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Finite Element Analysis of Stress and Displacement of Centrifugal Pump Impeller Model For Performance Improvement.

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ABSTRACT
The study, Finite Element Analysis of stress and displacement of centrifugal pump impeller model for performance improvement, was successfully investigated. The modeled open impeller by the researchers, had diameter of 60 mm; hub diameter of 20mm with central shaft hole of 10mm. impeller model retained 6 blades with a maintained thickness of 2 mm and height of 3 mm. In addition, the impeller model was subjected to finite element analysis to predict stress and displacement under turning moment of 100 N mm, fixed rotational constraints, with fluid force of 6.00 N acting on the impeller vanes. Results revealed that, the maximum 1st and 3rd principal stresses were found to be 0.437364 MPa and 0.0221447 MPa respectively; this suggested that the centrifugal pump impeller failure would be due to tensile stress rather than compressive stress under the given loading condition. Maximum displacement was found to be 0.0000456105 mm at maximum stress of 0.869492 MPa along XZ axis within a safety factor of 15. This result, suggested that to improve reliability and stability of operation, excessive loading of pump impeller along XZ axis must be avoided. Von Mises stress was found to be 2.103 MPa and yield strength of the assigned material was 228 MPa, which indicated that failure of impeller due to yielding is not possible. Stress concentration was found to be much at the impeller eye, weld heads and tails of blades, as well as rotor edges. The researchers made the following recommendations: Excessive loading of impeller along XZ axis must be avoided to reduce stress and displacement within permissible limit, impeller material must have higher tensile strength rather than compressive strength, since failure due to tensile stress is predominant, etc.

Keywords: *stress, impeller, centrifugal pump, displacement, finite element analysis, turning moment, constraints.*

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I. INTRODUCTION

Mohamed, Moey, Ibrahim, Yazdi, & Merdji (2022) opined that the impeller blade is one of the most critical components in a centrifugal pump that affect the efficiency of the pump, since the fluid passes through it. As a result, the impeller requires as stress and displacement analyses if efficiency must be maximized. The main requirement is to ensure that the impeller blade can withstand the level of stress thereby reducing the chance of blade fracture/failure.

Centrifugal pump is a contrivance which provides energy to a fluid in a fluid system; it assists to increase the pressure energy or kinetic energy, or both of the fluid by converting the mechanical energy of a prime mover or electric motor coupled to its shaft (Rajput, 2008).

An impeller is a wheel or rotor with a series of backward curved vanes or blades and it is mounted on a shaft which is usually coupled to an electric motor.

Nataraj and Singh (2013) stated that the centrifugal pump is a useful rotor dynamic machine in fluid flow arena as it is extensively used in irrigation, industry, large plants, domestic, and river water pumping systems. These pumps are used at places where the requirements of head and discharge are moderate. The operational characteristics of the pump such as power, head, and flow rate mainly depend on impeller geometry.

As the impeller of centrifugal pump is a key component to convert the energy, its reliability and stability has a great influence on the stable operation and pump efficiency. Therefore, it is of paramount to research on the stress, displacement and vibration characteristics of the pump impeller (Wei, Leilei , Weidong , Ling , Xiaoping & Yang, 2015).

There are no doubts that stress and displacement on centrifugal pump impeller influence pump reliability and stability during operation. Review of related literature done by the authors proved that excessive stress and displacement on impeller vanes or blades can ruin or lower pump operational performance and also lower service life of mechanical machine elements in the pump. Hence, the paper aimed at studying finite element analysis of stress and displacement of centrifugal pump impeller model for performance improvement.

II. METHODOLOGY

The researchers considered an open impeller model with assigned material Austenitic Stainless Steel to reduce corrosion and peeling effect as shown in **Figure 1.0.** An open impeller is a type of impeller that has no shrouds to direct the flow of liquid. The diameter of the open impeller is 60 mm; impeller hub diameter is 20mm with central shaft hole of 10mm. Impeller model retained 6 blades with a maintained thickness of 2 mm and height of 3 mm. The radius of impeller at inlet and outlet were 8 mm and 28 mm respectively. The vanes have 80 degrees inlet angle and 130 degrees outlet angle respectively. The impeller model was prepared with the aid of inventor software and imported to; Finite Element Analysis software where stress and displacement were predicted. Impeller model was subjected to turning moment of 100 N mm, angular velocity of 2 deg/s and angular acceleration of $4deg/s^2$ with fixed rotational constraints (See **Table 1.0**).

MESHING

Meshing was used to divide the centrifugal pump impellers into section with nodes of 7474 and elements of 4251. Increasing the number of elements, means more computations and more mathematical formula for the element. Hence, the more precise the results would be. Mesh settings used is shown below. **See Figure 2.0.**

General objective and settings:

Design Objective	Single Point
Study Type	Static Analysis
Last Modification Date	11/11/2022, 11:29 AM
Detect and Eliminate Rigid Body Modes	No

Mesh settings:

Avg. Element Size (fraction of model diameter)	0.1
Min. Element Size (fraction of avg. size)	0.2
Grading Factor	1.5
Max. Turn Angle	60 deg
Create Curved Mesh Elements	Yes

CONSTRAINTS

A fixed constraint was applied at the impeller eye. This applies a constraint where all translational degrees of freedom are fixed and all rotational are free. With a blade fluid remote force of 6.00 N acting at a distance of 2 mm each along X, Y, Z axes, the correct direction of rotation for these impellers is counter-clockwise. See **Figure 3.0.**

Table 1.0: Model Parameters

S/N	NAME	VALUE
1	Diameter of open impeller	60 mm
2	Hub diameter	20 mm
3	Hub hole	10 mm
4	Hub height	8 mm
5	Number of blades	6
6	Thickness of blades	2 mm
7	Height of blades	3 mm
8	Radius of impeller at inlet R1	8 mm
9	Radius of impeller at outlet R2	28 mm
10	Vane inlet angle	80 degrees
11	Vane outlet angle	130 degrees
12	Turning moment	100 N m
13	Angular velocity	2 deg/s
14	Angular acceleration	4 deg/s2
15	Fluid force	6.0 N

DESIGN ANALYSIS/CALCULATIONS
The stress components in an element are given as below.

$(\sigma_x)_n = \frac{E}{(1+v)(1-2v)}[(1-v)a_n + ve_n] \ldots\ldots(1.0)$ (Westmann, 2004)

$$(\sigma_y)_n = \frac{E}{(1+v)(1-2v)}[va_n + (1-v)e_n] \ldots\ldots(1.1)$$

$$(\tau_{xy})_n = \frac{E}{2(1+v)}(b_n + d_n) \ldots\ldots(1.2)$$

$$v = Poisson's\ ratio, E = modulus\ of\ elasticity$$

The displacement field is shown below.

$$a_n = \frac{\partial u_n}{\partial x} \ \ldots(1.3)$$

$$e_n = \frac{\partial v_n}{\partial y} \ \ldots(1.4)$$

$$b_n + d_n = \frac{\partial u_n}{\partial y} + \frac{\partial v_n}{\partial x} \ldots.(1.5)$$

$$v\ and\ u\ are\ velocity\ components\ of\ x\ and\ y$$

The principal strains are given below
$e_x = \frac{1}{E}\left[\sigma_x - \frac{1}{m}(\sigma_y + \sigma_z)\right] \ldots\ldots(1.5.1)$ (Rajput, 2008).

$$e_y = \frac{1}{E}\left[\sigma_y - \frac{1}{m}(\sigma_x + \sigma_z)\right] \ldots\ldots(1.5.2)$$

$$e_z = \frac{1}{E}\left[\sigma_z - \frac{1}{m}(\sigma_x + \sigma_y)\right] \ldots\ldots(1.5.3)$$

Von Mises Stress can be given as below.

$Von - mises\ stress = \sqrt{{\sigma_x}^2} - \sigma_x\sigma_y + {\sigma_y}^2 \ldots.(1.5.4)$

$Angular\ velocity, \omega = \frac{2\pi N}{60}$ rad/s …….(1.6) (Rajput, 2008)

Where N = rpm of rotor;
$$Angular\ speed, \omega = 0.0698\ rad/s$$

$$N = \frac{60\ \times 0.0698}{2\pi} = 0.665 = say\ 2\ rpm$$

$u_1 = tangential\ velocity\ of\ impeller\ at\ inlet = \ \omega R_1$…….. (1.7)

$$u_1 = tangential\ velocity = 0.0698 \times 0.008 = 0.0006\ m/s$$

$u_2 = tangential\ velocity\ of\ impeller\ at\ outlet = \ \omega R_2$ …….(1.8)

$$u_2 = tangential\ velocity = 0.0698 \times 0.028 = 0.002\ m/s$$

$Work\ done\ per\ seconds = Torque \times angular\ velocity$ …… (1.9)

$$Work\ done\ per\ seconds = 100 \times 0.0698 = 6.98\ watts$$

$Discharge = \ \pi D_2 B_2 \times V_{f2}$…… (1.10)

$$B_2 = width\ of\ impeller\ at\ exit$$

$$D_2 = diameter\ of\ impeller\ at\ exit$$

$$V_{f2} = velocity\ of\ flow\ at\ exit = \ u_2$$

$$Discharge = \ \pi \times 0.058 \times 0.003 \times 0.002 = 1.093 \times 10^{-6}\ m^3/s$$

RESULTS AND PRESENTATIONS

⊟Project

Part Number	IMPELLER PUMP 2
Designer	EWURUM TENNISON
Cost	$200.00
Date Created	11/11/2022

⊟Physical

Material	Stainless Steel, Austenitic
Density	8 g/cm^3
Mass	0.181247 kg
Area	8523.25 mm^2
Volume	22655.8 mm^3
Center of Gravity	x=-0.00344626 mm y=4.27672 mm z=0.0445966 mm

⊟Material(s)

Name	Stainless Steel, Austenitic	
General	Mass Density	8 g/cm^3
	Yield Strength	228 MPa
	Ultimate Tensile Strength	540 MPa
Stress	Young's Modulus	190.3 GPa
	Poisson's Ratio	0.305 ul
	Shear Modulus	72.9119 GPa
Part Name(s)	IMPELLER PUMP 2	

⊟Operating conditions

⊟Moment:1

Load Type	Moment
Magnitude	100.000 N mm

Vector X	0.000 N mm
Vector Y	-100.000 N mm
Vector Z	0.000 N mm

⊟Remote Force:1

Load Type	Remote Force
Magnitude	6.000 N
Vector X	0.000 N
Vector Y	6.000 N
Vector Z	0.000 N
Remote Point X	2.000 mm
Remote Point Y	2.000 mm
Remote Point Z	2.000 mm

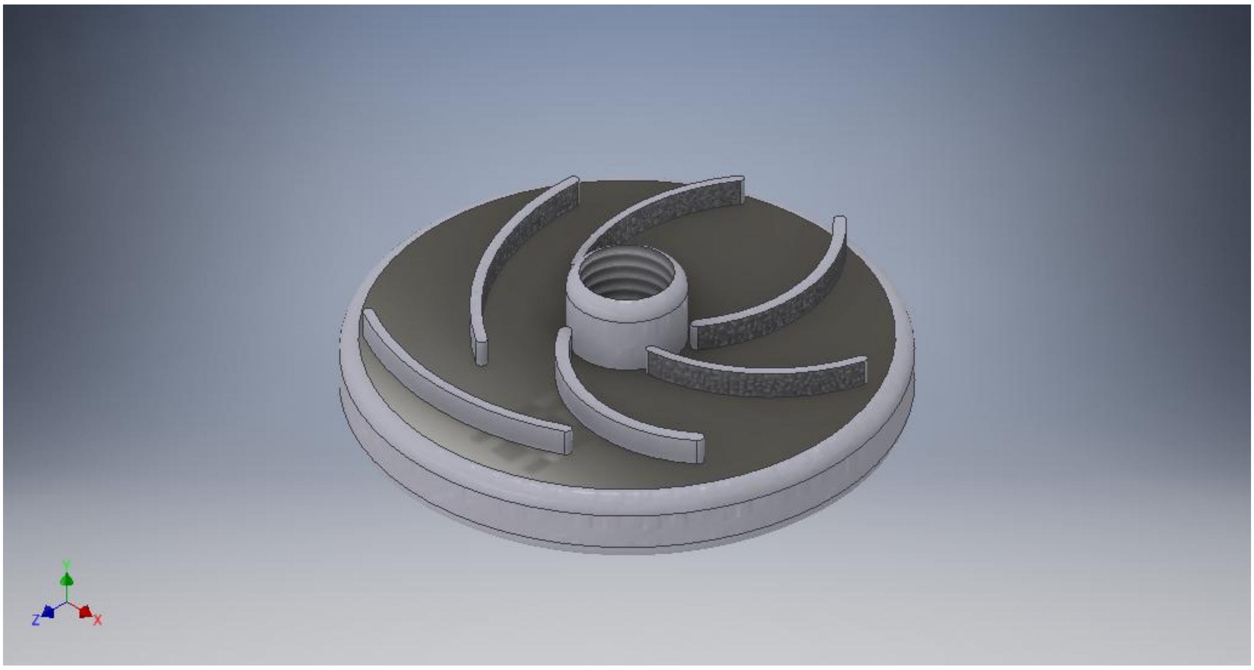

Figure1.0. Open Impeller Model

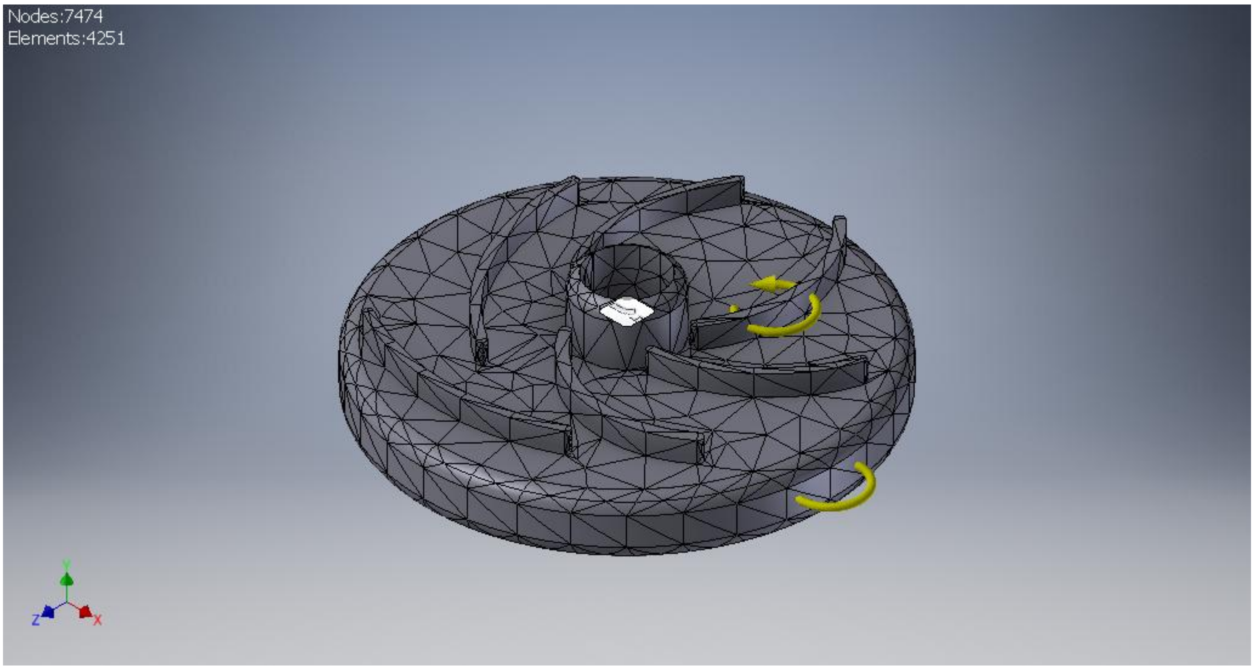

Figure2.0. Meshing of Impeller

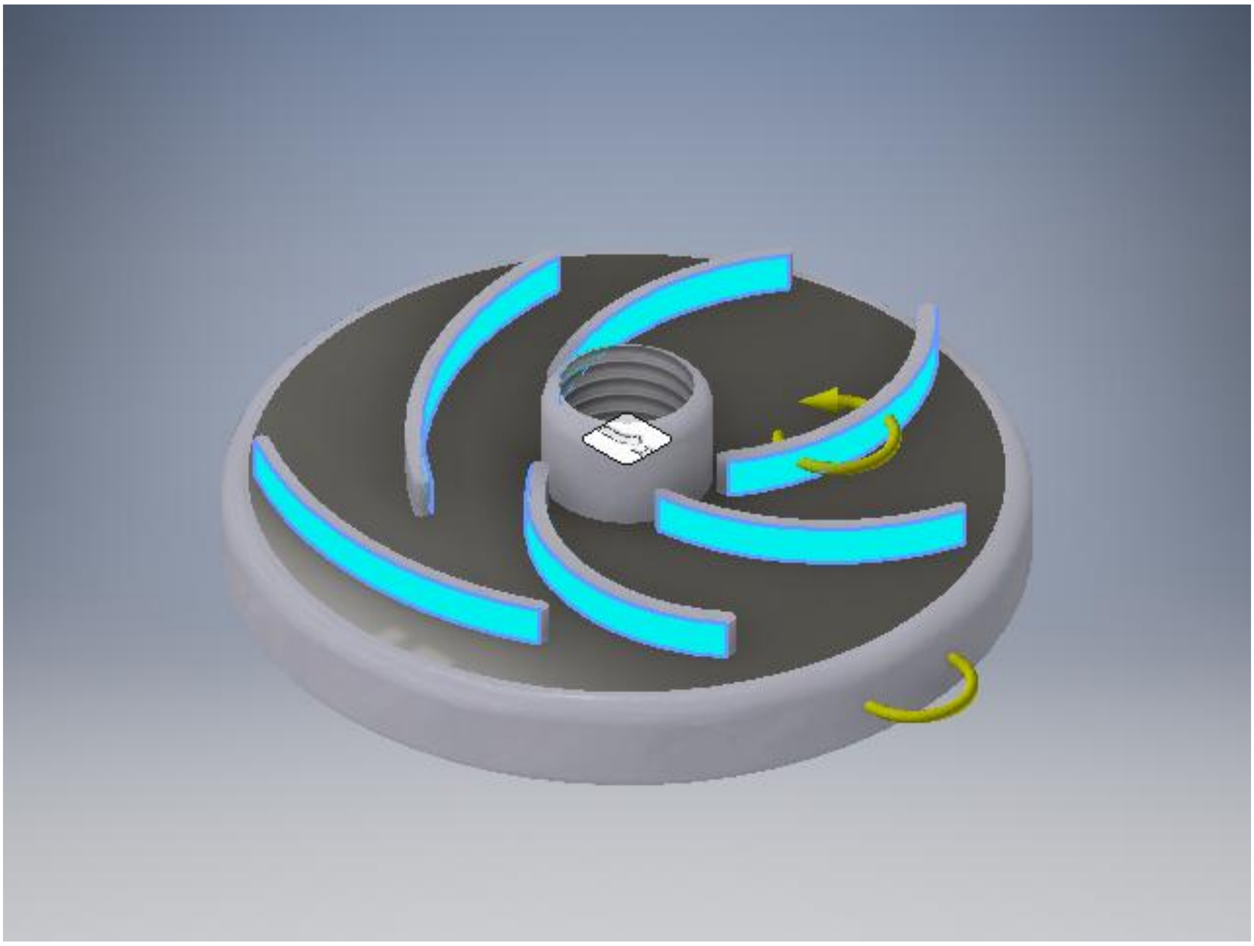

Figure3.0. Constraints and Load on Impeller

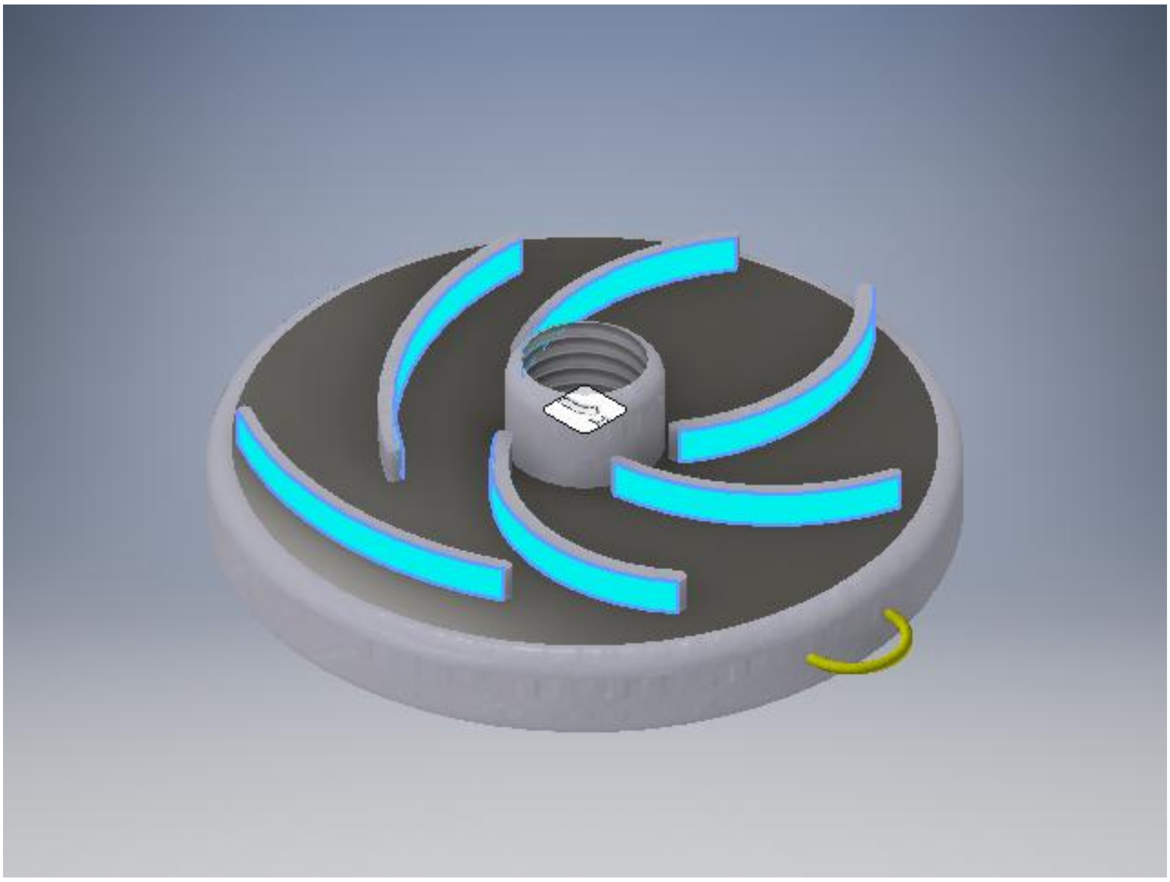

Figure4.0. Impeller Selected Faces.

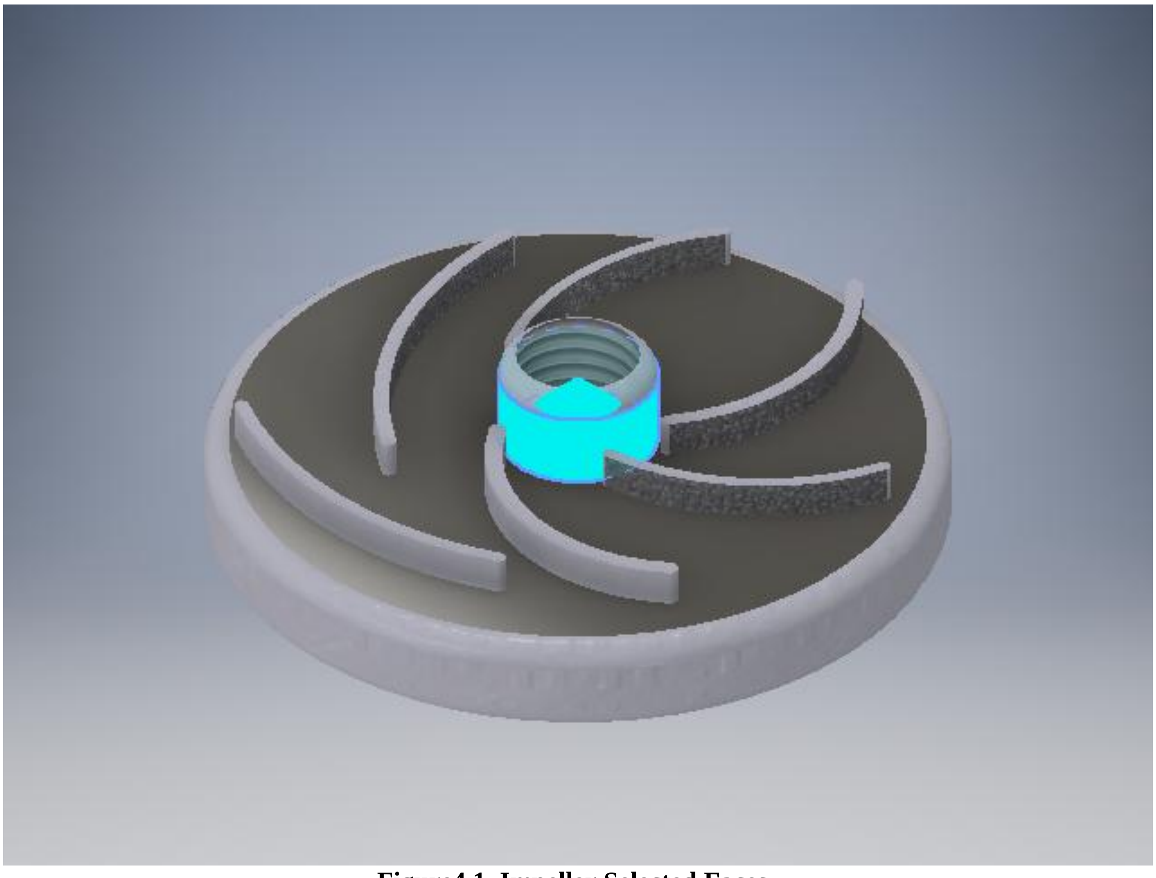

Figure4.1. Impeller Selected Faces.

⊟ Reaction Force and Moment on Constraints

Constraint Name	Reaction Force		Reaction Moment	
	Magnitude	**Component (X,Y,Z)**	**Magnitude**	**Component (X,Y,Z)**
Fixed Constraint:1	5.99972 N	0 N	0.101439 N m	0.0120987 N m
		-5.99972 N		0.0999948 N m
		0 N		-0.0120209 N m

⊟Result Summary

Name	Minimum	Maximum
Volume	22655.8 mm^3	
Mass	0.181247 kg	
Von Mises Stress	0.0000544399 MPa	2.10286 MPa
1st Principal Stress	-0.0523604 MPa	0.437364 MPa
3rd Principal Stress	-2.13875 MPa	0.0221447 MPa
Displacement	0 mm	0.0000456105 mm
Safety Factor	15 ul	15 ul
Stress XX	-1.1538 MPa	0.269114 MPa
Stress XY	-0.171366 MPa	0.470831 MPa
Stress XZ	-0.317356 MPa	0.869492 MPa
Stress YY	-0.835567 MPa	0.108773 MPa
Stress YZ	-0.723186 MPa	0.281149 MPa
Stress ZZ	-0.837131 MPa	0.425031 MPa
X Displacement	-0.0000338274 mm	0.0000362235 mm
Y Displacement	-0.000000141994 mm	0.0000301125 mm
Z Displacement	-0.0000337869 mm	0.0000363587 mm
Equivalent Strain	0.000000000412639 ul	0.00000987019 ul
1st Principal Strain	-0.0000000045899 ul	0.00000494271 ul
3rd Principal Strain	-0.0000109581 ul	0.0000000000179558 ul
Strain XX	-0.00000549455 ul	0.00000237232 ul
Strain XY	-0.00000117516 ul	0.00000322877 ul
Strain XZ	-0.0000021763 ul	0.00000596262 ul
Strain YY	-0.00000202624 ul	0.0000012435 ul
Strain YZ	-0.00000495932 ul	0.000001928 ul
Strain ZZ	-0.00000383579 ul	0.00000383821 ul

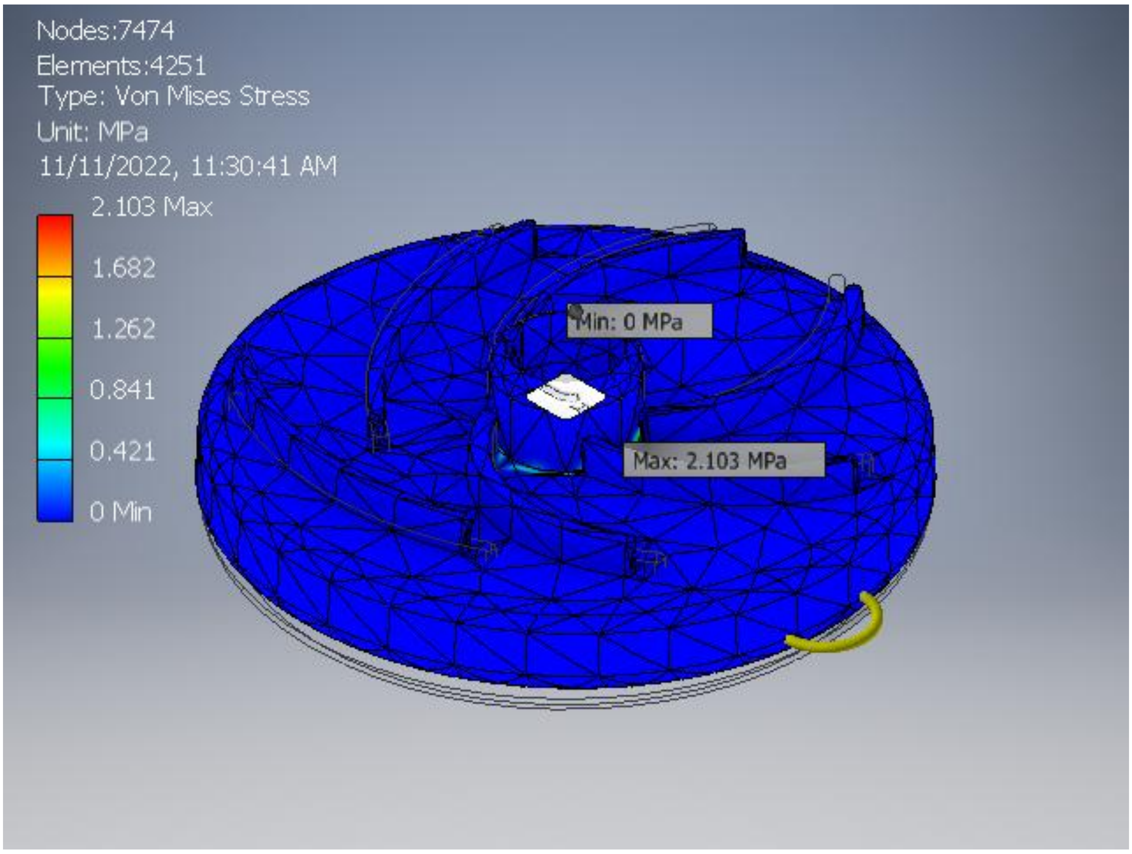

Figure 5.0. Von Mises Stress

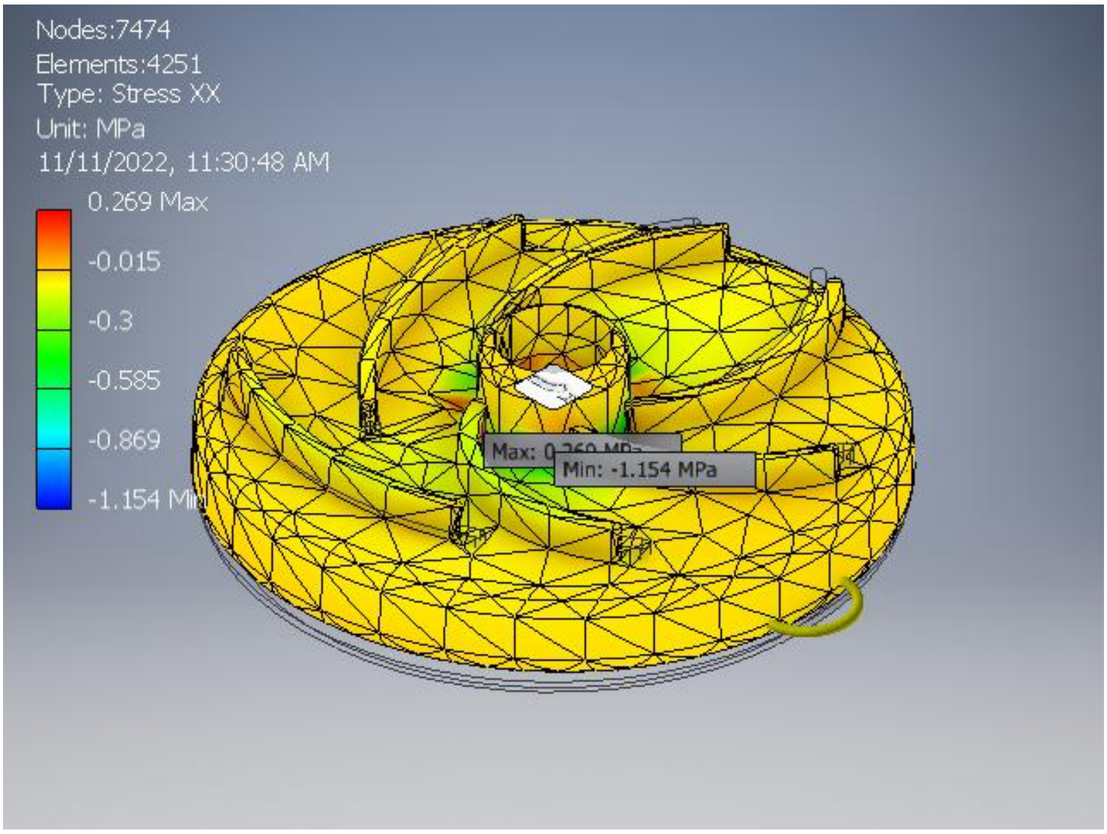

Figure 5.1. Stress along XX

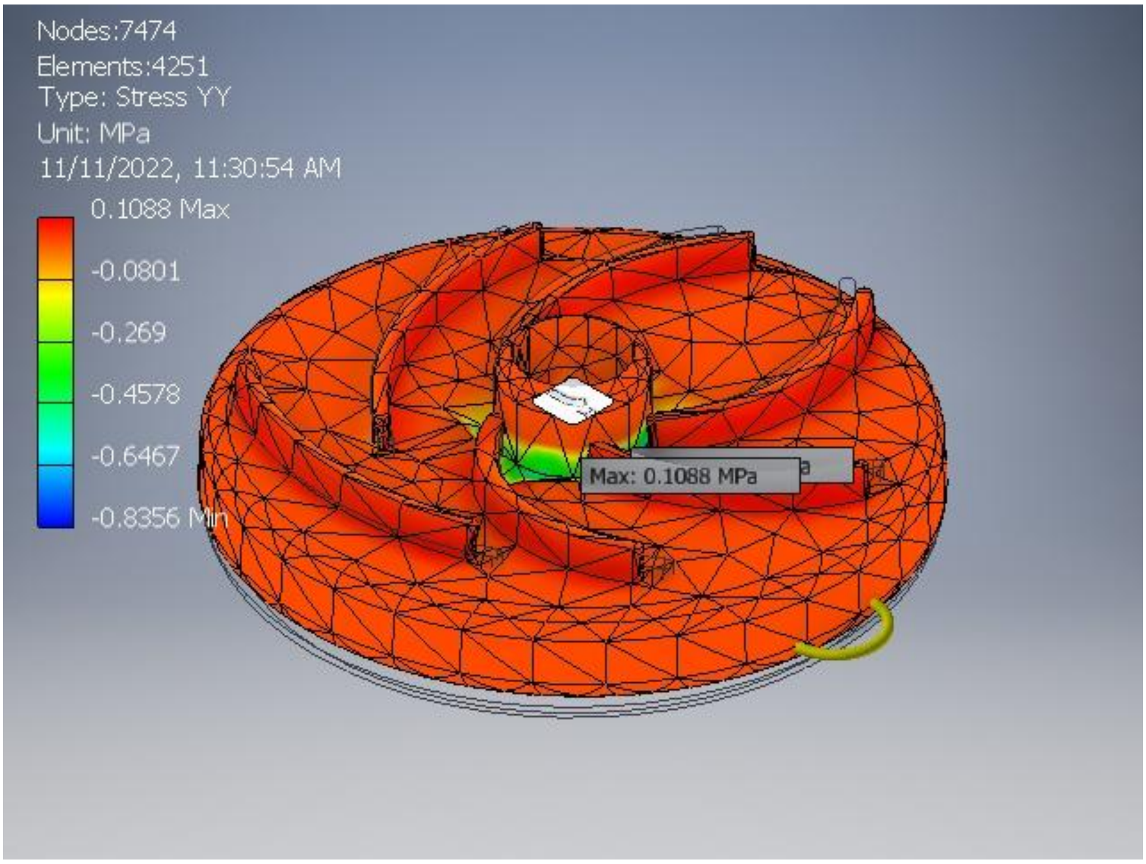

Figure 5.2. Stress along YY

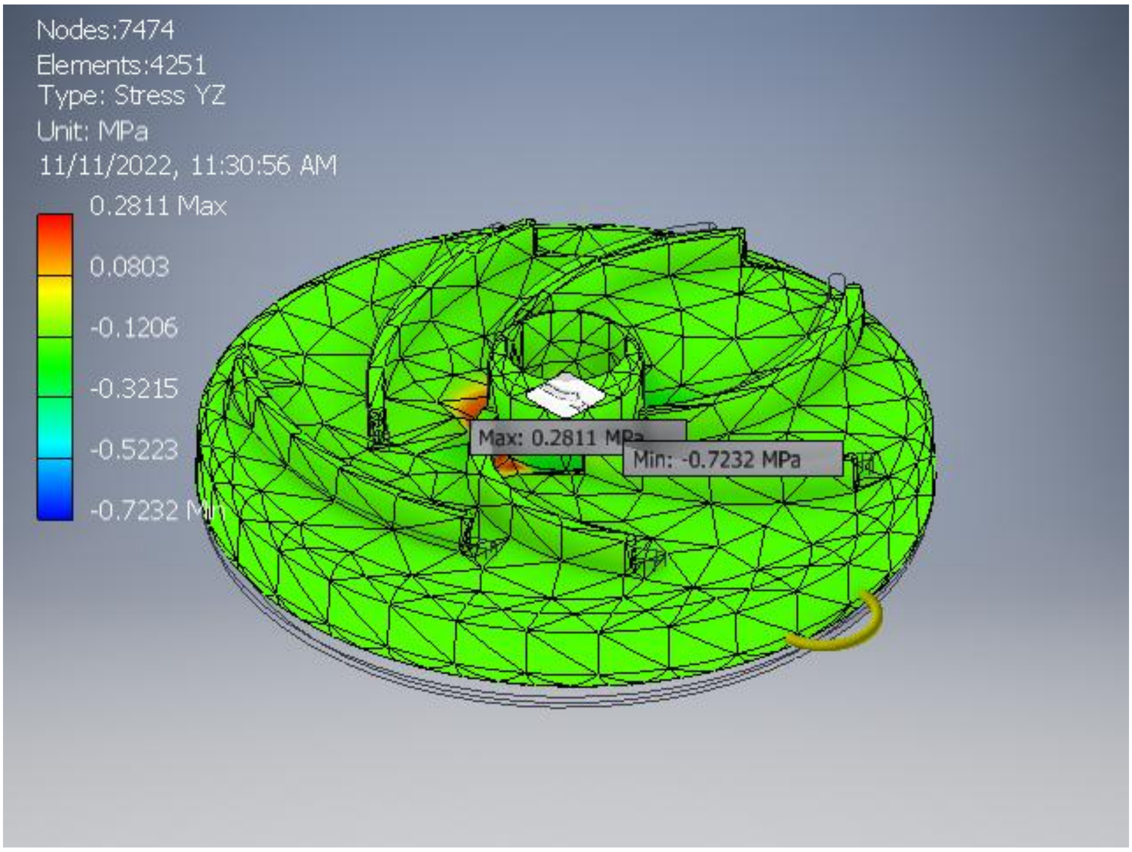

Figure 5.3. Stress along YZ

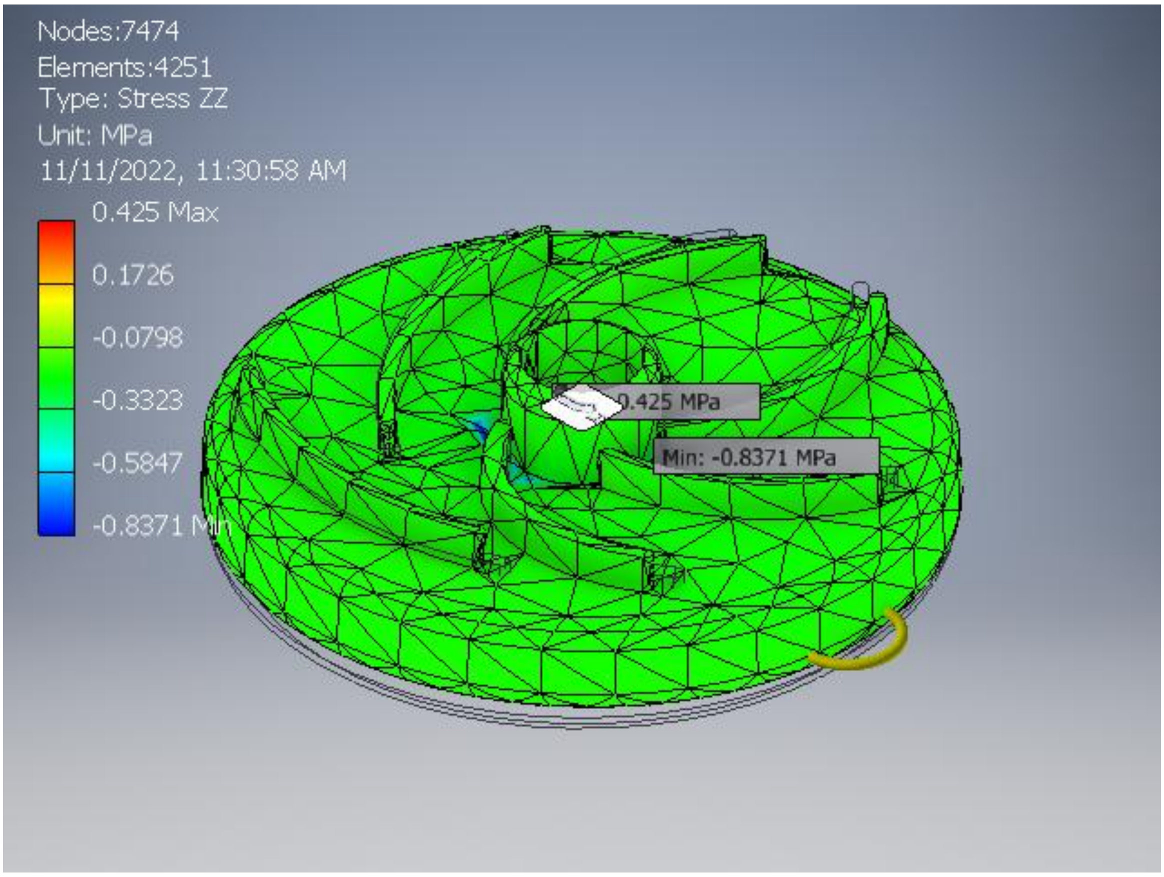

Figure 5.4. Stress along ZZ

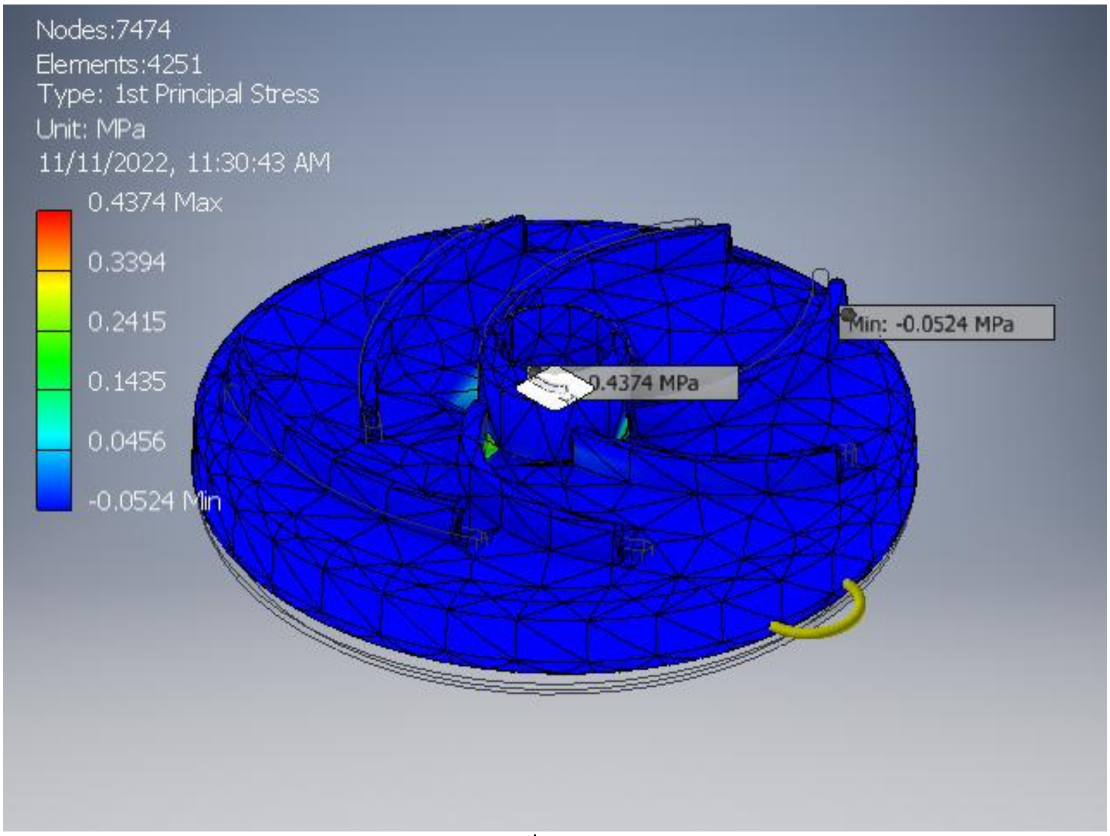

Figure 6.0. 1st Principal Stress

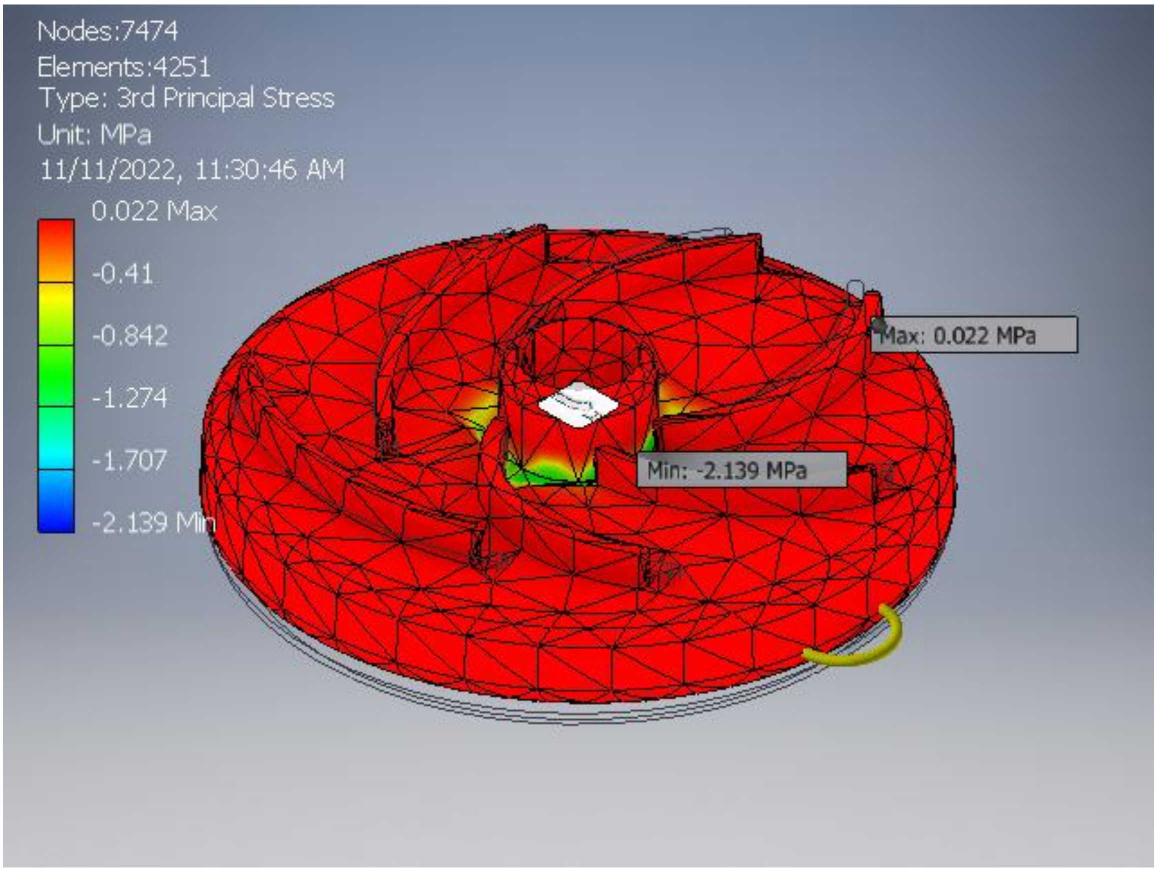

Figure 7.0. 3rd Principal Stress

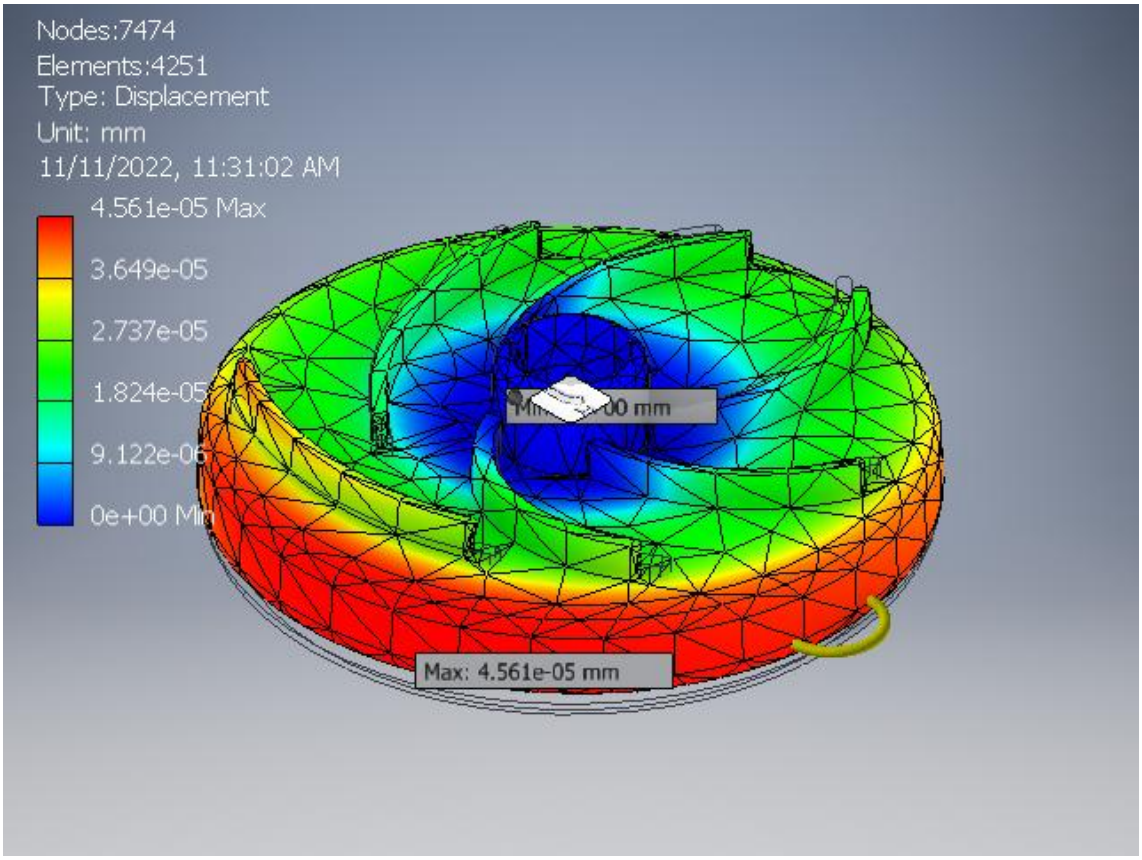

Figure 8.0. Displacement

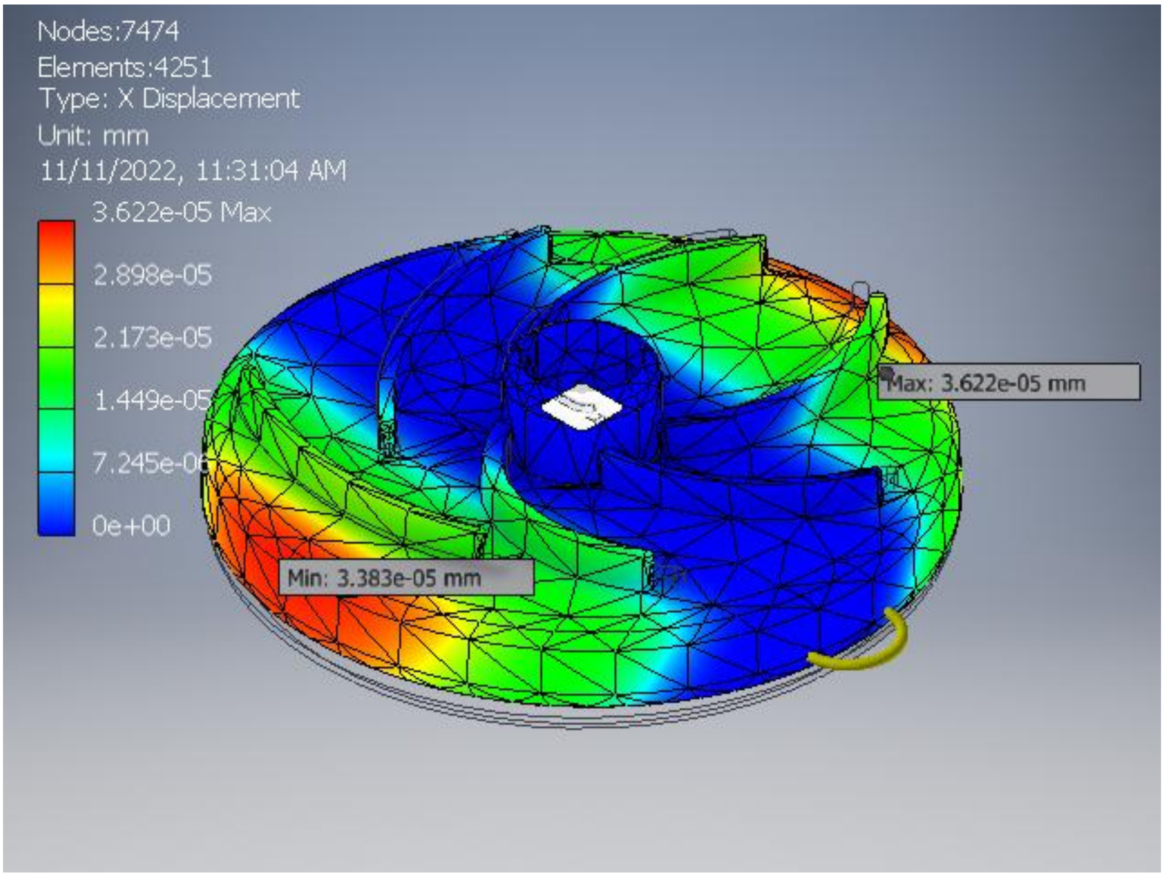

Figure 9.0. Displacement along X

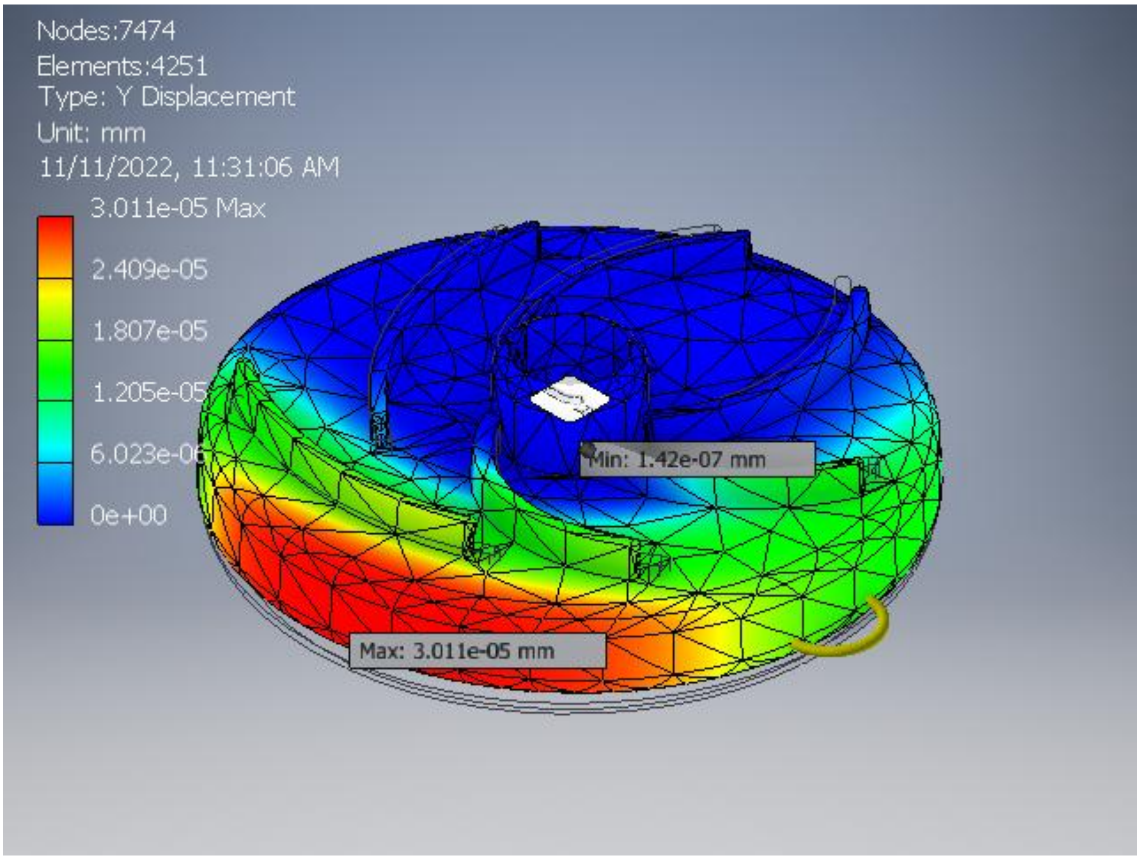

Figure 10.0. Displacement along Y

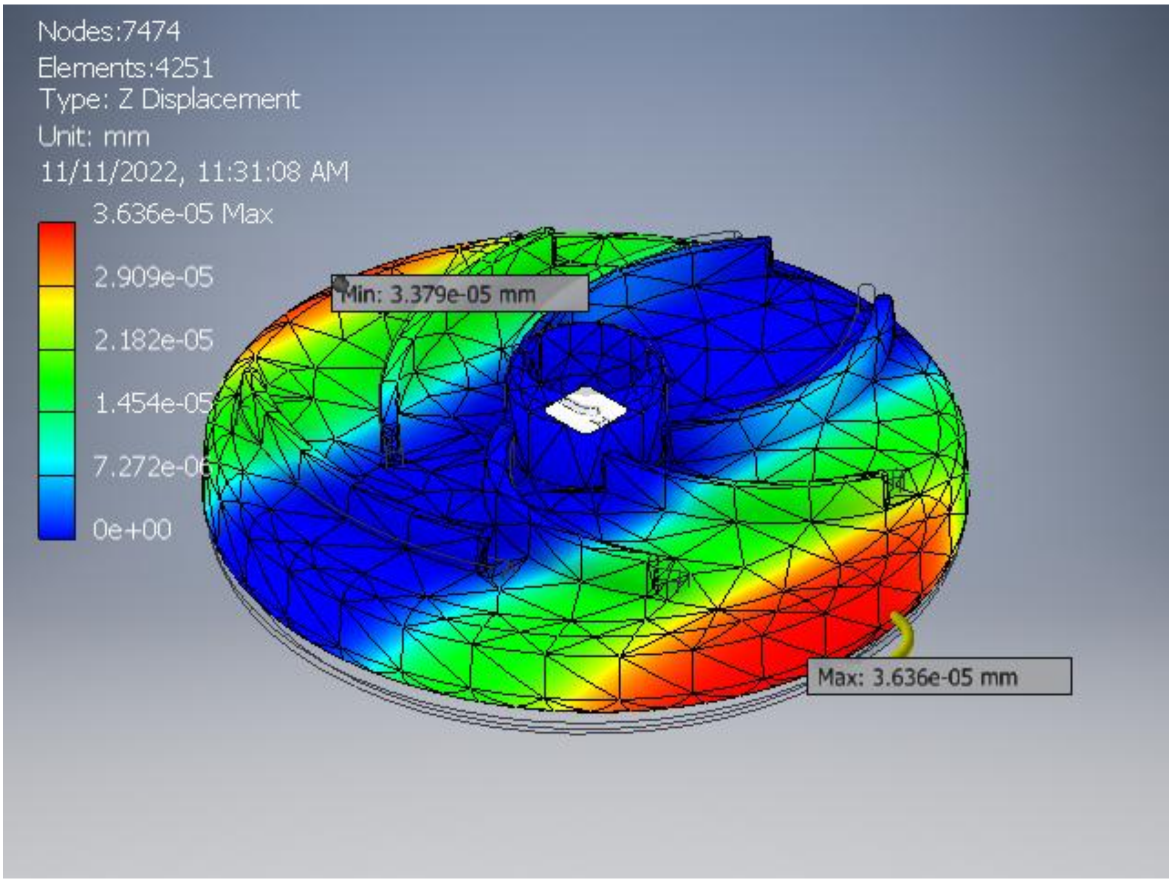

Figure 11.0. Displacement along Z

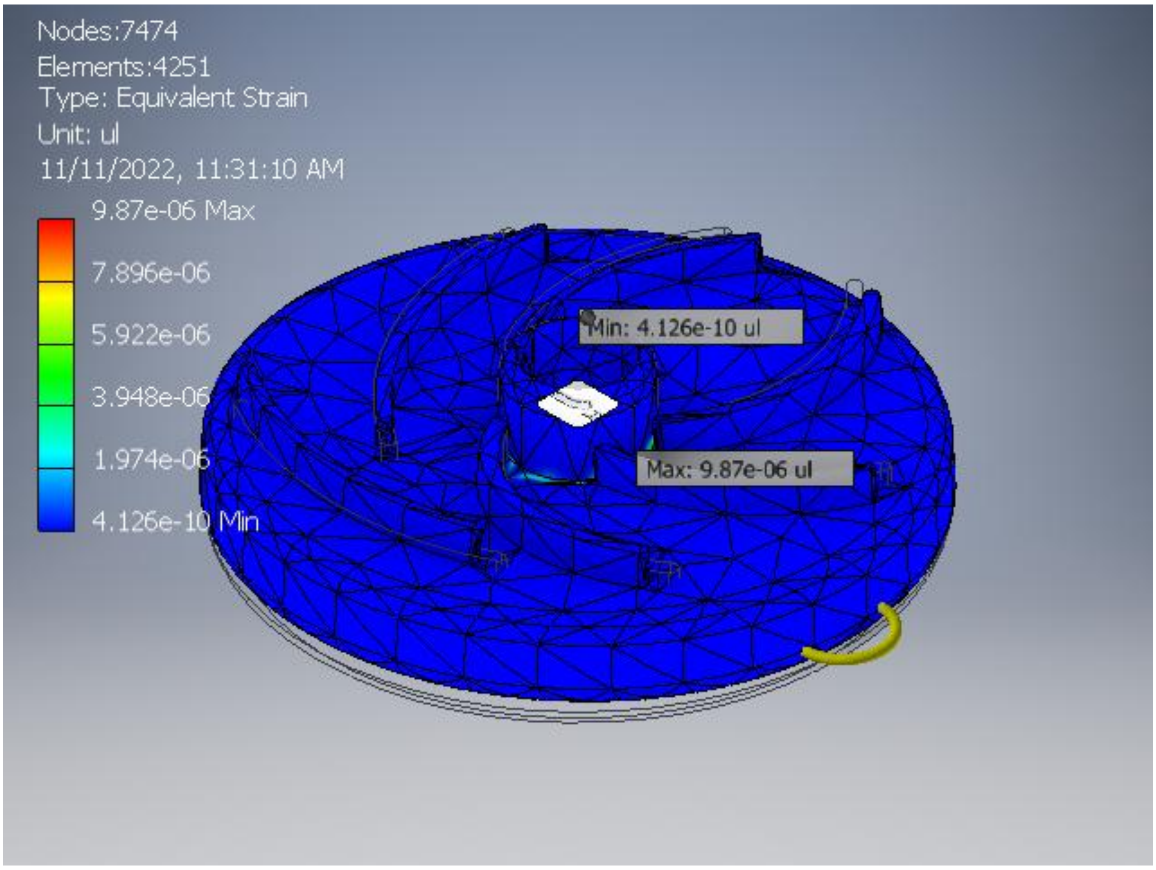

Figure 11.0. Equivalent Strain

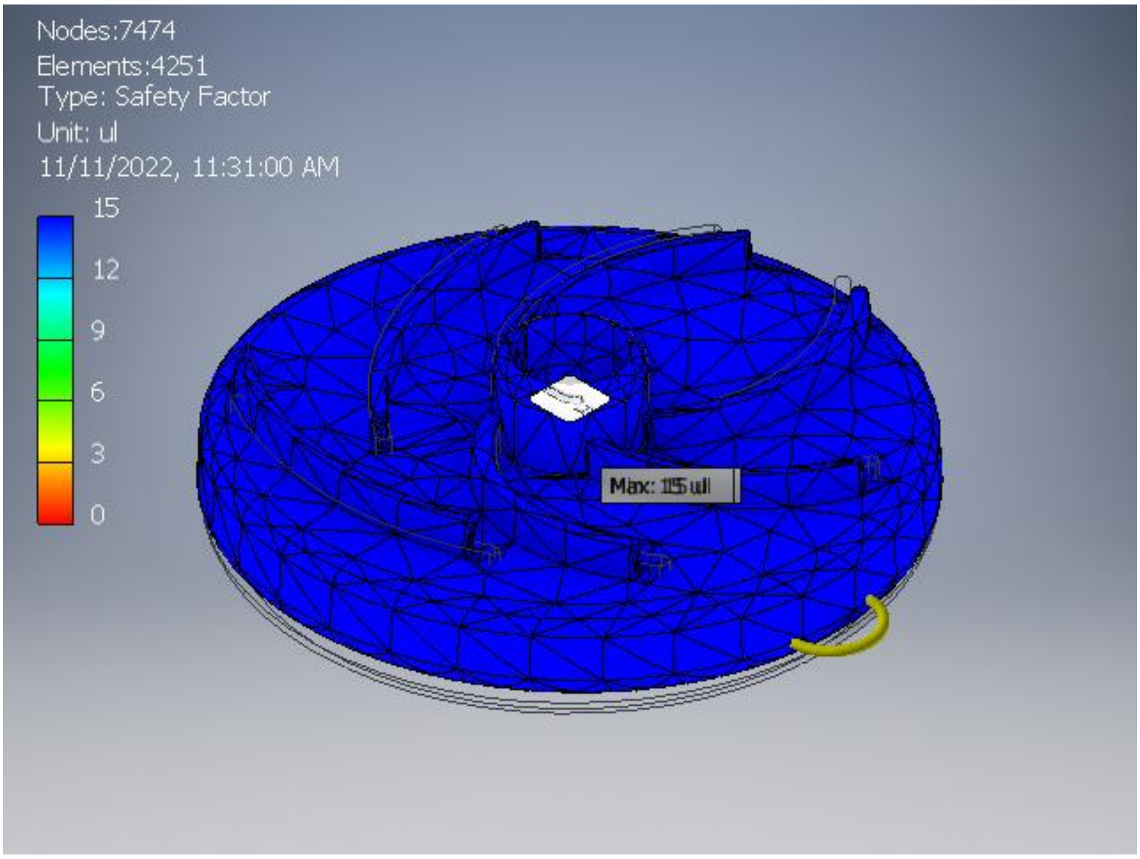

Figure 12.0. Safety Factor

III. DISCUSSION

Finite Element Analysis of stress and displacement of centrifugal pump impeller model for performance improvement was investigated. The diameter of the open impeller model is 60 mm; impeller hub diameter is 20mm with central shaft hole of 10mm. Impeller model retained 6 blades with a maintained thickness of 2 mm and height of 3 mm.

Furthermore, the impeller model was subjected to finite element analysis to predict stress and displacement under turning moment of 100 N mm, fixed rotational constraints, and fluid force of 6.00 N acting on the impeller vanes. Von Mises stress was found to be 2.103 MPa and yield strength of the assigned material was 228 MPa, which indicated that failure of impeller due to yielding is not possible.

Also, maximum 1^{st} and 3^{rd} principal stresses were found to be 0.437364 MPa and 0.0221447 MPa respectively , this suggested that the centrifugal pump impeller failure would be due to tensile stress rather than compressive stress under the given loading condition. In addition, maximum displacement was found to be 0.0000456105 mm at maximum stress of 0.869492 MPa along XZ axis within a safety factor of 15. This result, suggested that to improve reliability and stability of operation, excessive loading of pump impeller along XZ axis must be avoided. Stress concentration was found to be much at the impeller eye, weld heads and tails of blades, as well as rotor edges (See **Figure 5.0 – 12.0**).

IV. CONCLUSION

According to the findings, it can be deduced that the values of stress and displacement acting on centrifugal pump impeller during operation, influences pump reliability and stability and hence, control limits must be set to stabilize pump performance.

V. RECOMMENDATIONS

The following recommendations are suggested based on the study:

1) Excessive loading of impeller along XZ axis must be avoided to reduce stress and displacement within permissible limit.

2) Impeller material must have higher tensile strength rather than compressive strength, since failure due to tensile stress is predominant.

3) This research can also be done in future using different impeller designs and other advanced software for generalization.

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