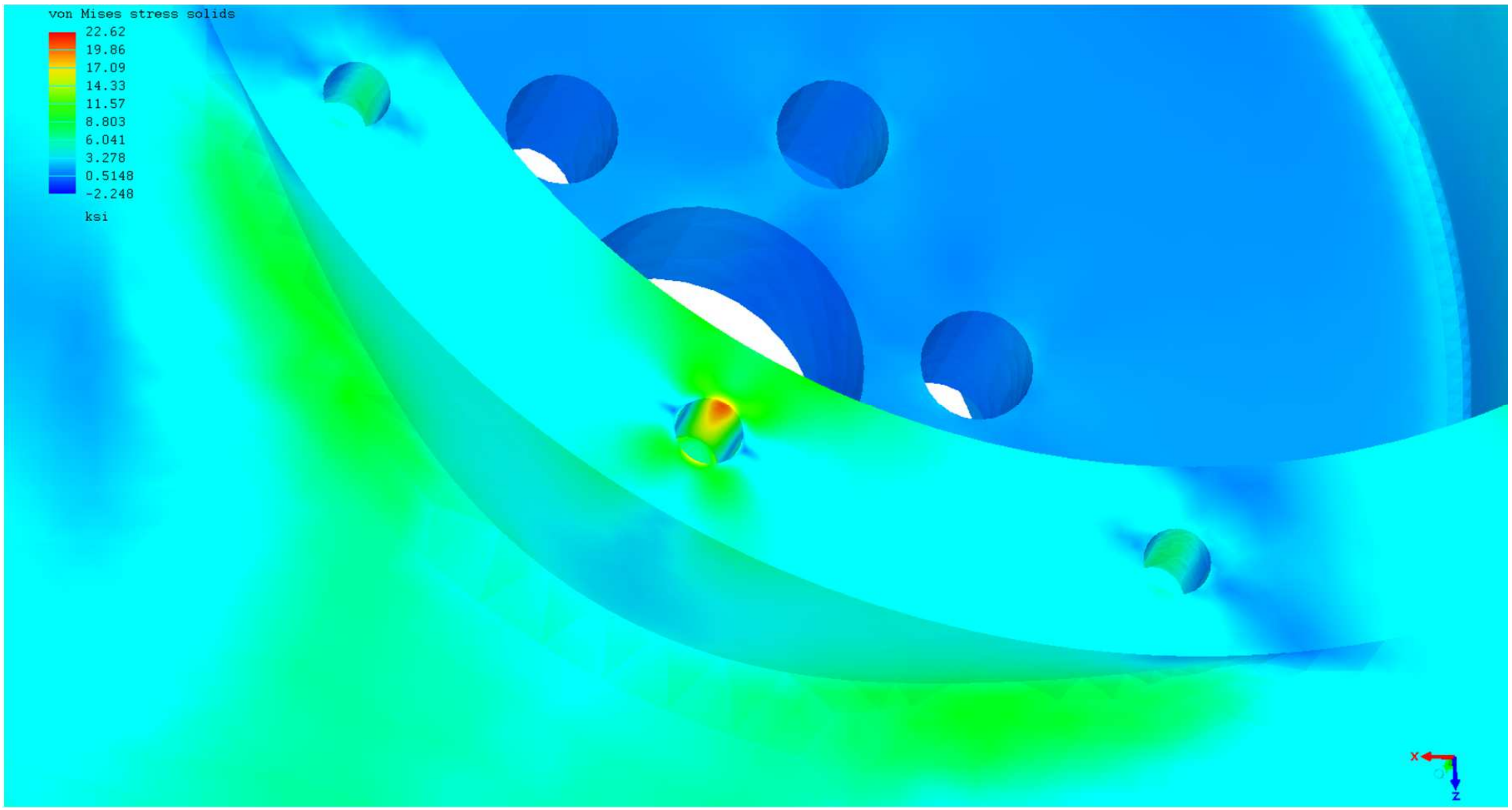


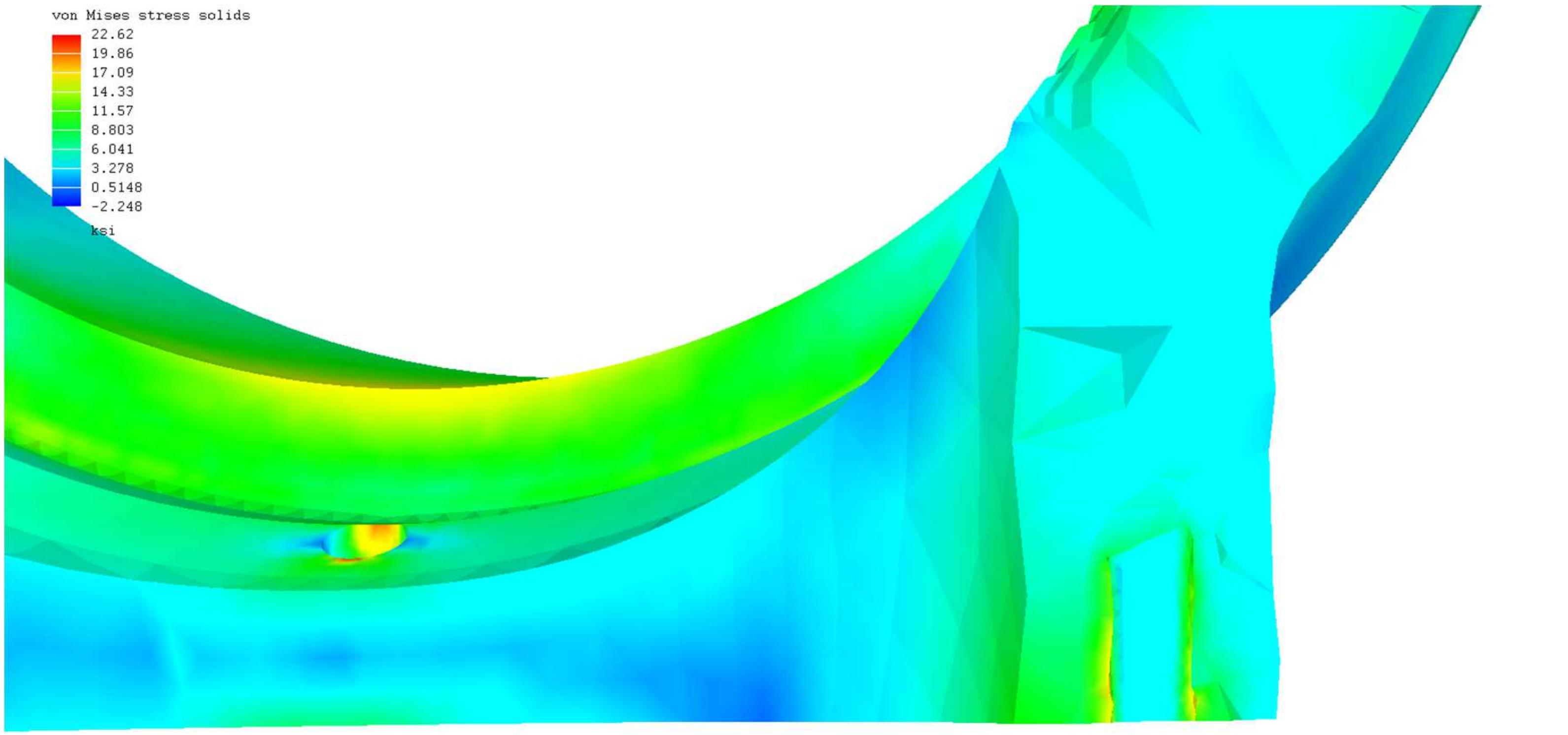
Von Mises Stress, no Cap



Von Mises Stress, no Cap

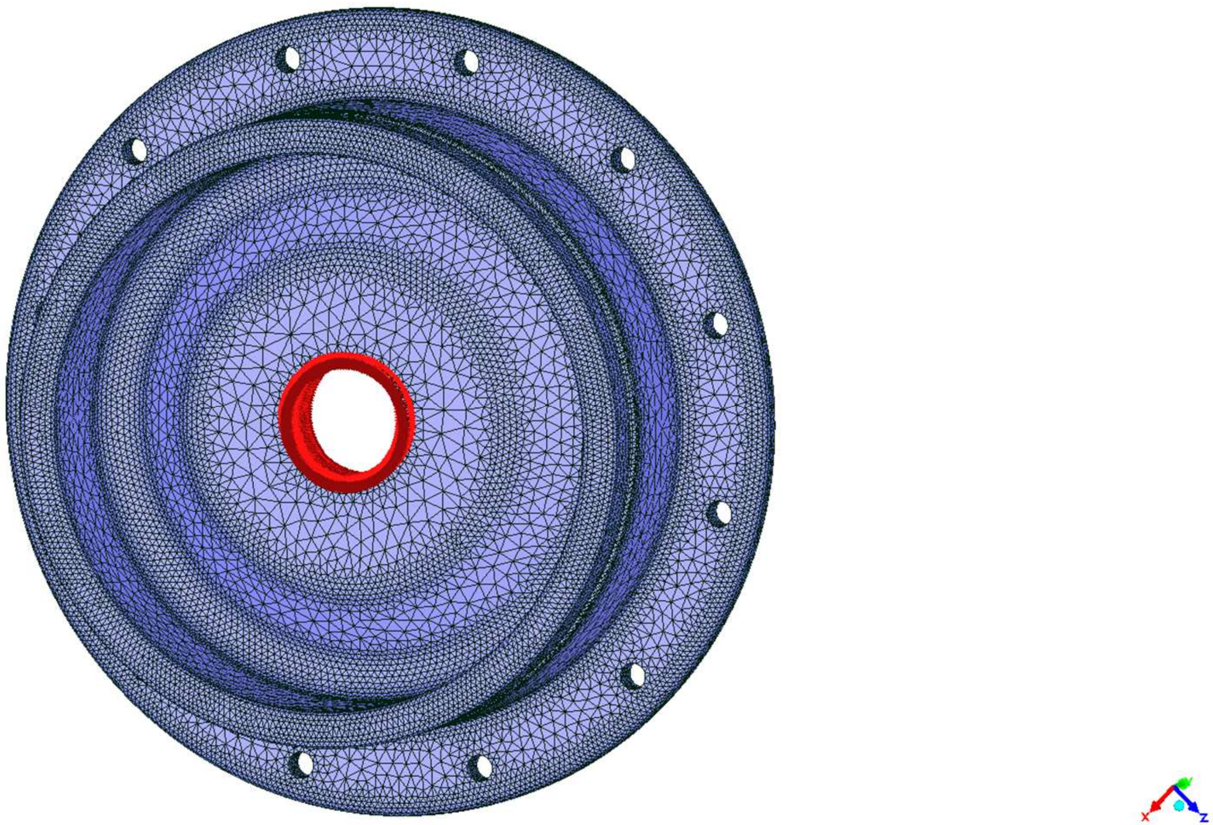


Von Mises Stress, no Cap

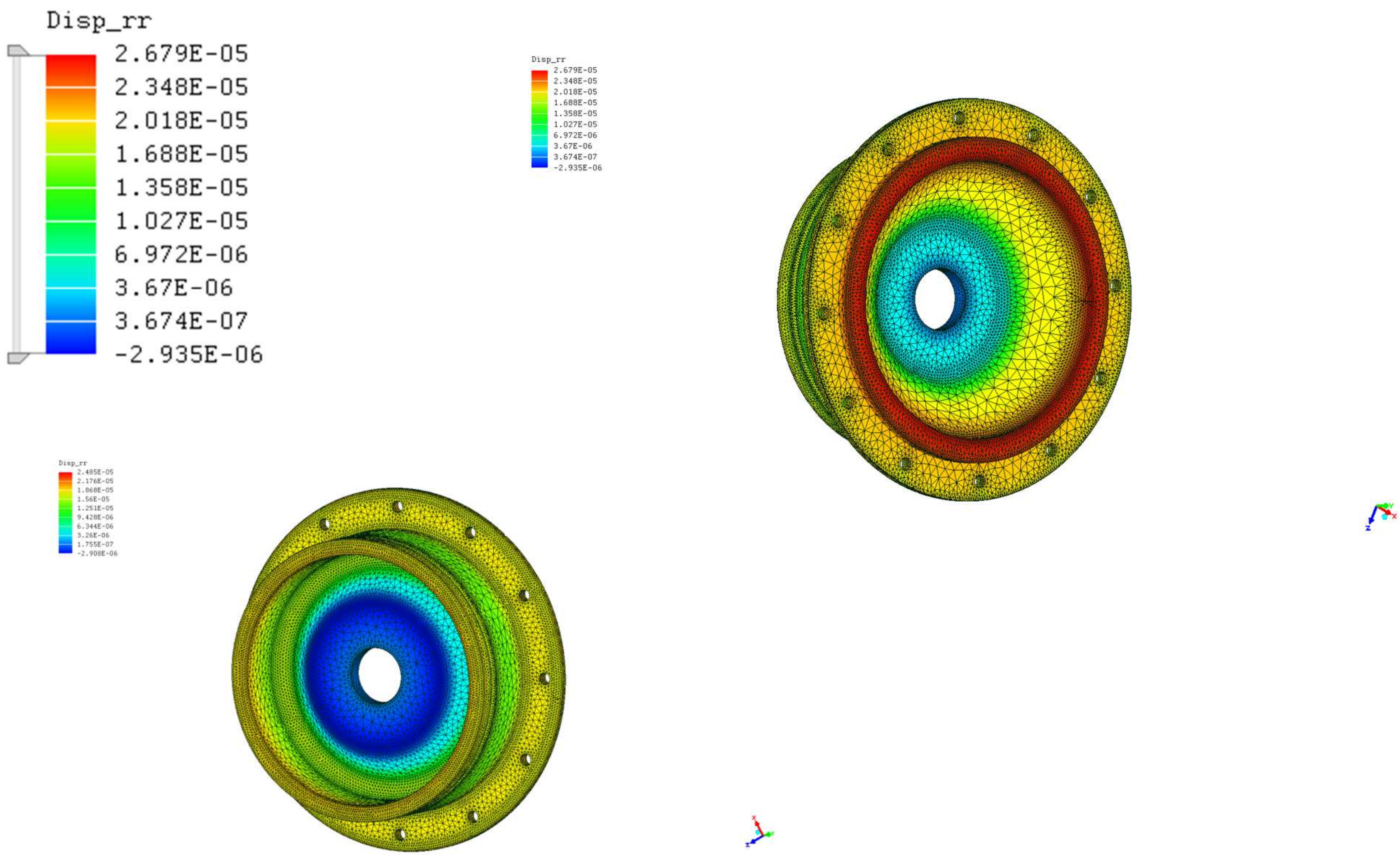


Hub Results meet LCF as Stand Alone part, no Cap

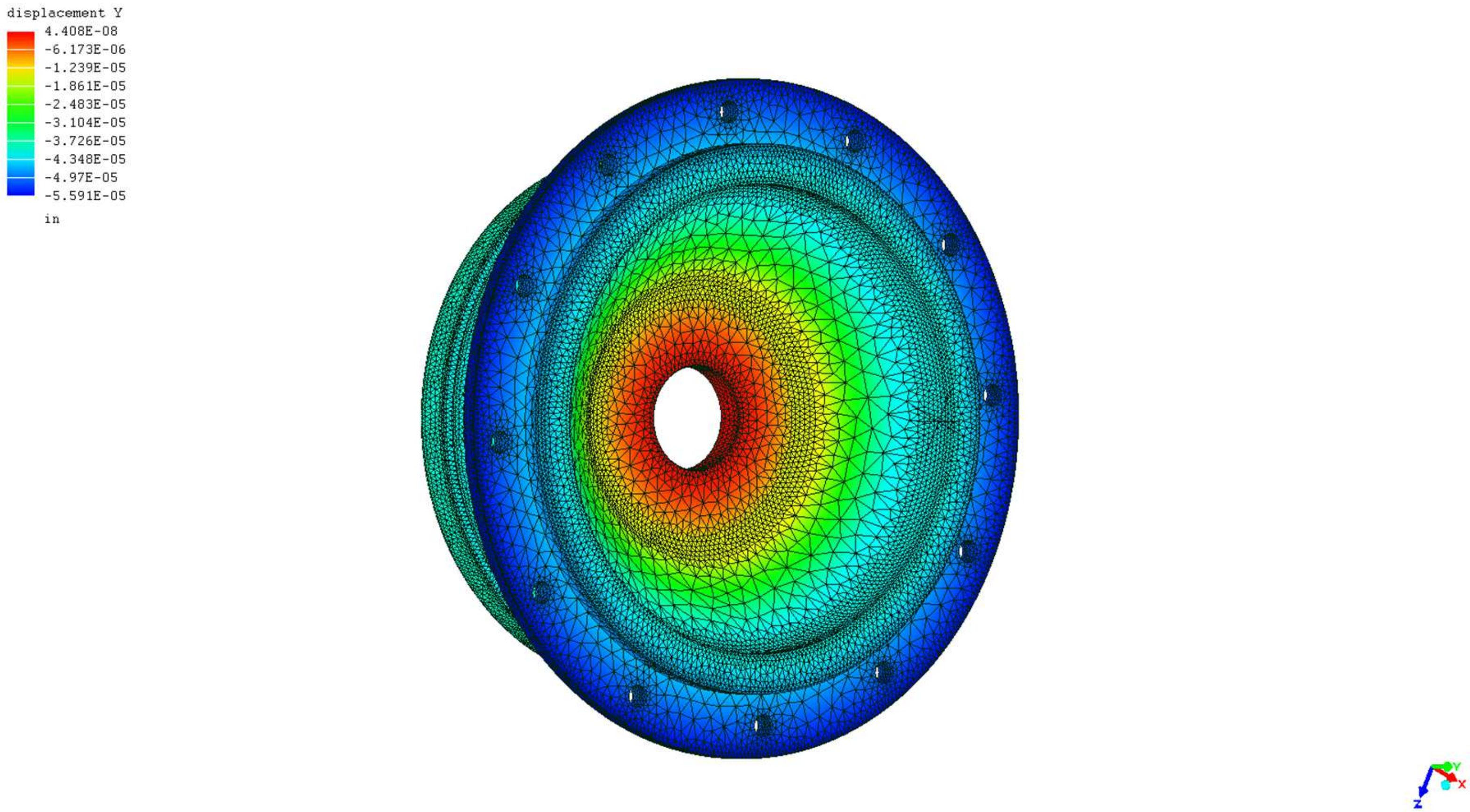
Cap Model
(this is a beefy cap)



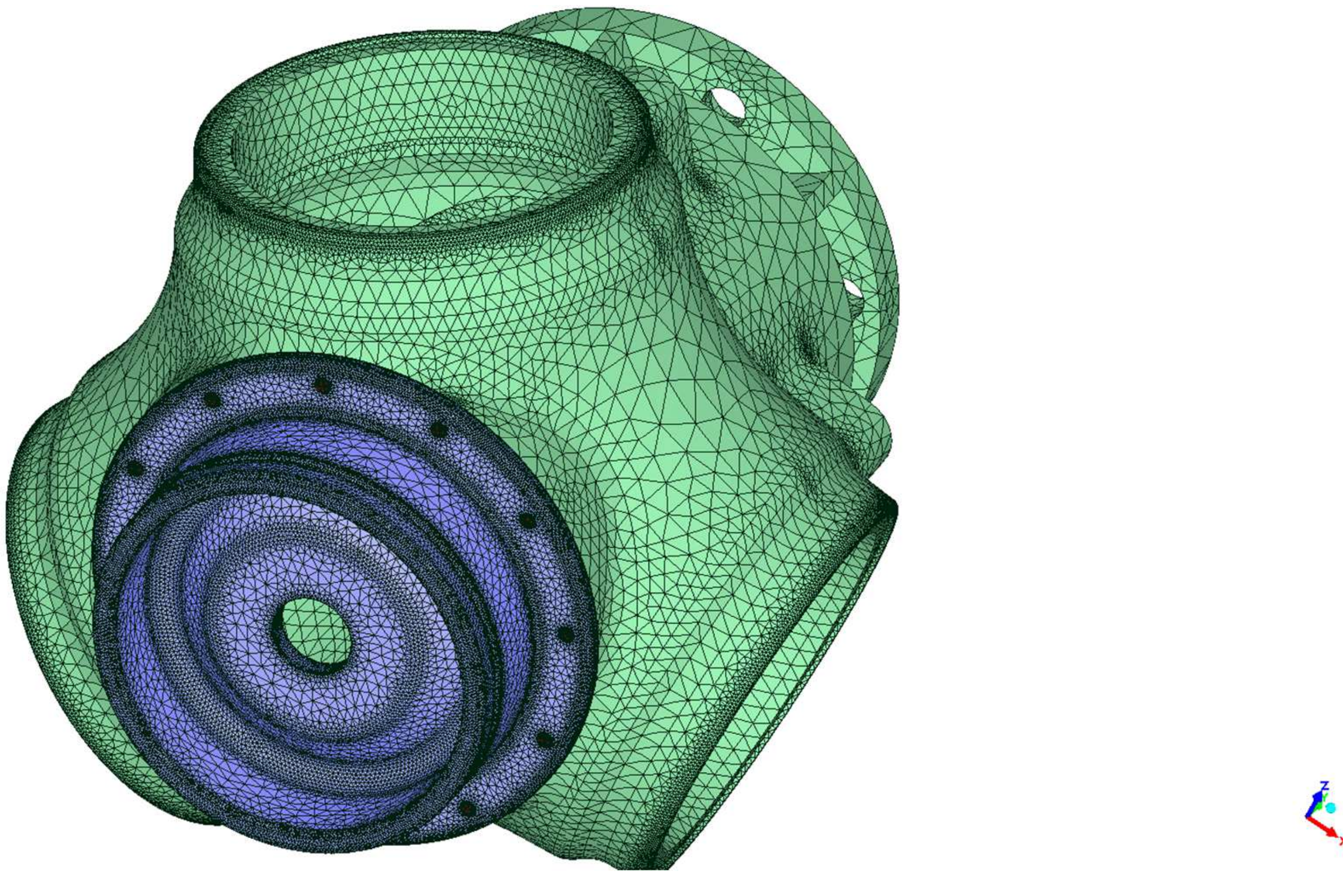
Radial Displacement (inches)



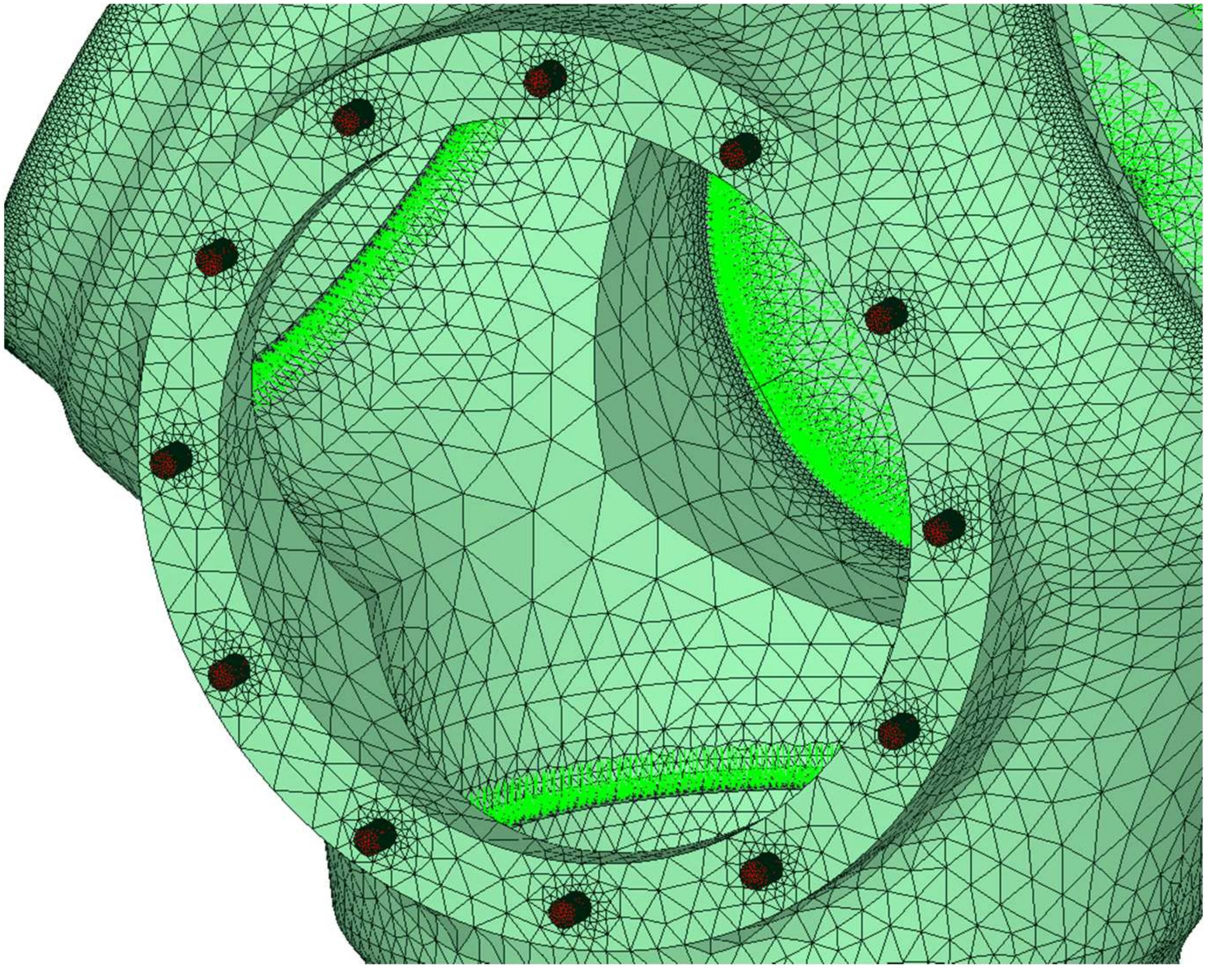
Axial Displacement (inches)



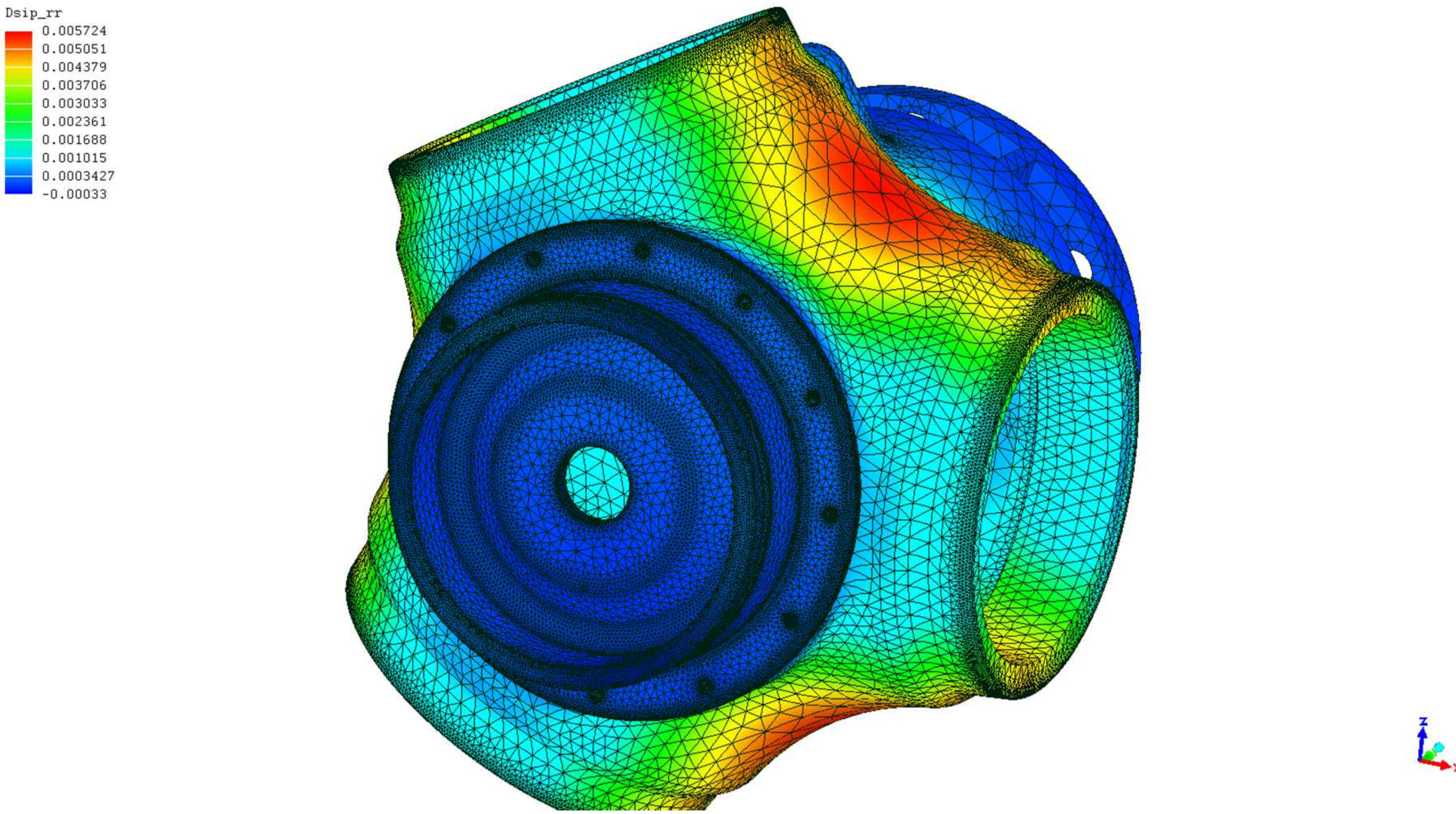
Assembled Model



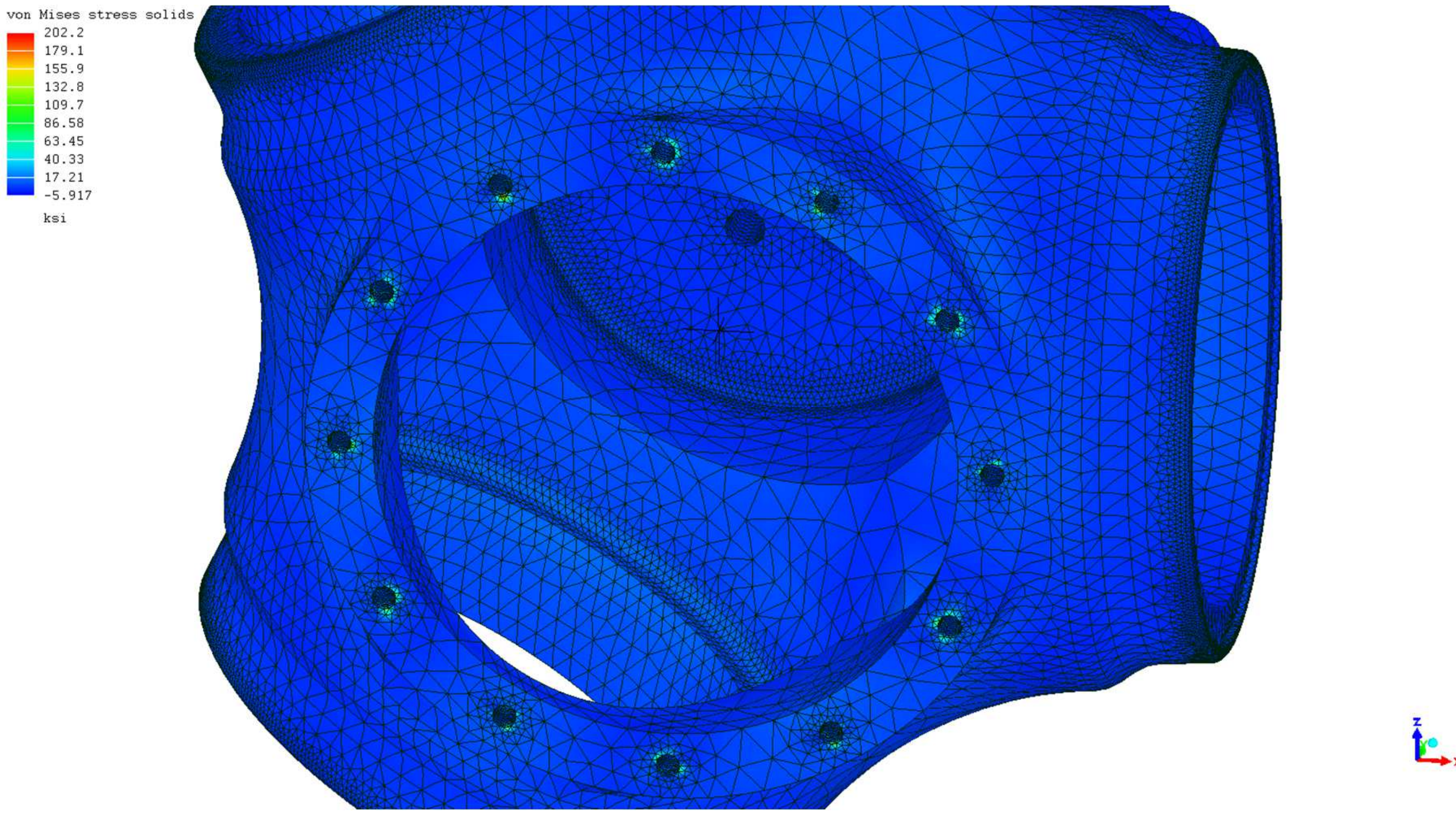
Bonded pins for bolts



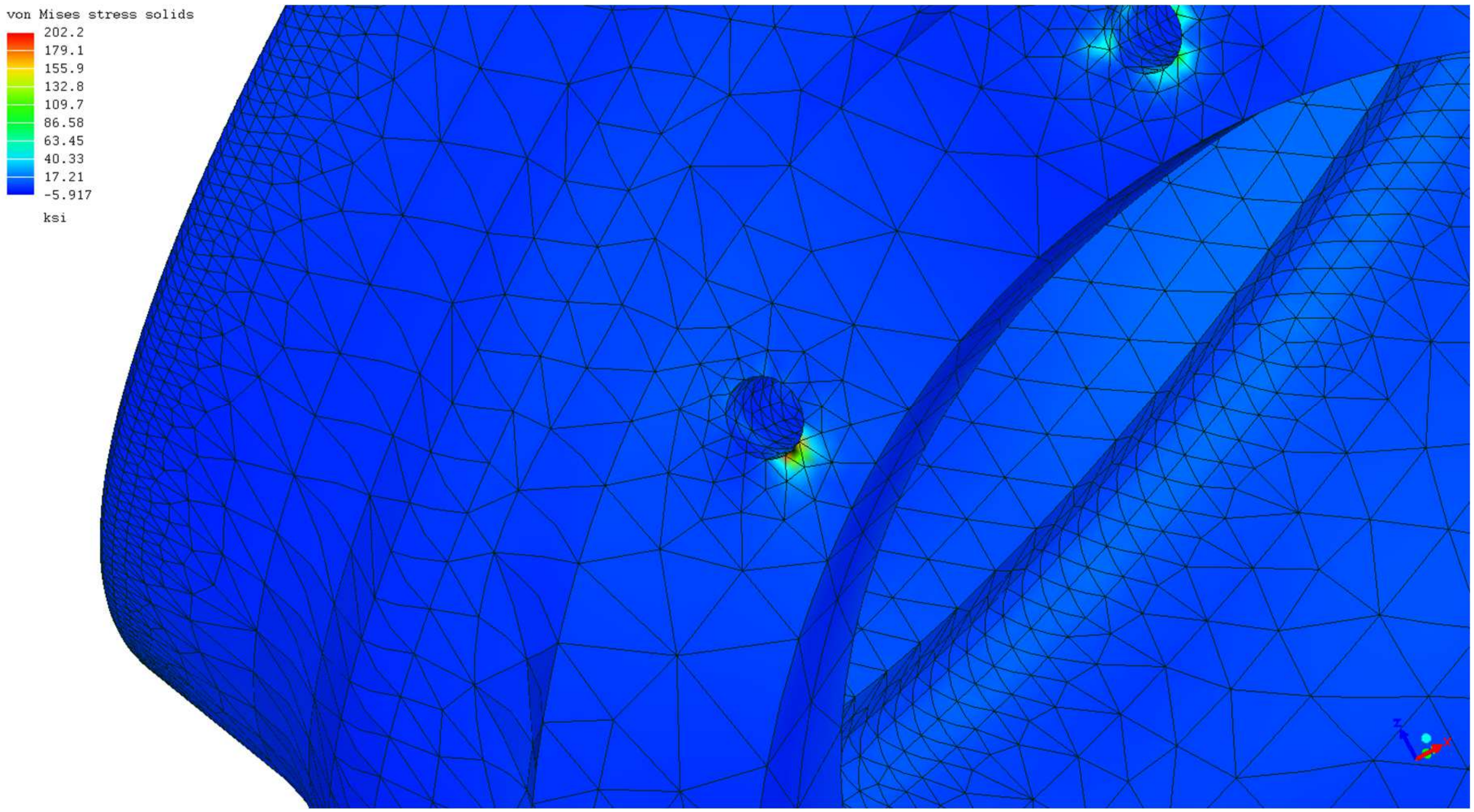
Radial Displacement (inches)



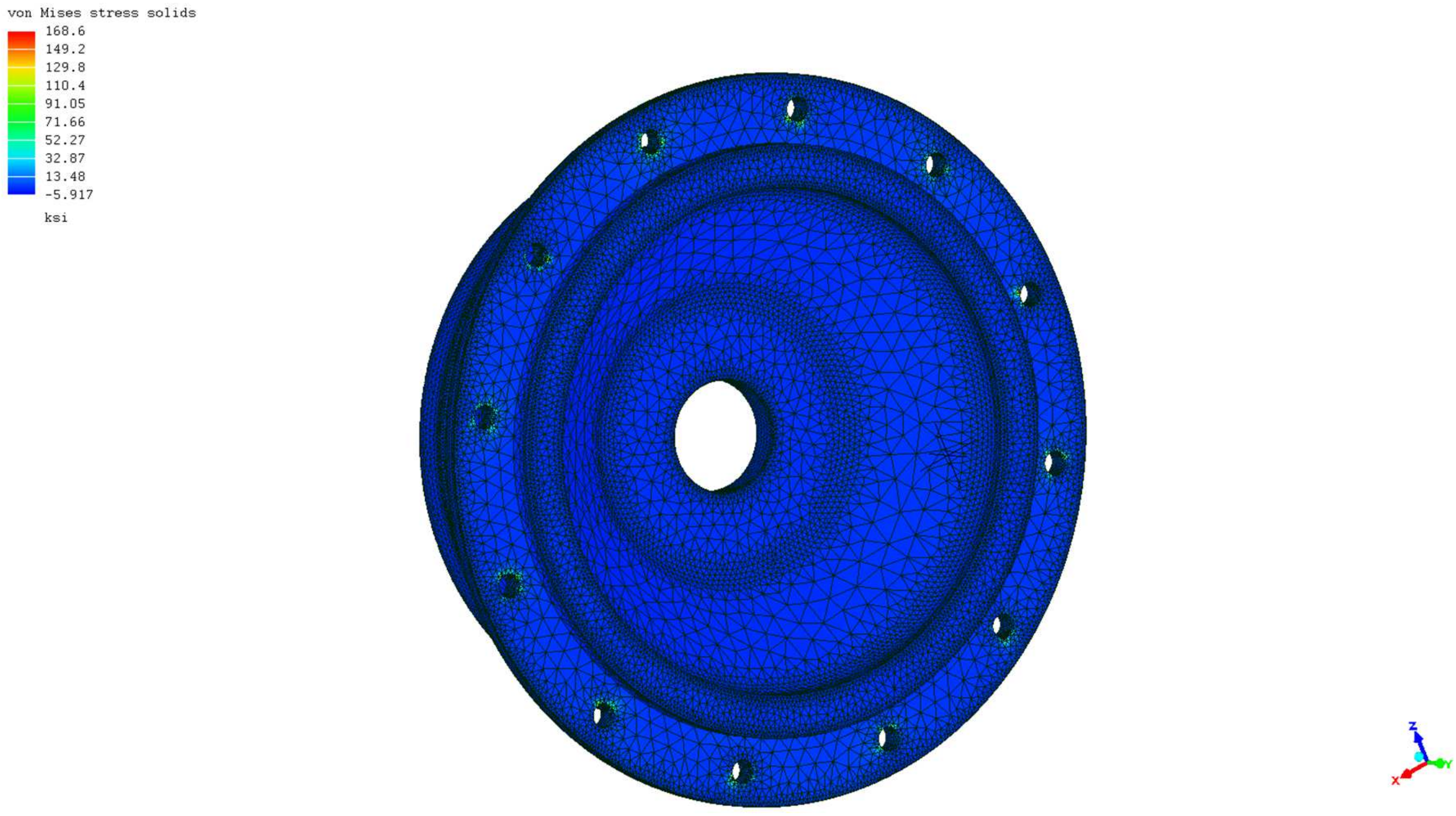
High Stress at Pin Locations



High Stress at Pin Locations



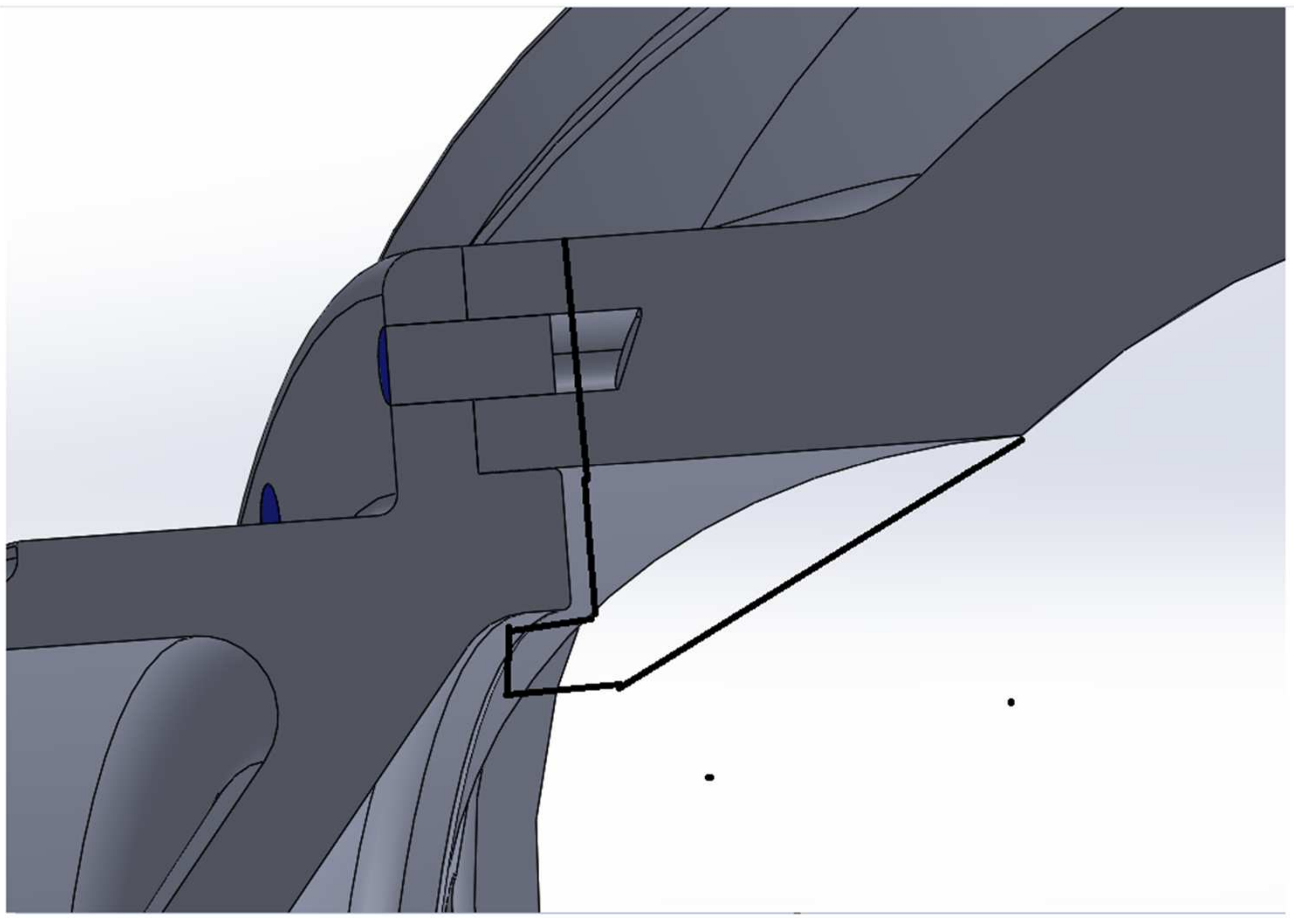
High Stress at Pin Locations



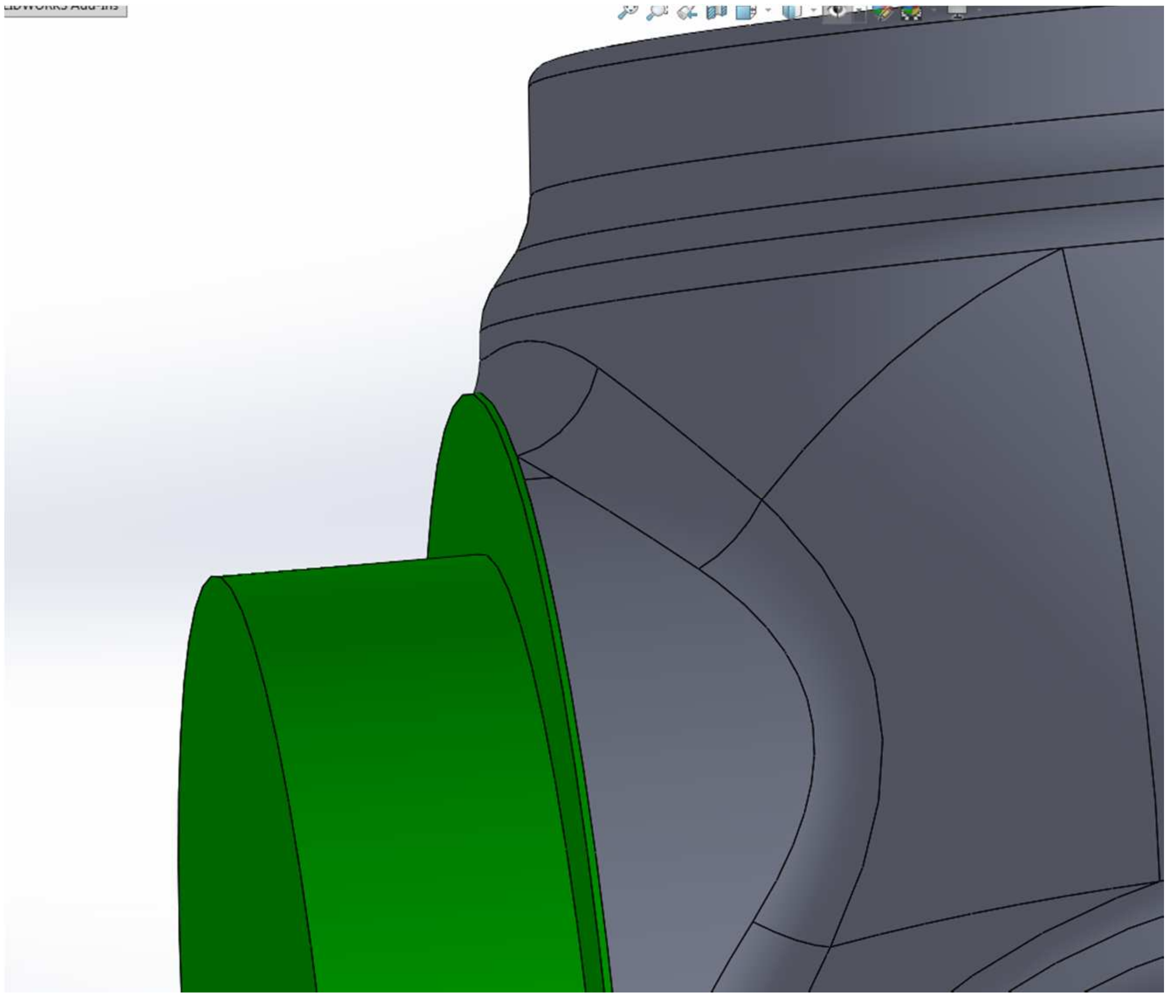
Options

Option A and B are presented on the next slides as a possible solution to eliminate the high stress bolt locations

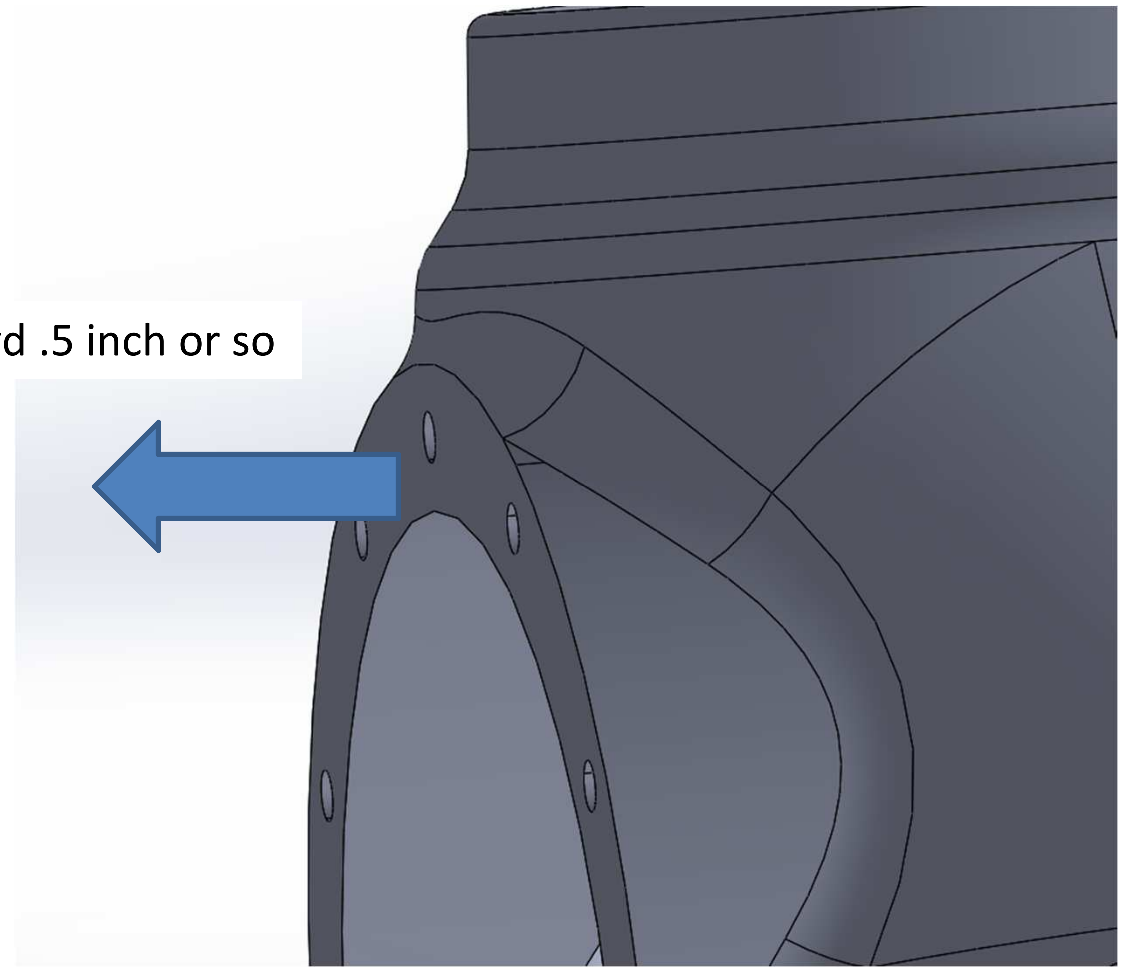
Option A
Reverse the Rabbet fit so the structural cap can carry load



Option B
Make the cap very flexible so that it does not induce load to the hub at the bolt locations

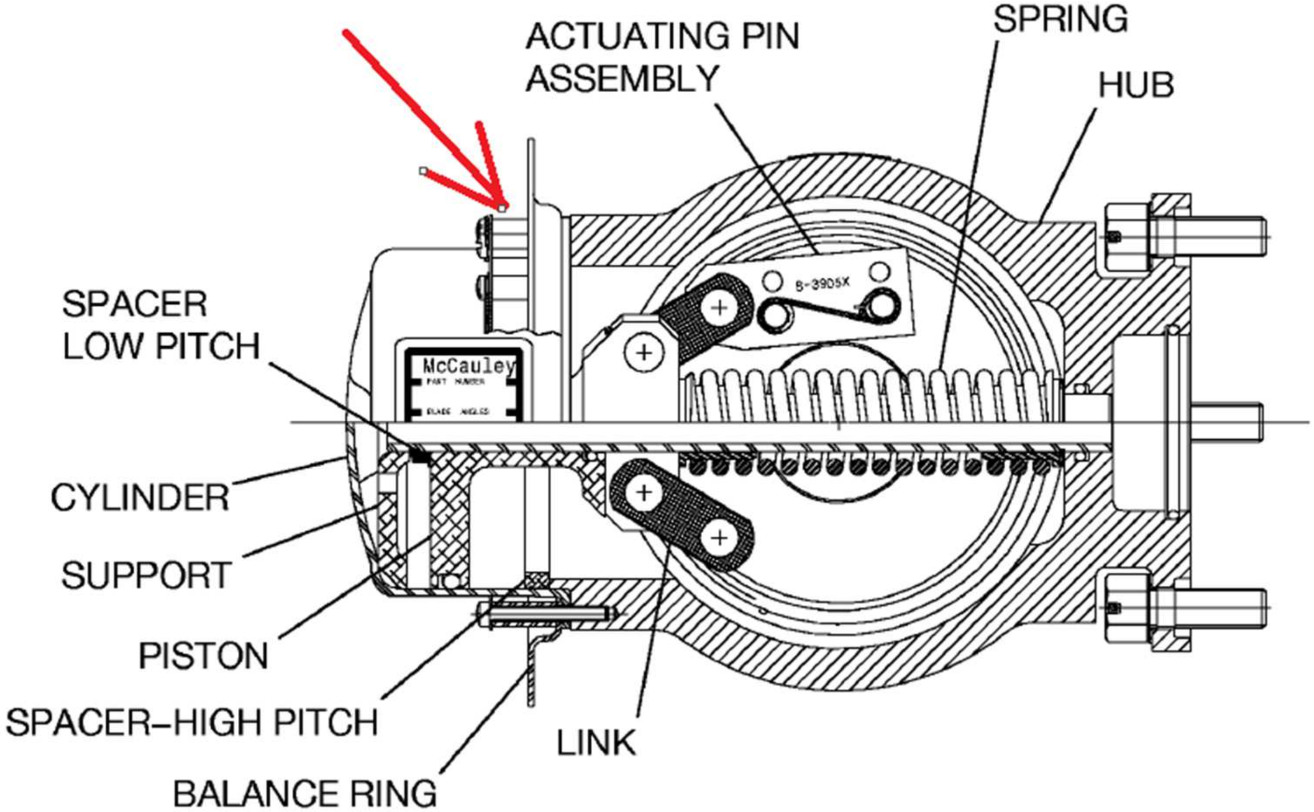


Option B (continued)
Also may extend the hub fwd flange to provide additional axial stiffness for the hub

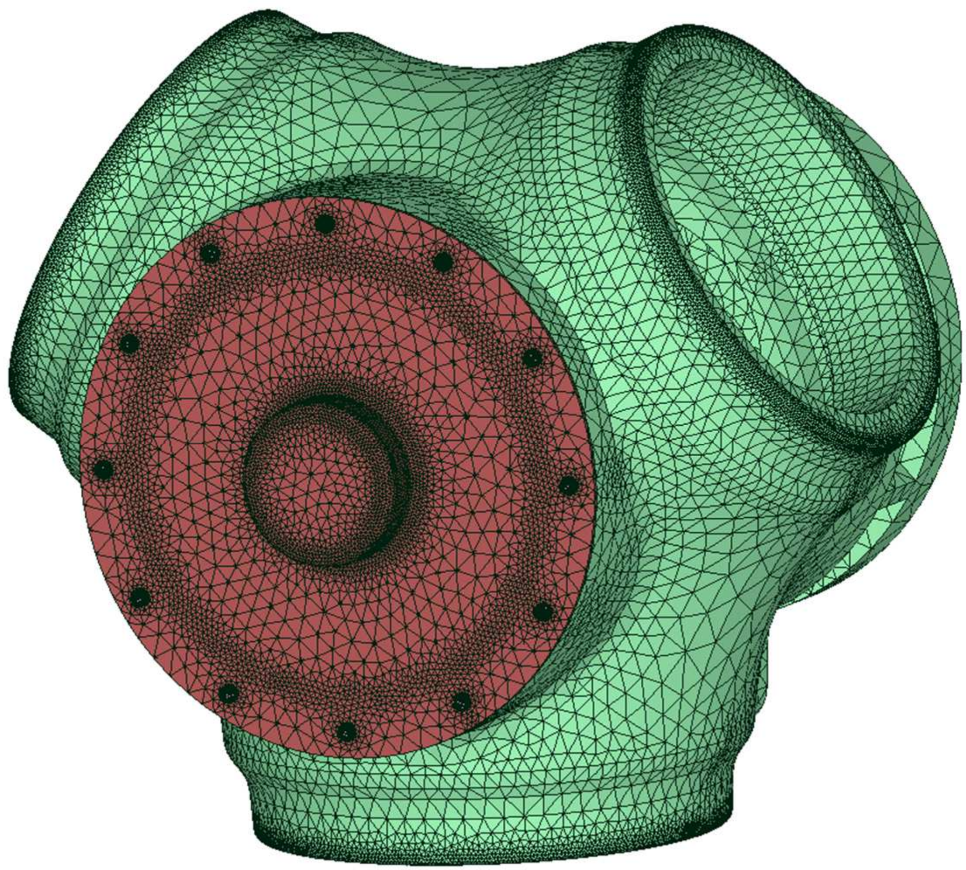


Option B screws

Use spacers and long screws to attach the cap with a hoop load/damper ring like the McCauley hub.   Short screws do not have the ability to stretch and provide adequate clamp. The spacers allow for increased screw length and is needed.



Hub V2

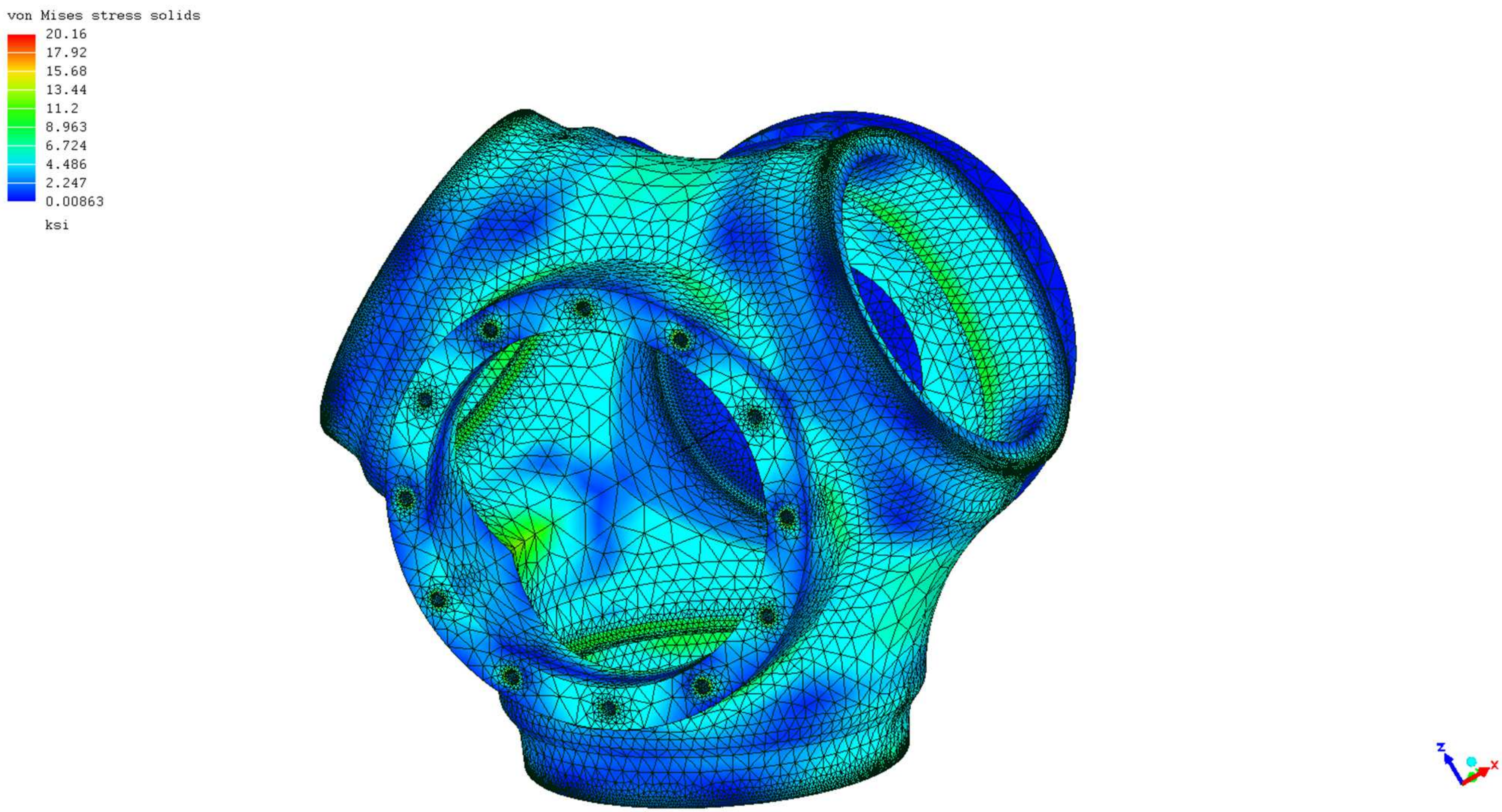


Hub V2
Fwd Face Flange Extended 0.5 inch and Flexible Cover Plate

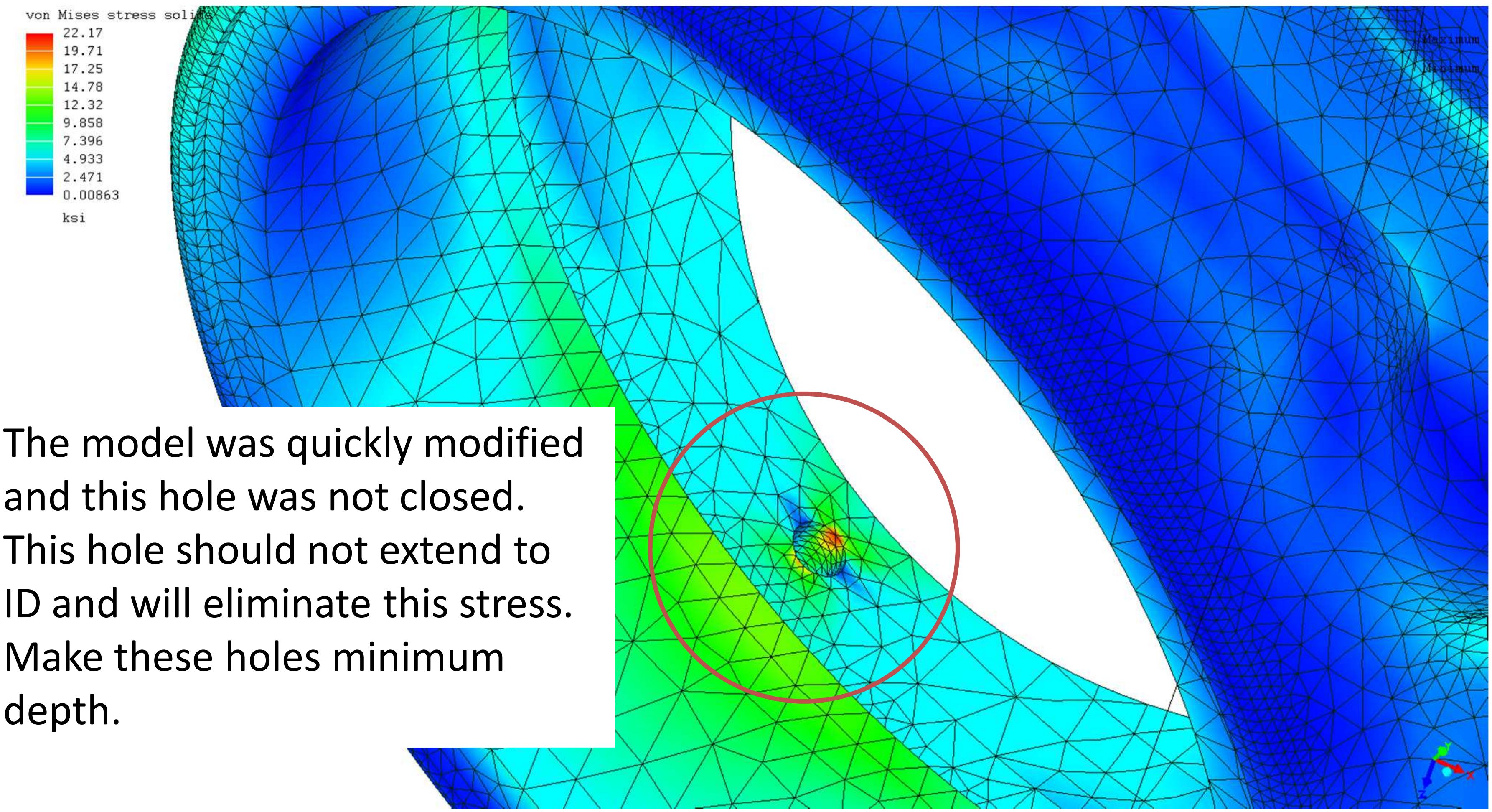
Summary:

- Same loading conditions as Hub V1
- Peak stress reduced from 200 ksi to 20 ksi at the fwd flange holes, it is very localized and should not present an issue for threaded locking inserts to be installed.
- The hub design should be capable of 100000 LCF cycles for a max allowable stress = 20 ksi.

Von Mises Stress



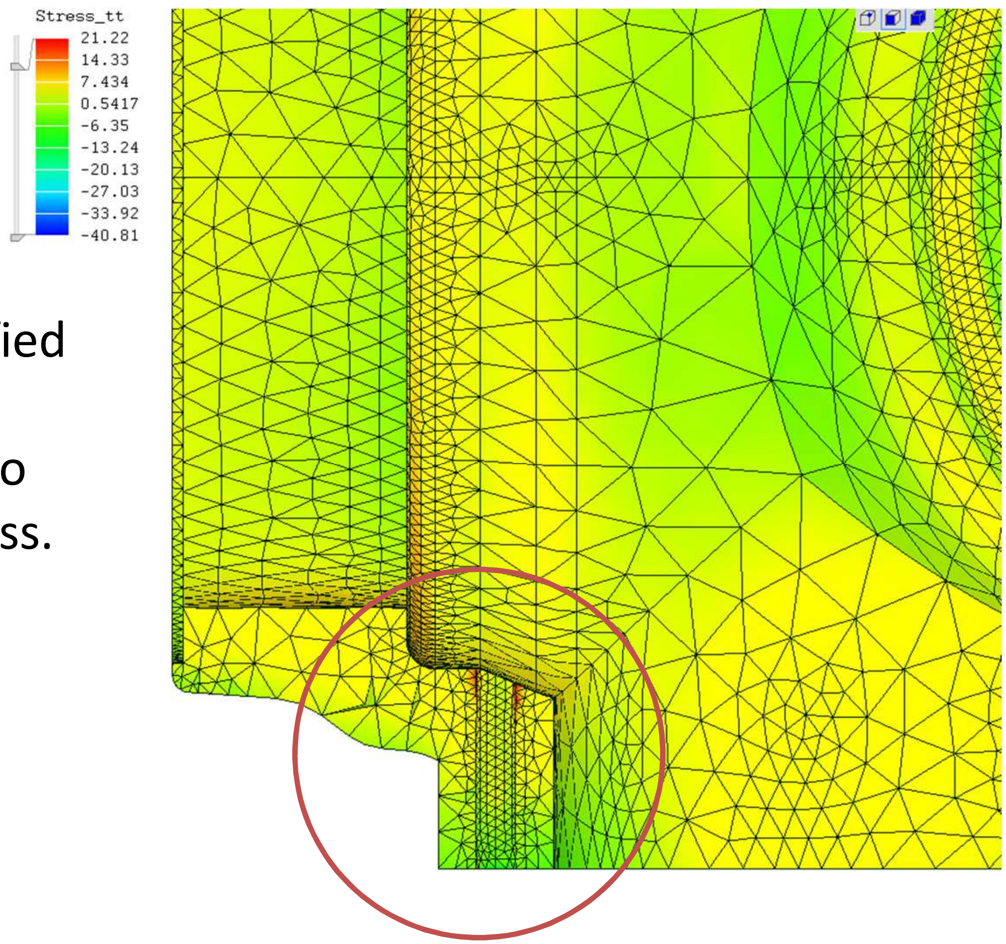
Von Mises Stress



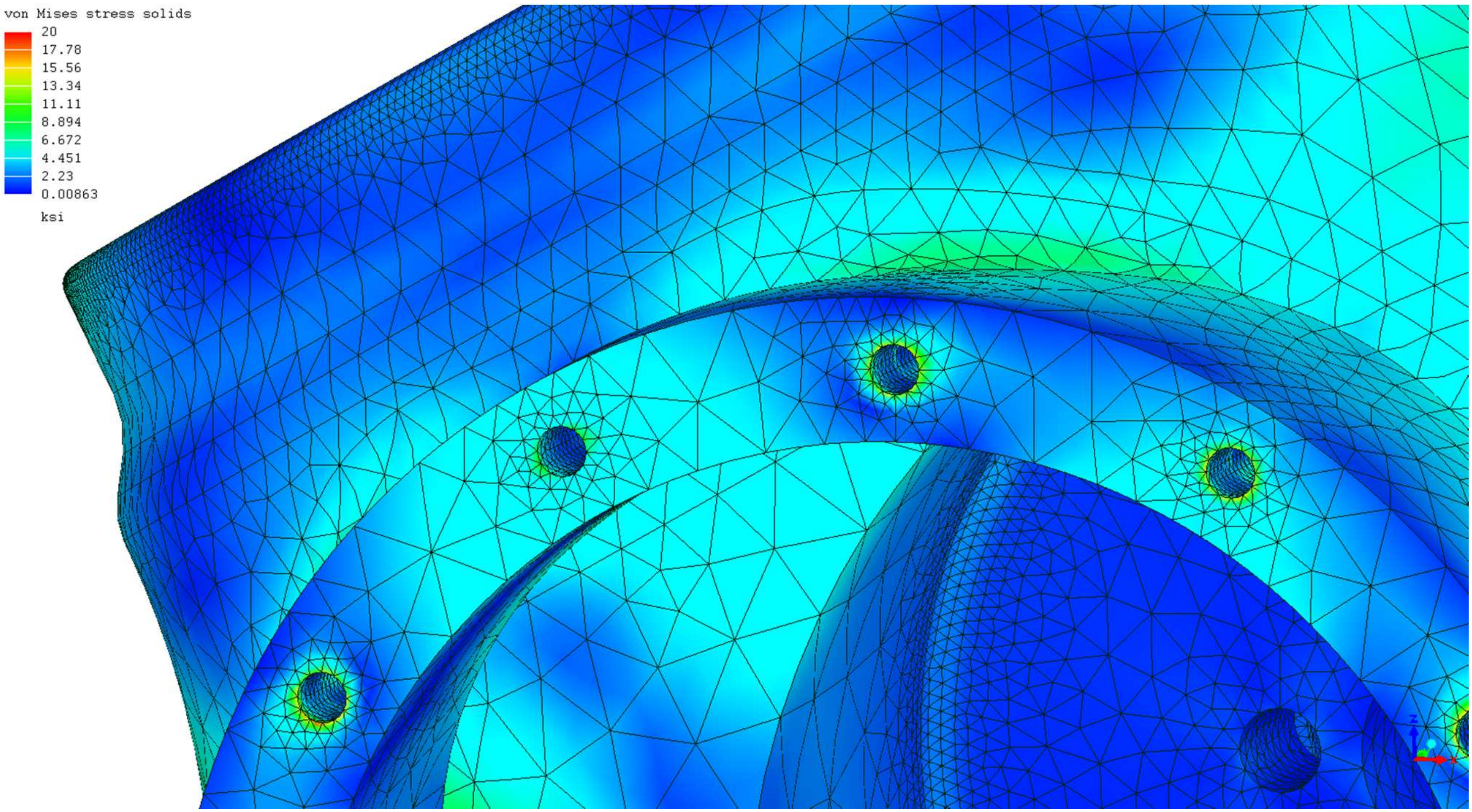
The model was quickly modified and this hole was not closed. This hole should not extend to ID and will eliminate this stress. Make these holes minimum depth.

Hoop Stress at Fwd Face

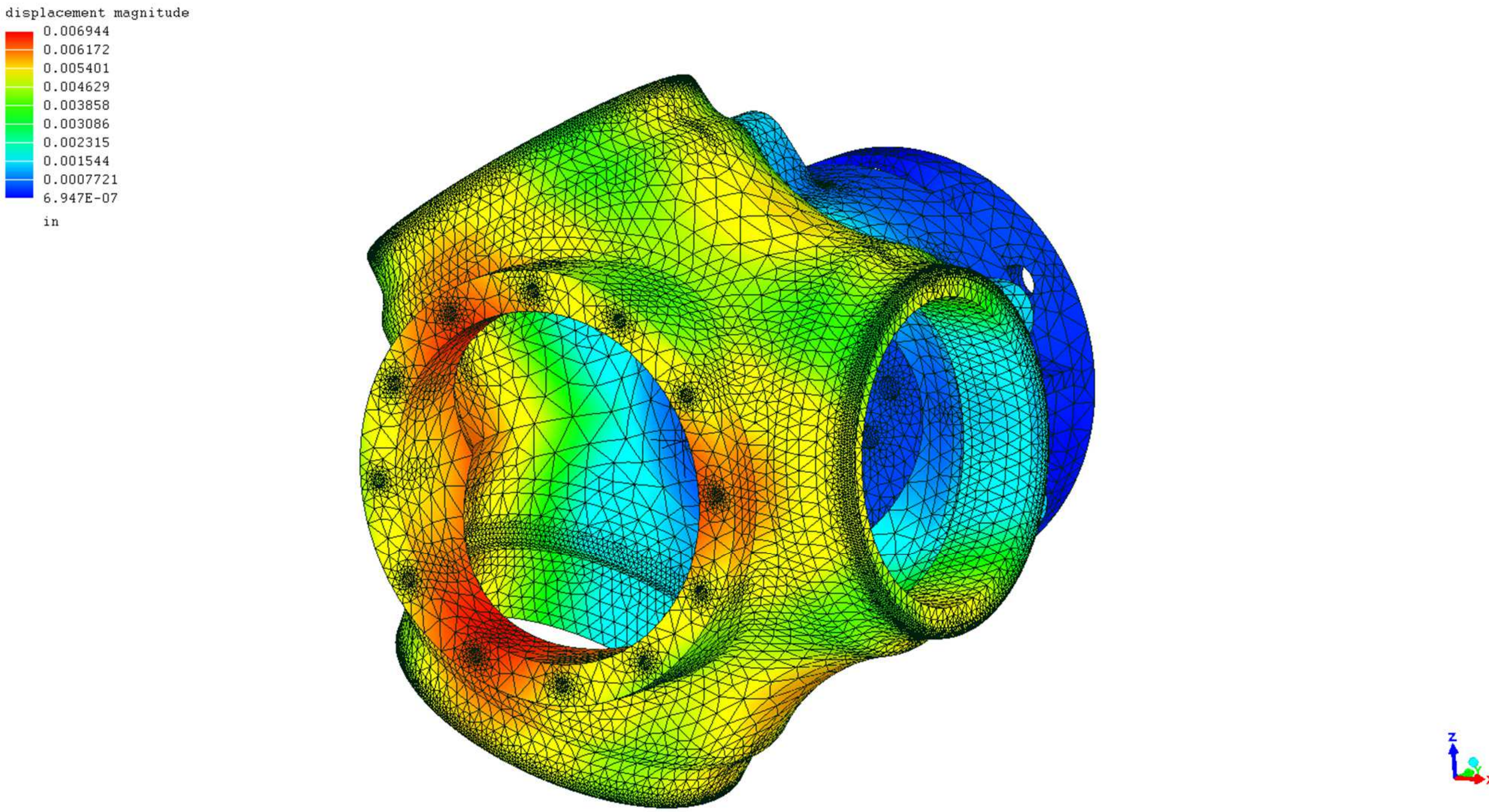
The model was quickly modified and this hole was not closed. This hole should not extend to ID and will eliminate this stress. Make these holes minimum depth.



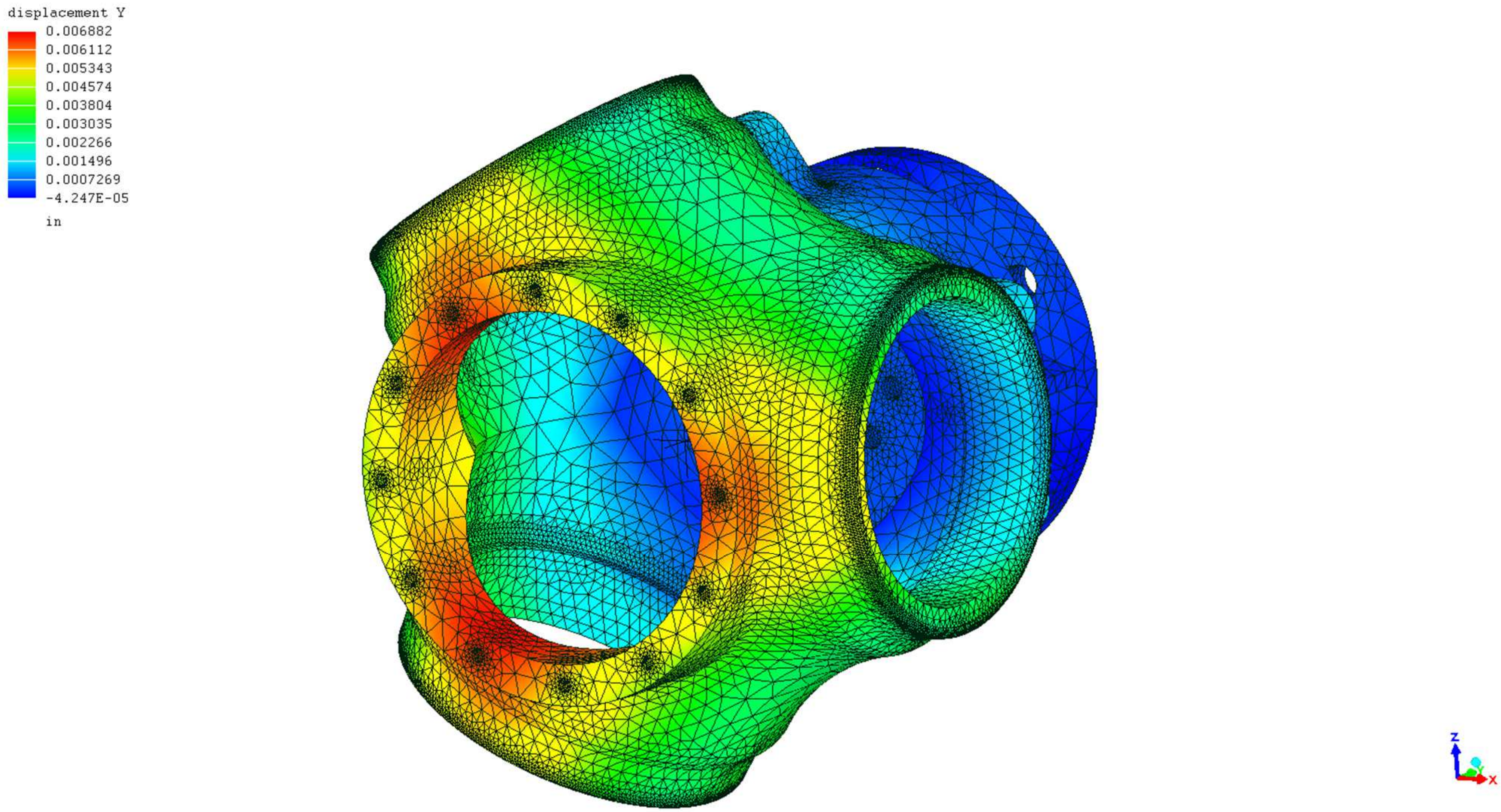
Von Mises Stress



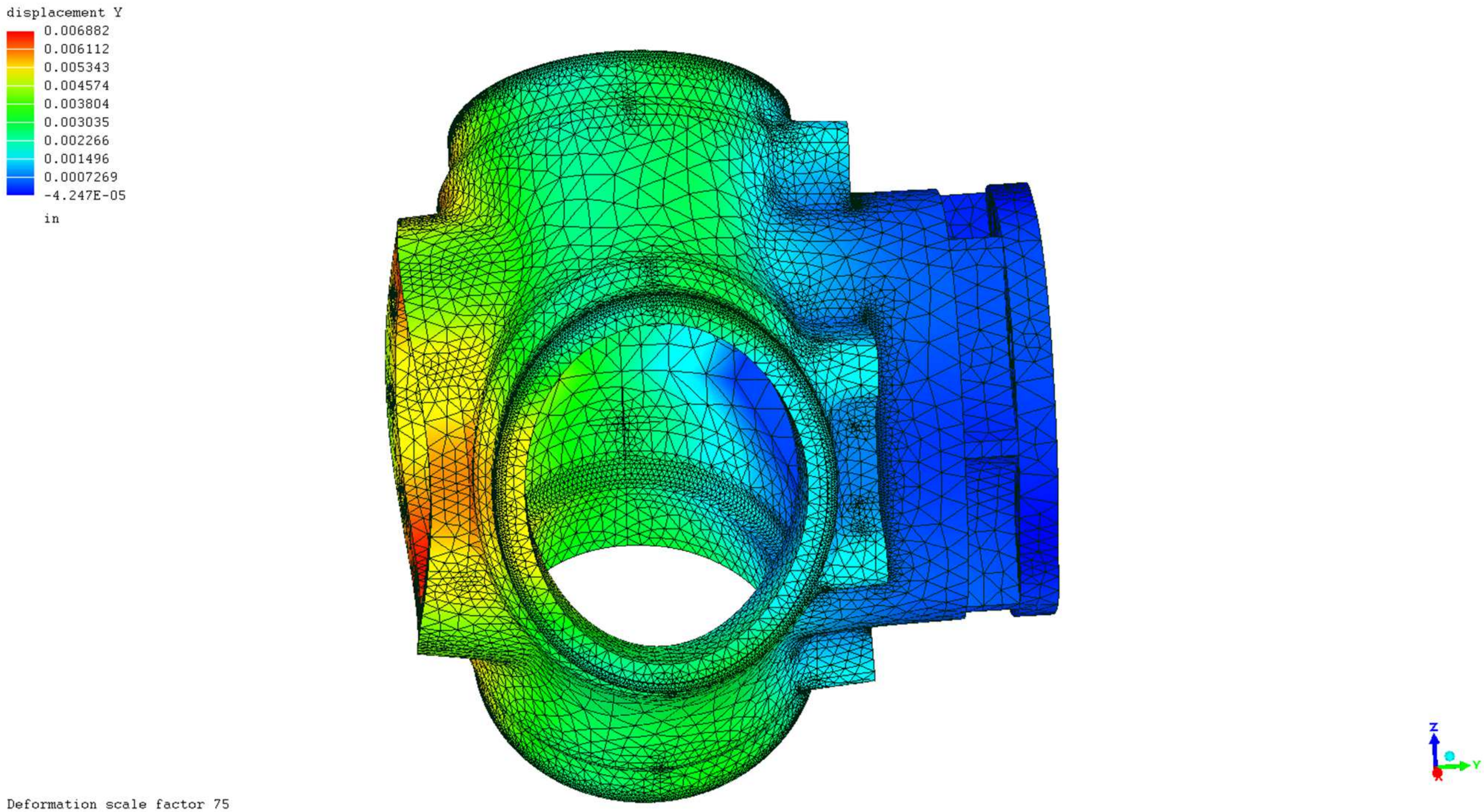
Displacement Magnitude (inch)
All Directions



Displacement Axial Direction
Fwd Face Variation
.0068 - .0048 = .002 inch

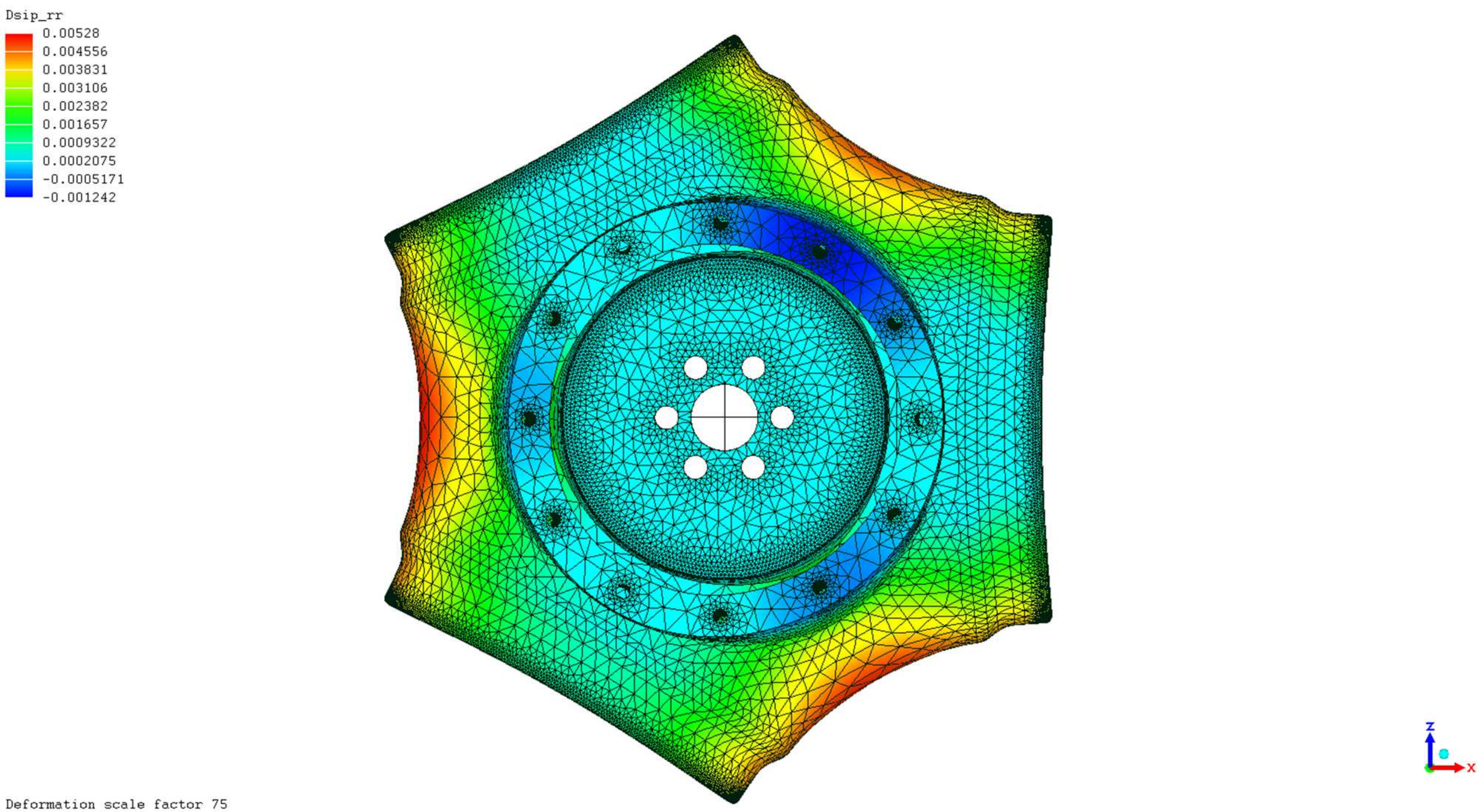


Magnified Axial Displacement (inch)



Magnified Radial Displacement (inch)

not sure why it is not perfectly symmetrical, need to look at that.



Magnified Radial Displacement (inch)

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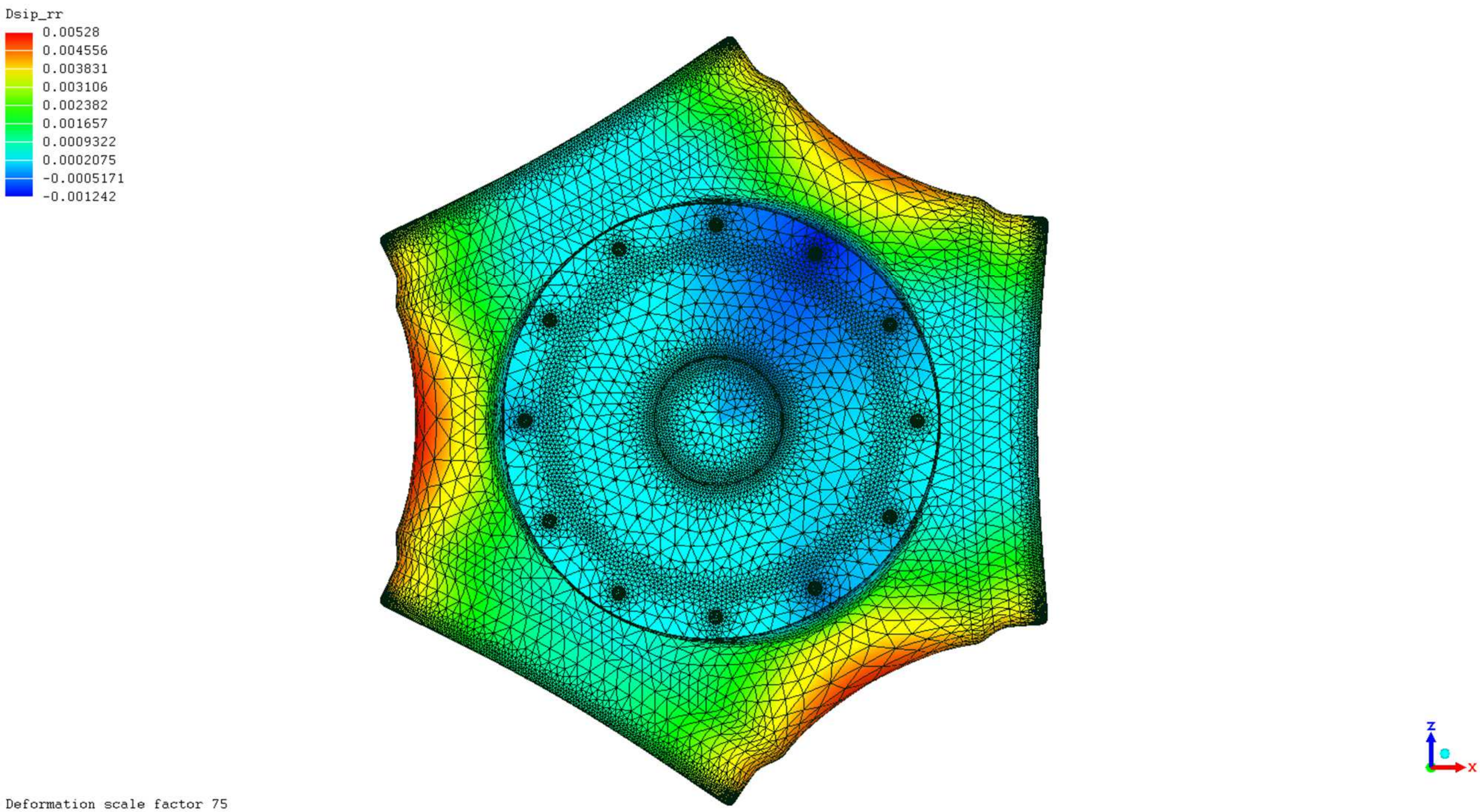
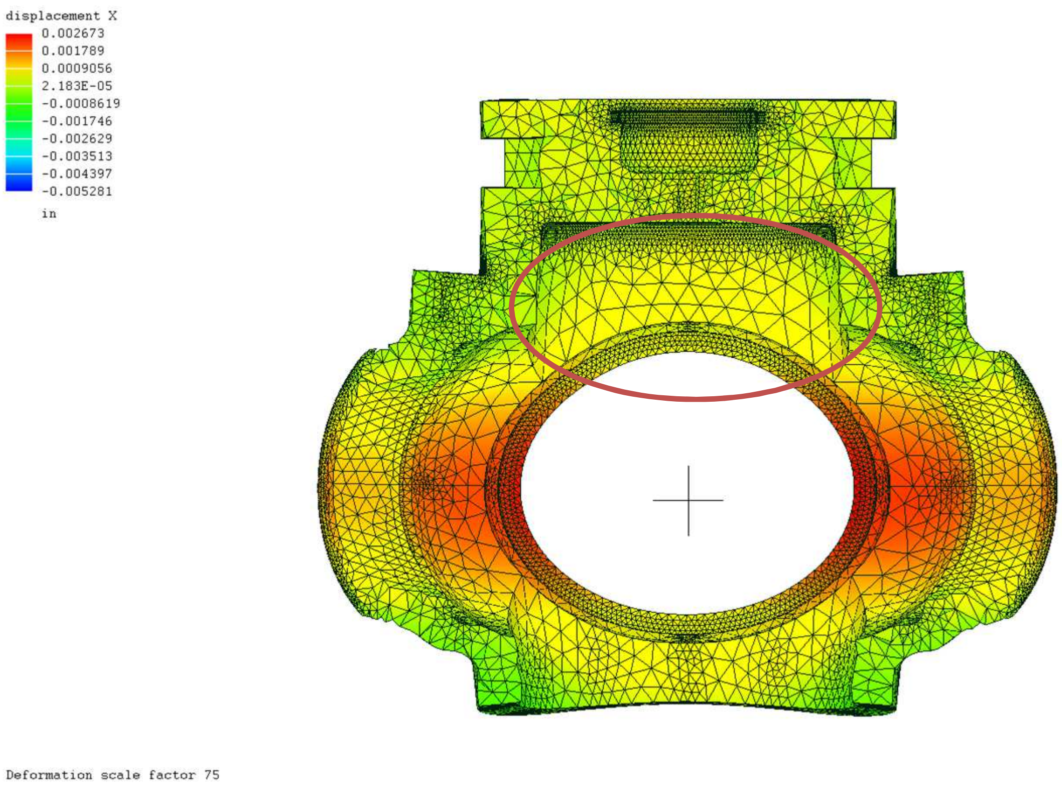
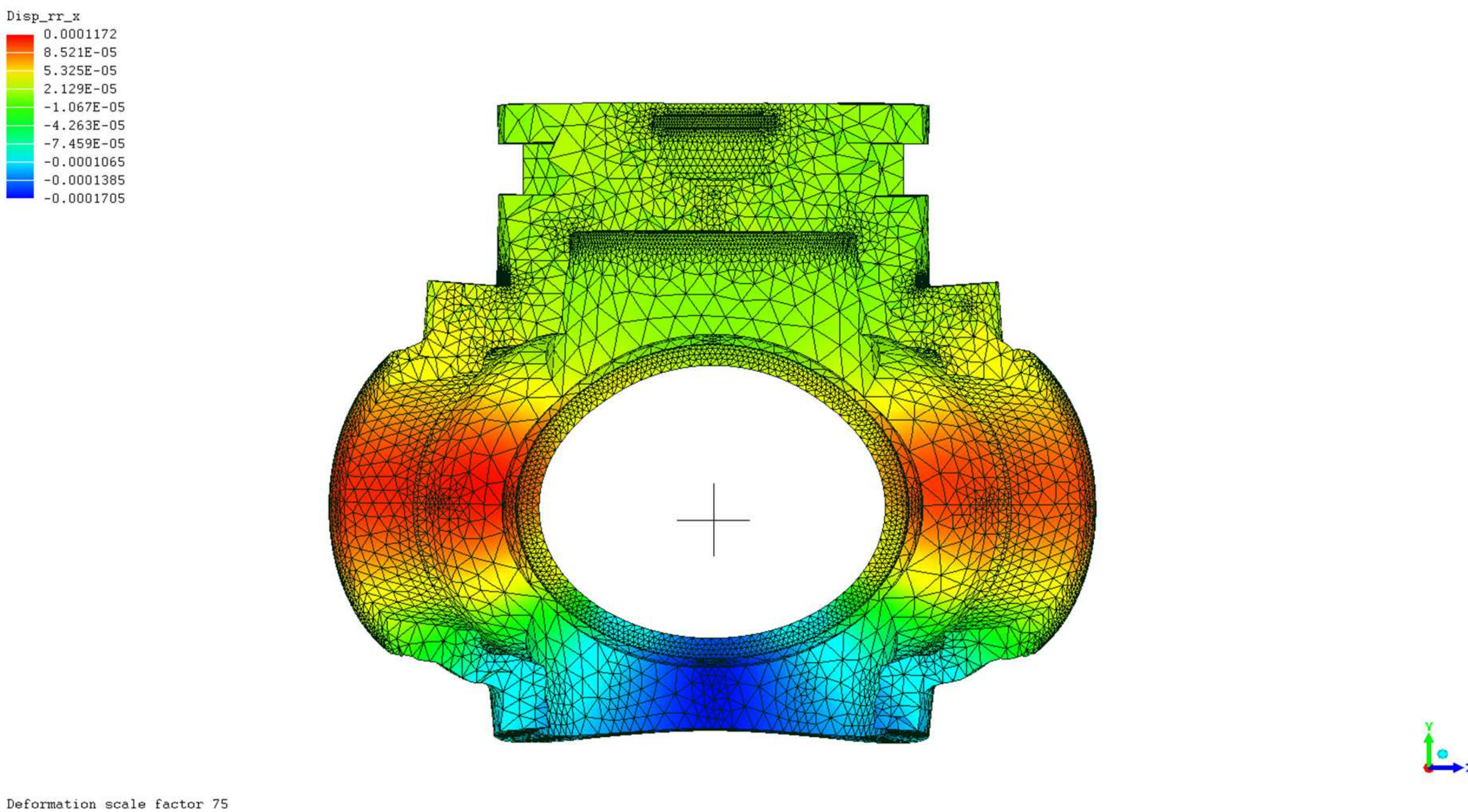


Magnified Displacement INTO the page
Ball race surface flatness variation
.00267 - .001 = .00167 inch

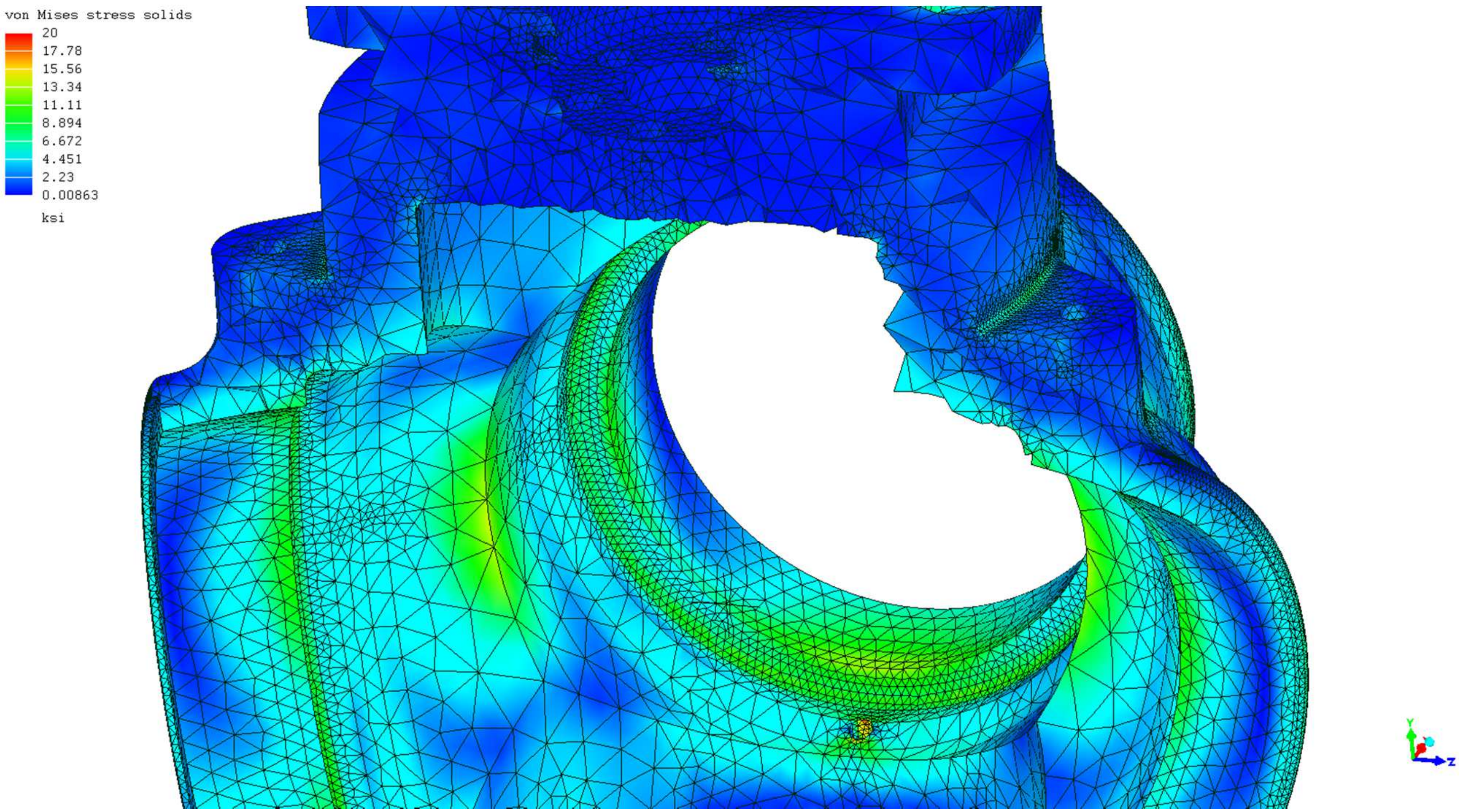


Note: this model assumes an even centrifugal load around the bearing race for simplicity. Because of the hub flex, the load would actually be more concentrated at the aft portion of the race. The aft edge will carry more load because it is stiffer. Upon tear down inspections pay special attention to the aft edge.

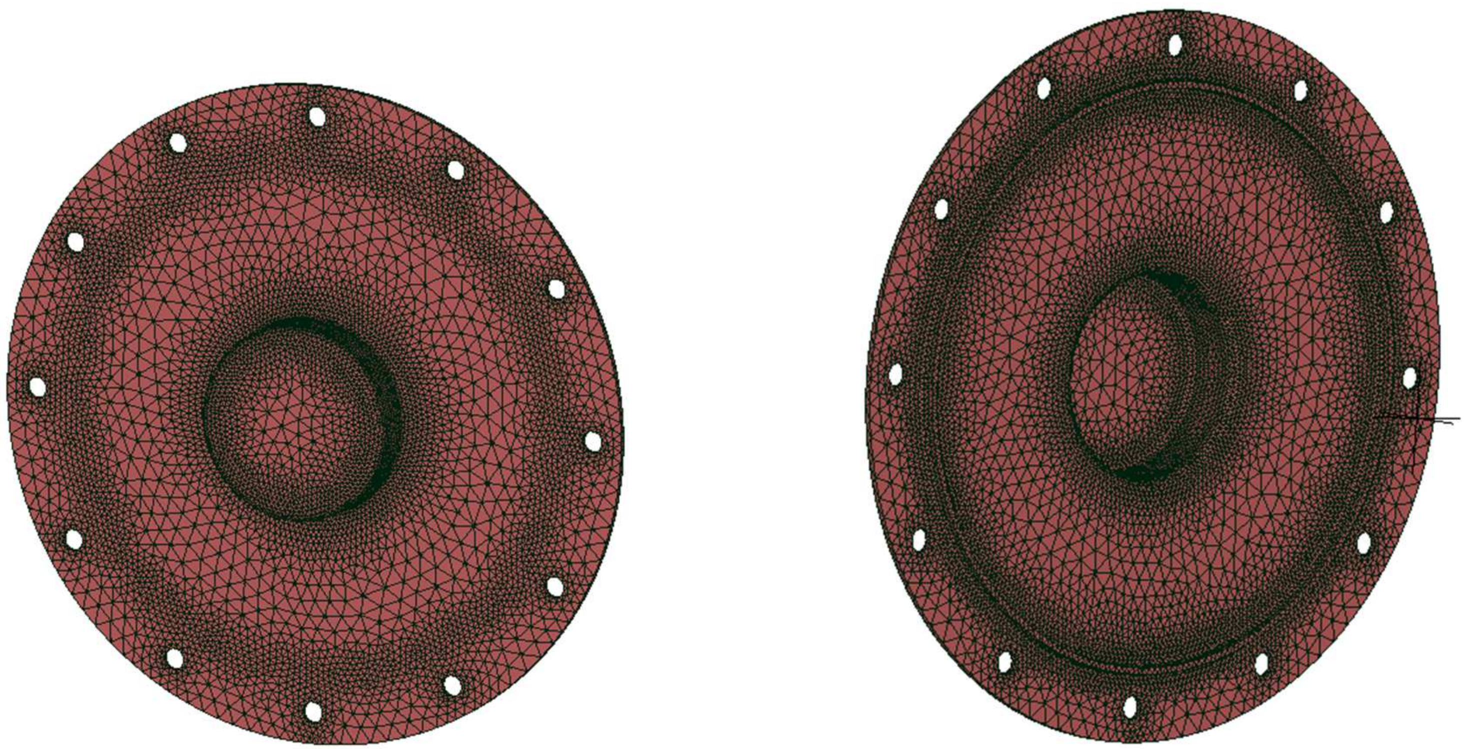
Magnified Radial Displacement ABOUT the Bearing Center
(this is ovalization of the blade bore)
.00011 – (-.00017) = 0.00028



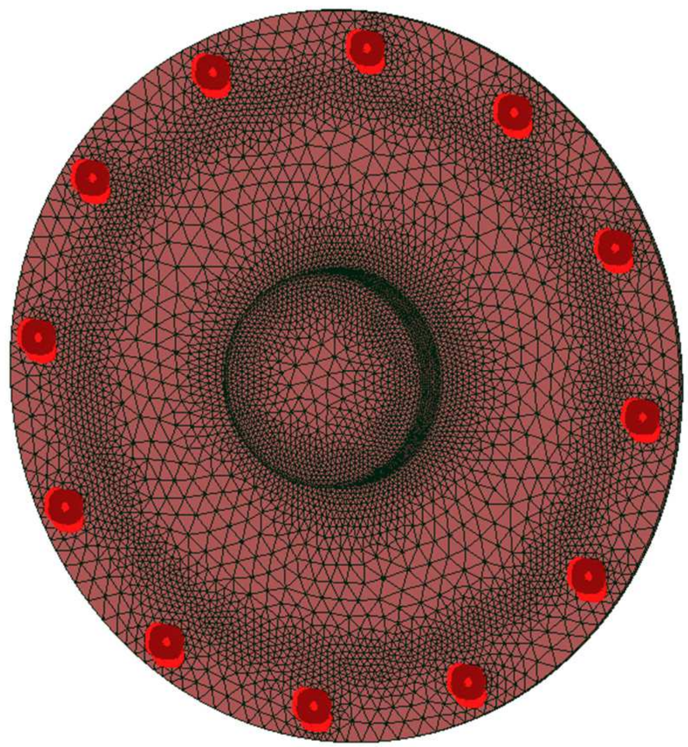
Von Mises Stress



Cap Natural Frequency Model



Cap Natural Frequency
Model Boundary Condition
Fixed at bolt hole ID only



Cap Natural Frequency

Boundary conditions: bolt hole ID fixed

Possible driving frequencies:
1/rev from engine imbalance
2/rev from crank position
3/rev from blades
6/ rev from blades passing cowl

2835 rpm / 60 = 47 Hz

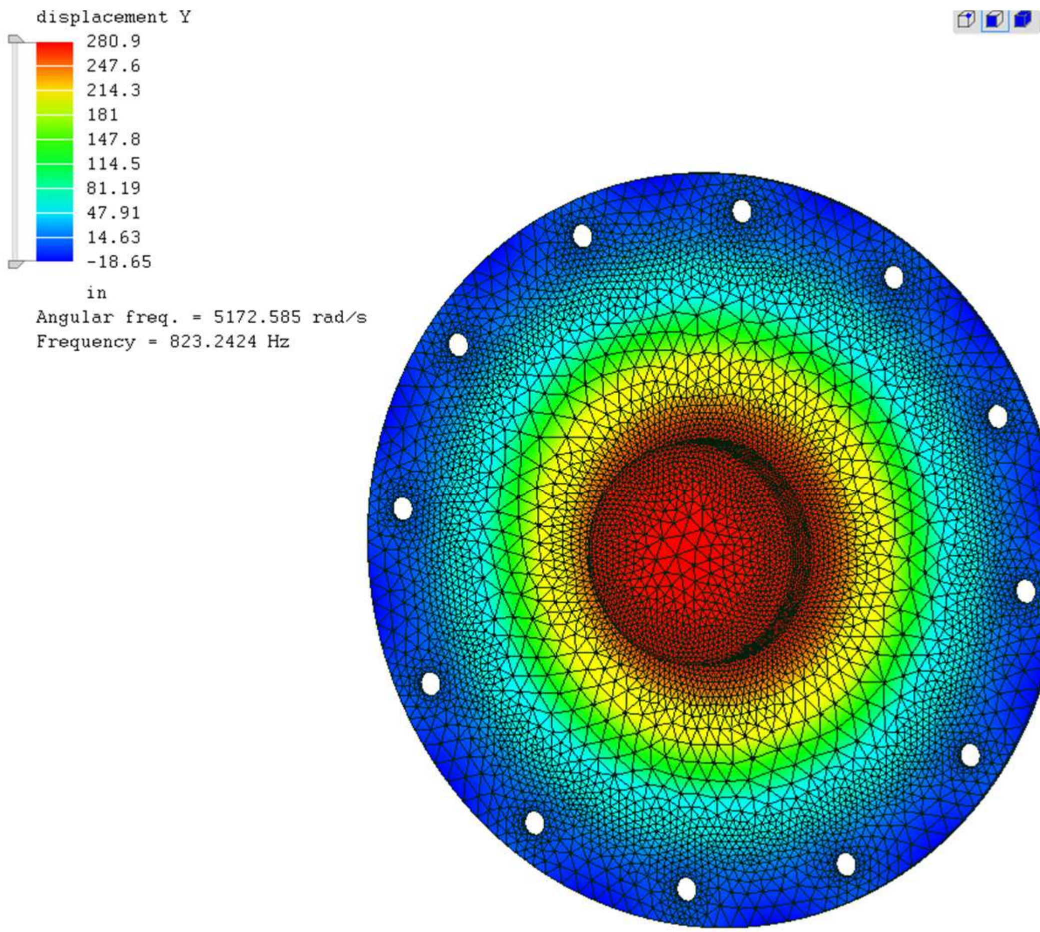
47 x 1 = 47 Hz
47 x 2 = 94 Hz
47 x 3 = 141 Hz
47 x 6 = 282 Hz

Analysis Results:
Mode 1 = 823 Hz
Mode 2 = 1425 Hz
Mode 3 = 3833 Hz
Mode 4 = 3923 Hz

Natural frequencies are well above possible driving frequencies

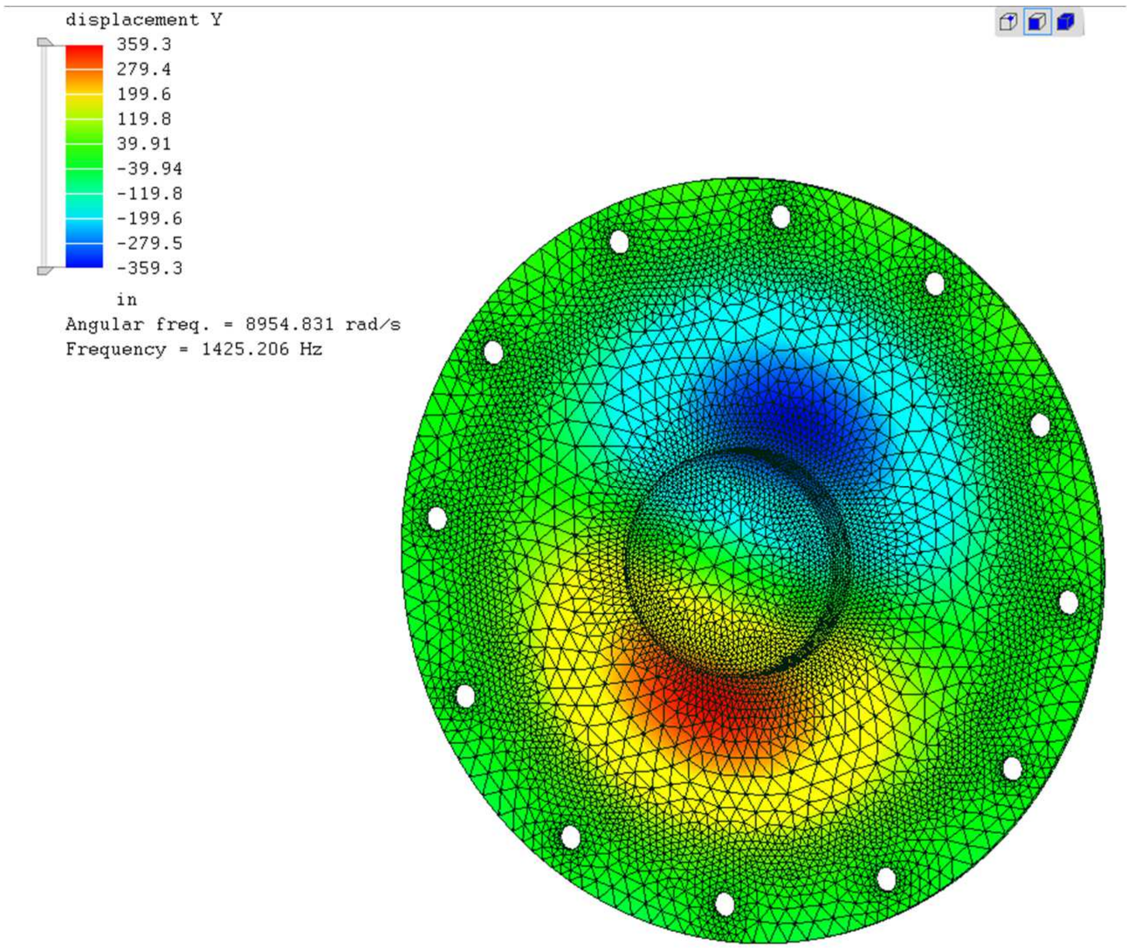
Frequency margin = 823/282 = 290%

Mode 1



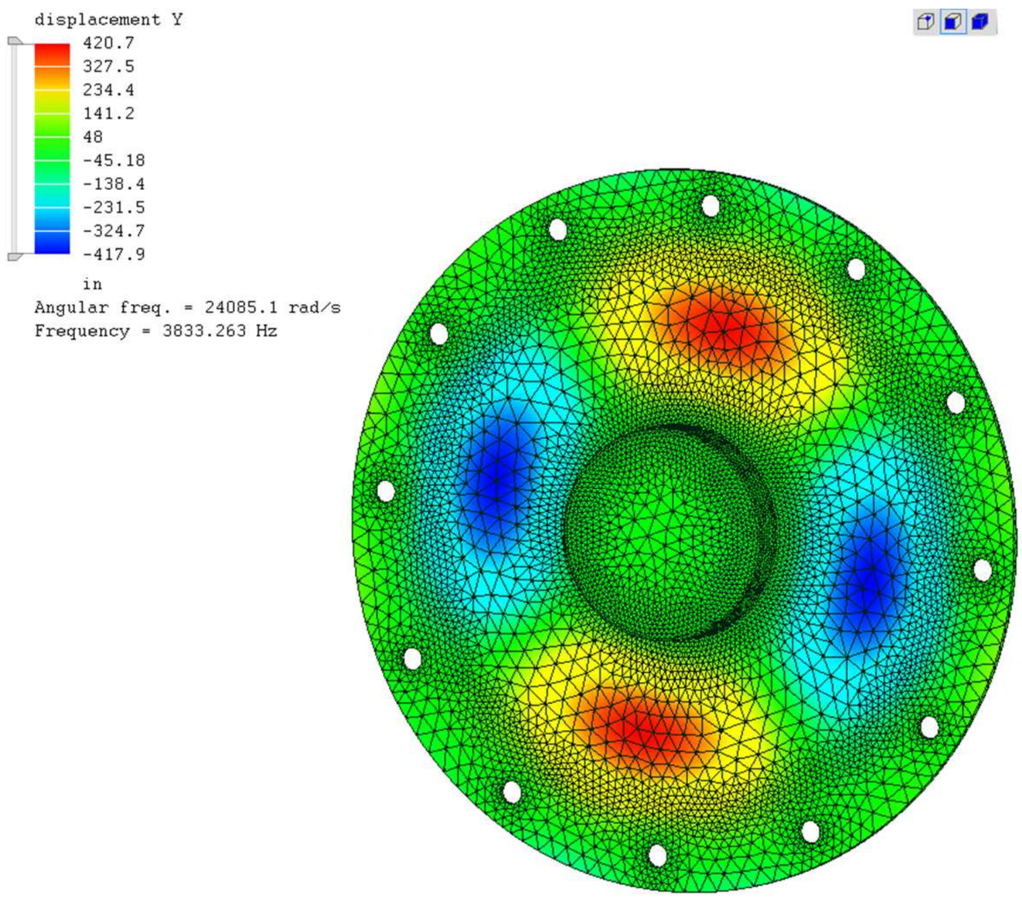
displacement Y
280.9
247.6
214.3
181
147.8
114.5
81.19
47.91
14.63
-18.65
in
Angular freq. = 5172.585 rad/s
Frequency = 823.2424 Hz

Mode 2

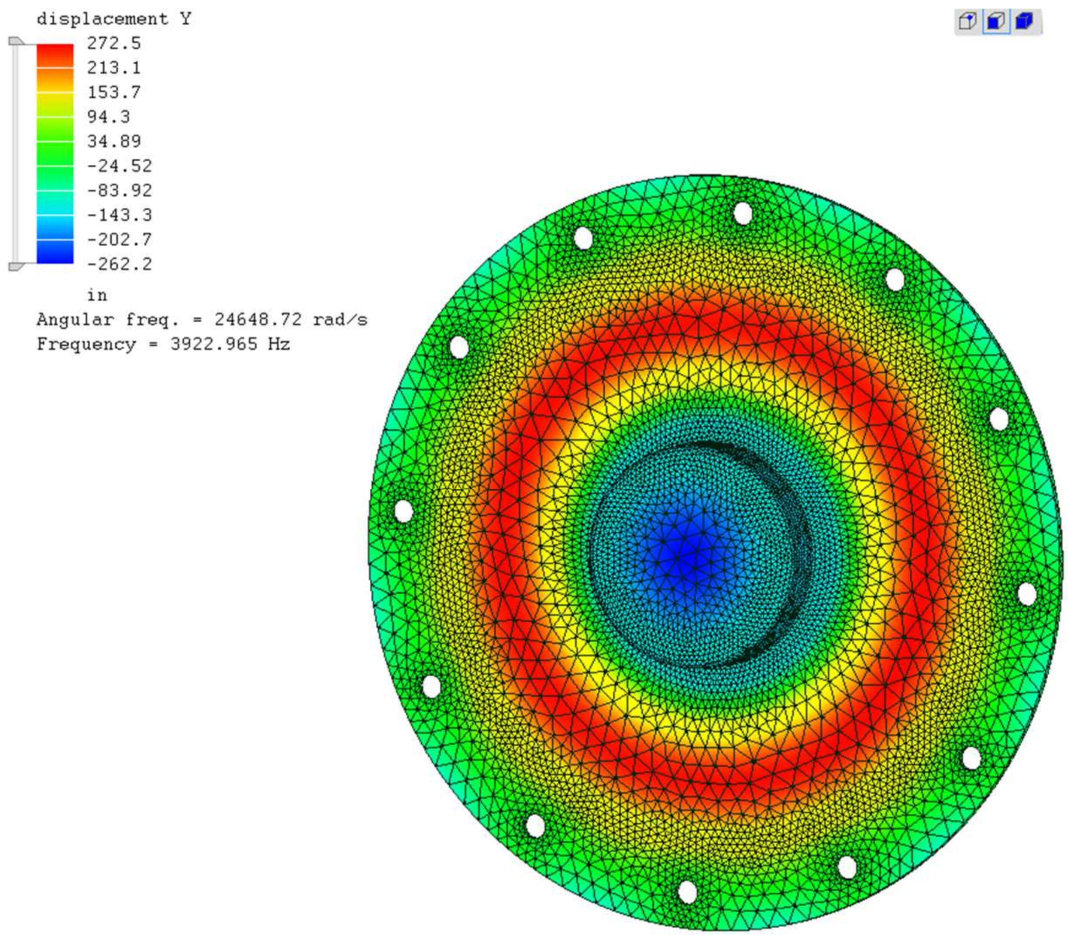


displacement Y
359.3
279.4
199.6
119.8
39.91
-39.94
-119.8
-199.6
-279.5
-359.3
in
Angular freq. = 8954.831 rad/s
Frequency = 1425.206 Hz

Mode 3


displacement Y
420.7
327.5
234.4
141.2
48
-45.18
-138.4
-231.5
-324.7
-417.9
in
Angular freq. = 24085.1 rad/s
Frequency = 3833.263 Hz

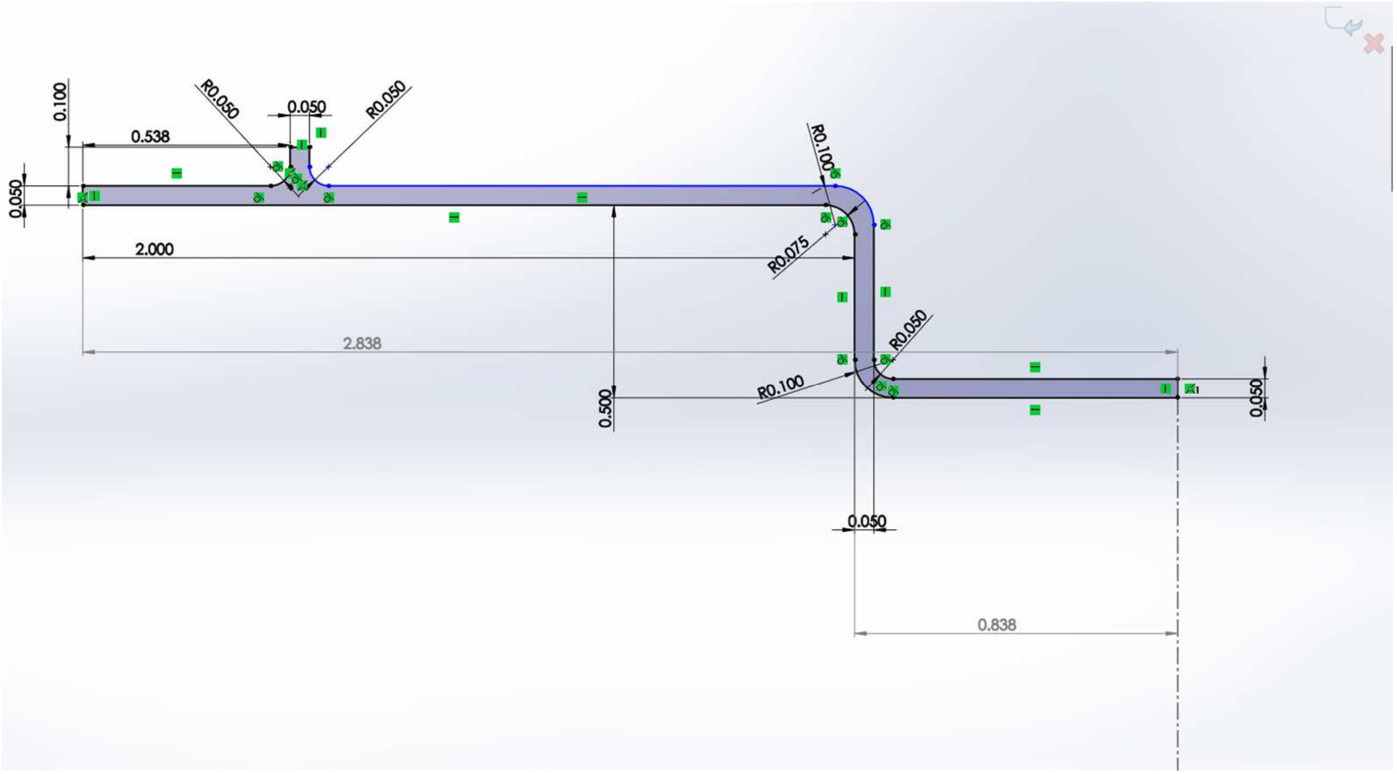
Mode 4


displacement Y
272.5
213.1
153.7
94.3
34.89
-24.52
-83.92
-143.3
-202.7
-262.2
in
Angular freq. = 24648.72 rad/s
Frequency = 3922.965 Hz

Cap Geometry

the flexible cap geometry can be different shape, this was my first draft and was sufficient. It should be no more than .050 thick, Aluminum material.

the attachment screws should have spacers and a hoop carrying/damper ring similar to the McCauley hub. The damper ring should be thin steel.



Fracture Mechanics

Placeholder

- Flaw size
- Crack growth rate
- Safe Inspection interval