INVESTIGATION OF SEA WAVE POINT ABSORBER (THE ENERGY CONVERSION SYSTEM).

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JULY 2021

INVESTIGATION OF SEA WAVE POINT ABSORBER (THE ENERGY CONVERSION SYSTEM).

by

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Thesis submitted in fulfilment of the requirements for the degree of Mechanical Engineering.

JULY 2021

ACKNOWLEDGEMENT

I am overwhelmed in all humbleness and gratefulness to acknowledge my depth to all those who have helped and motivated me in completing the final year project. I am able to finish the project with their supports. Thus, I would like to take this occasion to express my gratitude for their generous assistance and support.

First and foremost, I would like to express deepest gratitude to my supervisor, Ir. Dr. Chan Keng Wai as well as the coordinator, Dr. Muhammad Fauzinizam Bin Razali for giving me the golden opportunity to carry out the thesis about Investigation of Sea Wave Pointer Absorber in terms of energy conversion system. Ir. Dr. Chan Keng Wai was always eager to take time out of his busy schedule to discuss with me and give me suggestions on the improvement of my work. It is a pleasure to work on this project under his guidance, and I am grateful for his confidence in me.

Secondly, I would like to thank my friends for their technical support in the simulation guidance for this project. A lot of thanks to them for supporting me throughout this project.

Last but not list, I would like to express my gratitude to my family for their support and affection as I worked on this project.

MUHAMMAD FAWWAZ BIN SHAHBUDDIN
JULY 2021

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LIST OF SYMBOLS

I	Moment of Inertia
ω	Angular velocity
m	Mass of flywheel
r	Radius of flywheel
ρ	Mass density
υ	Poisson's ratio

LIST OF ABBREVIATIONS

WEC	Wave energy converter
PTO	Power take-off
CAD	Computer aided design
USM	Universiti Sains Malaysia

INVESTIGATION OF SEA WAVE POINT ABSORBER (THE ENERGY CONVERSION SYSTEM).

LIST OF APPENDICES

ABSTRAK

Salah satu sumber tenaga alternatif dengan sejumlah besar tenaga adalah tenaga ombak. Walaupun terdapat banyak reka bentuk penyerap tenaga ombak yang dipatenkan, teknologi penuaian tenaga ombak masih belum dikembangkan atau digunakan secara meluas seperti sumber tenaga alternatif lain. Terdapat banyak jenis penukar tenaga gelombang, salah satunya adalah penyerap titik ombak, yang merupakan peranti yang dapat menghasilkan sejumlah besar tenaga. Oleh itu, tujuan projek ini adalah untuk menentukan reka bentuk terbaik penjana penyerap titik ombak berputar dengan tujuan agar reka bentuk dapat mencapai sistem penukaran tenaga yang optimum. Reka bentuk penjana penyerap titik gelombang laut dimodelkan dan dihasilkan menggunakan perisian Solidworks. Komponen utama yang mempengaruhi prestasi penjana untuk reka bentuk ini adalah roda tenaga. Tiga geometri berbeza dipilih untuk reka bentuk roda tenaga. Antaranya adalah geometri keratan rentas segi empat tepat, keratan rentas segitiga dan rim. Selain itu, dua jenis bahan juga digunakan pada roda tenaga, iaitu gray cast iron dan epoxy glass. Kerana pandemi COVID-19, fabrikasi penjana tenaga tidak dapat dihasilkan. Oleh itu, eksperimen terhadap penjana tenaga tidak dapat dijalankan. Projek ini kemudian dilanjutkan ke simulasi menggunakan ANSYS. Dua jenis simulasi dilakukan seperti Static Structural Analysis dan Explicit Dynamic Analysis. Simulasi dilakukan pada geometri yang berbeza dan jenis bahan roda tenaga seperti yang dinyatakan sebelumnya. Kelajuan putaran yang digunakan untuk simulasi ini ialah 100 rpm. Tenaga kinetik roda tenaga diperoleh daripada Analisis Dinamik Eksplisit. Daripada tenaga kinetik yang diperoleh, pengiraan dilakukan untuk menentukan ketumpatan tenaga roda tenaga. Ketumpatan tenaga dari roda tenaga akan menjadi parameter prestasi roda tenaga. Daripada pengiraan, roda gila dengan geometri keratan rentas rim dan diperbuat daripada epoxy glass mempunyai ketumpatan tenaga tertinggi berbanding roda tenaga yang lain.

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ABSTRACT

One of the alternative energy sources with a large amount of energy is wave. Despite the fact that there are numerous patented wave energy absorber designs, wave energy harvesting technology is still not as developed or widely used as other alternative energy sources. There are many different types of wave energy converters, one of which is a point absorber, which is a device that can generate a large amount of energy. Therefore, the purpose of this project is to the determine best design of generator of spinning wave point absorber with the intention that the design can achieves the optimal energy conversion system. The design of sea wave point absorber generator is modelled and generated using Solidworks software. The major component that affects the performance of the generator for this design is flywheel. Three different geometries are chosen for the design of the flywheel. They are rectangular cross-sectional, triangular cross-sectional and rim cross-sectional geometries. Besides that, two types of materials also applied to the flywheel, which are gray cast iron and epoxy glass. Due to pandemic COVID-19, the fabrication of the generator cannot be generated. Thus, the experiment on the generator cannot be conducted. The project is then proceeded to simulation using ANSYS. Two types of simulation are done such as Static Structural Analysis and Explicit Dynamic Analysis. The simulations are done on different geometries and type of material of the flywheel as stated before. The rotational speed used for this simulation is 100 rpm. Kinetic energy of the flywheel is obtained from Explicit Dynamic Analysis. From the acquired kinetic energy, calculation is done to determine the specific energy of the flywheel. The energy density from the flywheel will be the parameter of the flywheel. From the calculation, the flywheel with rim cross-sectional geometry and made of epoxy glass has the highest specific energy.

CHAPTER 1

INTRODUCTION

1.1 Overview

There are two types of energy which are renewable energy and non-renewable energy [1]. Renewable energy is important as the source will not have depletion for a lifetime compared to non-renewable energy. Thus, the global community should not hit the panic button regarding to the run out of energy source with the presence of renewable energy. There are many renewable energy sources. The most common renewable energy sources that are used globally are solar energy, wave energy, geothermal energy, biomass energy, wind energy, etc [2]. For this project, wave energy will be focused compared to the other renewable energy sources. Ocean wave has a huge potential in supplying to the production of electrical energy.

The first time recorded regarding to the energy harvesting from the tide is in 1799 founded by Pierre-Simon Girard. He had the idea to invent a mechanical device that can harvest the energy from the ocean wave. Then, Girard with the help of his son, designed and built the model. The device was capable converting the wave energy to mechanical work to operate sawmills, pumps etc. In the modern world, Japanese naval commander, Yoshio Masuda was a pioneer in wave energy technology. He did a research about the development of wave energy technology development since 1940. The device that Masuda developed was mainly for military purpose. He introduced the navigation buoys that attached to the air turbine [3] . This technology was then called the oscillating water column (OWC). Thanks to them, the development of the wave energy technology is existing and still improving until now.

Nowadays, the device that is usually used in harvesting energy from the ocean wave are sea wave pointer absorber, attenuator and terminator [4]. Point absorber will be more focused for this project. If you realize, sea wave pointer absorber is a device that is left floating in the middle of the sea or ocean [4]. Commonly, the main purpose of this device is for energy harvesting from the ocean wave. The ocean wave can continuously provide the motion enough to ensure the sea wave pointer absorber to operate. There are several types of sea wave pointer absorber. The mechanism of each type may be quite different from each other.

1.2 Project Background

Ocean wave can be a great prospect to be the provider in generating electrical energy. However, the utilization of the ocean wave with the motive of energy harvesting is not within its potential as ocean wave can produce a large amount of energy. Compared to the devices from the other sources, they are far away better in term of the technology development [5].

For this project, sea wave pointer absorber will be studied. This device is commonly used for harvesting wave energy and convert it to electrical energy. Sea wave pointer absorber consists of float or buoy. The motion of the wave will induce the float or buoy to move in vertical axis (oscillating motion). Subsequently, this motion will be converted to the rotational motion by the spiral gears of the system. Then, this rotational motion will drive the hydraulic turbine or generator with the intention of generating electrical energy.

To harvest energy from the ocean wave, the parameters such as simple harmonic motion of the buoy should be studied. The reason is to obtain the optimum oscillation of the buoy itself. This will be contributed to the Power Take-Off (PTO) mechanism. Therefore, the power transmission to the shaft can be achieved optimum [6].

Besides that, the crucial thing for this project is the design of the generator. The generator will be designed so that the effective energy conversion can be achieved. The first trait of the generator design is the rotation of the turbine should be converting from two ways to one way. Next, the rotation should be in one axis rotation which is vertically. The most important thing about the design of the generator is it must be fully sealed. This is to make sure no water can enter the generator. If there is any leakage on the generator, the water that enter will interrupt its operation. Since that, the generator will be less effective.

1.3 Problem Statement

Ocean wave can be a huge capability in providing the production of electrical energy. Since ocean wave is a renewable energy, there should not be a worry about the run out of the energy source. Spinning sea wave pointer absorber is a potential device that can contribute to the harvesting and conversion of energy from the ocean wave. However, there is limited study on the spinning sea wave pointer absorber. Therefore, the aim of this project is to explore the best design of generator that may achieve the optimal energy conversion system.

1.4 Objectives

The purpose of this project is to find out the best design of spinning wave pointer absorber generator with the intention that the design can achieves the optimal energy conversion system.

CHAPTER 2

LITERATURE REVIEW

2.1 Wave Energy Converter

There are three major types of wave energy converter (WEC). Each type of WEC has its significant and function. The design and concept also vary each other. The types of WEC are such as attenuator, point absorber and terminator. Attenuator is a type of WEC that rest parallel to the direction of wave. It is like attenuator itself is ‘riding’ the waves. The example of attenuator WEC type is Pelamis. The second type of WEC is point absorber. Point absorber is a device that is either floats on the surface of the sea water that move up and down (oscillation) based on the motion of the sea wave or it can be submerged exactly under the sea water surface. Point absorber usually has a small dimension depending on the incident wavelength. This type of WEC is quite not affected to the direction of wave because of its size. Next, the terminator WEC is a device that is lie perpendicular to the direction of wave. The example of this type is Salter’s Duck. For this project, the second type of WEC which is point absorber will be more focused [4].

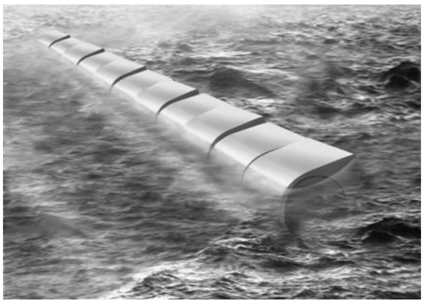


Figure 1: Pelamis WEC and Salter’s Duck.

2.2 Modes of Operation

Besides the types of WEC that mentioned above, there are modes of operation that determine the category of the devices. Submerged pressure differential is one of the modes of operation. This mode is usually used for the point absorber that submerge exactly below the surface of the sea. This kind of point absorber consists of seabed (fix with air-filled cylinder) that is attached to movable upper cylinder. This mode will be operated by the difference in pressure between the wave throughs and crests. The air inside the cylinder of the seabed will be compressed by the water pressure when the wave crest is passing through the device, causing the upper cylinder to move downward. But when the wave through passing through the device, the upper cylinder will move upward because of the decreasing of water pressure. The second operation method is oscillating wave surge converter. The type of WEC that commonly uses this mode is the terminator. The device that compromises with this operation mode consists of a deflector with hinge that is set 90 degrees to the direction of wave. The sea wave will move the hinged-deflector back and this will affect the wave horizontal particle velocity. Oscillating water column is the other mode of operation. The thing that describes this mode is it comprise of a chamber that is exposed to the sea and it lies under the surface of the water. Next is overtopping device. The sea water of the incident waves will be captured by the overtopping device and pass through the reservoir. Then, through turbines, the will released back to the sea [4].

2.3 Challenges for the Wave Energy Converter

There are challenges that may be faced by the point absorber. The identification of these challenges may be good for the technology itself. Improvement of the system can be done to suit the situations [5].

Based on the research paper done by Ellie Al Shami, Ran Zhang and Xu Wang, one of the challenges is the survivability of WEC. The condition of the sea is difficult to predict. The sea wave may be harsh sometimes because of the weather such as heavy storm. The sea wave during this time usually is higher than the normal condition. The large wave can produce a huge force and may damage the WEC when it is hit. Besides that, the various mechanisms of PTO also may be the challenge faced by WEC. The examples of existing PTO mechanisms that are usually used in WEC system are power hydraulics, linear generators, transmission of linear to rotary motion, turbines, etc. The design of the PTO is usually done based on the specific condition. When the season or climate change from time to time, this will be an issue for the PTO as the condition changes [5].

2.4 Types of Existing Wave Energy Converter

There are many types of point absorber. Each type has its own characteristics and design but carry out the same purpose which is harvesting energy.

PS Frog MK5 is one of the many examples of sea wave point absorber. This device is incorporated with a huge paddle that is capable of buoyant, attached to the integral ballasted handle at the bottom part. On top of the device, there is a sliding mass attach to the paddle. The motion of the wave pushes the blade of the paddle, makes the device to swing. The presence of the ballasted handle and the sliding mass will enhance this motion. It can be said that this motion is very looks like pendulum motion. The second example of point absorber is Searev WEC. Roughly, this device also seems like makes swinging motion like pendulum. However, the mechanism of this device is quite different to PS Frog MK5 (Figure 2) [6]. Searev WEC (Figure 3) consists of a heavy wheel that is set in horizontal axis. This component is acting like a reference of internal gravity. This device oscillates like a pendulum because of the center of the gravity of the wheel. The power take-off will be activated by the reason of the pendular wheel rotational motion. These two devices (PS Frog MK5 and Searev WEC) are affected by the degrees of freedom for the pitching [6].

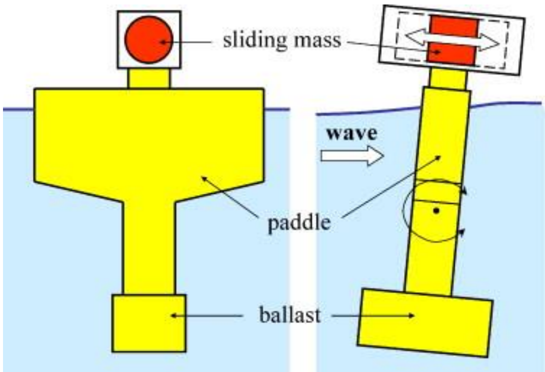


Figure 2: PS Frog MK5.

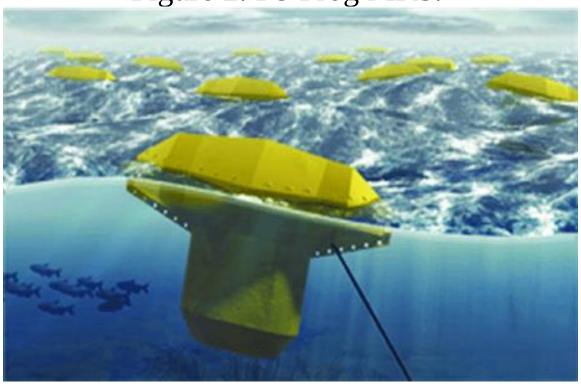


Figure 3: Searev WEC.

Wavebob (Figure 4) is the other example of sea wave point absorber. This device encloses of two bodies that are oscillates within the damping system. To maintain the average wave frequencies, the upper body that is semi-submerged utilizes the mass of the sea water to make it like its majority inertial mass. Within the upper body, there is an inner float together with an outer ring. The inner float heaves slowly imitating the wave motion within the outer ring. Then, the electricity is generated within the high-pressure oil system from the energy produced by the heaving motion [6].

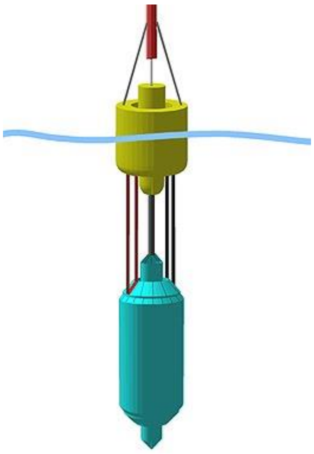


Figure 4: Wavebob.

The next example of point absorber is Aquabuoy (Figure 5). This device comprises of an accelerator tube (large cylinder) and a floater. Within the accelerator tube there is a hose pump that connects the cylinder to the bottom and top part of the buoy. The buoy and the piston will heave simultaneously relative to the sea wave. This motion will make the hose pump to stretch and compress and let the water to pass through Pelton turbine [6].

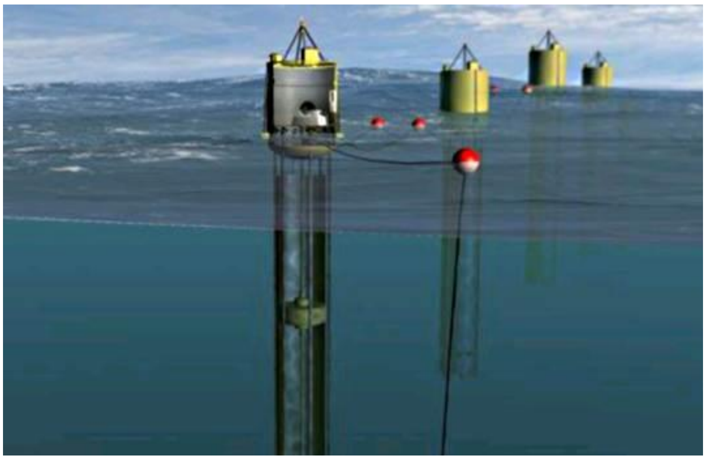


Figure 5: Aquabuoy.

The next sea wave point absorber example is Uppsala (Figure 6). This device consists of a buoy that is connected to the permanent magnet linear generator. There is a spring encloses to the generator translator for the purpose of storing energy besides acting like restoring force when passing through the wave throughs [6].

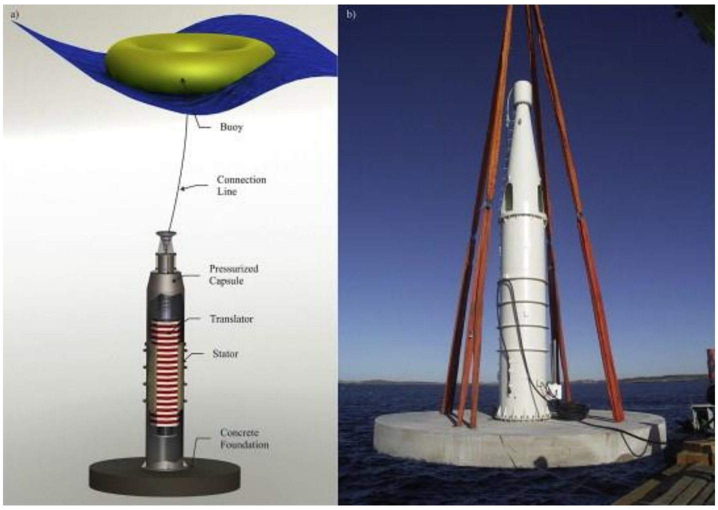


Figure 6: Uppsala.

2.5 Wave Energy Conversion

Power take-off mechanism plays an important role for energy conversion system. Generally, power take-off is a mechanism of capturing power from the source and then transmit it to another component or application. Related to this topic, the wave energy is captured by the WEC and then it is converted to the mechanical energy by the system. Power take-off (PTO) in this situation is the mechanism of converting that mechanical energy to the electrical energy. The power take-off system consists of two major classes. They are direct drive system and buffered system [6].

For direct drive system, the part of WEC that is movable will be connected directly to moving part of the electrical generator. This will make both parts are moving simultaneously. Thus, the motion of mechanical devices that is intermediate between the needed system for the power take-off mechanism will be eliminated. In a buffered drive system, the WEC system will harvest the wave energy, and then it is stored temporarily before it is transferred to the generator for production of electrical energy [6].

The behavior of the ocean can affect the PTO mechanism itself. The production of output power is depending on the PTO. Since that, the output power produced may be differ influenced by the behavior of the ocean. Thus, the energy capacity storage should be more several times from the nominal output power. As the behavior of the ocean cannot be predicted, the flux produce may be differ based on the situation. The PTO mechanism normally designed for consistent condition. Therefore, the process of generating output power will be disrupted [6].

Usually, PTO system consists of a flywheel. The existence of this device is to make sure the PTO mechanism can produce consistent rotation and speed. Besides that, the system should consider the use of asynchronous generator because power can be still generated by this device although from inconsistent speed rotation. Yet, the conditioning power output should be under proper control for the utilization of asynchronous generator. This is to make sure the system will not be damaged due to overspeed of PTO mechanism [6].

2.6 Flywheel.

The presence of flywheel is important in the generator of sea wave point absorber. It is mechanical device that rotates with the purpose of storing the rotational energy. There are two intentions of utilization of flywheel in any design. The first reason is to provide continuous energy as the energy source is in discontinuous state. Secondly is to supply the energy surpassing the continuous energy source ability [7].

The uncertain condition of the sea wave will produce an intermittent output. Since that, utilization of flywheel is aimed for storing energy within the period of high system energy with the purpose of development of power still can be done for a time being yet the end of the input load cycle. The rotational motion of the accelerating flywheel will produce kinetic energy. This kinetic energy is then stored in the flywheel energy storage.

Then, the stored energy will be transmitted to the generator for the purpose of generating power. Upon the generator receiving the stored energy, the operation of flywheel will be slowed down as the energy is drawn from the flywheel energy storage system. The utilization of the flywheel in sea wave point absorber will bring the advantage of smoothing the power output profile as the discontinuous input in a power production system provided by the flywheel energy storage system [8].

Here are the equations of kinetic energy from rotating flywheel:

$$E_{kinetic} = \frac{1}{2} I . \omega^2 \qquad (1)$$

Where,

I = Moment of Inertia,

ω = Angular velocity,

As the flywheel is solid and cylindrical, Moment of Inertia is given by,

$I_{disk} = \frac{1}{2}m.r^2$ (2)

Where,

m = mass of the flywheel,

r = radius of the flywheel.

$E_{kinetic}$ is divided by mass to obtain specific kinetic energy, $E_{kinetic,m}$.

$E_{kinetic,m} = \frac{1}{4}r^2.\omega^2$ (3)

To get the energy density of the flywheel, the mass density, ρ will be multiplied to the specific energy, $E_{kinetic,m}$.

$E_{density} = \frac{1}{4}\rho r^2.\omega^2$ (4)

There are two parameters in designing the flywheel. The first parameter of flywheel design is the flywheel material. The flywheel material can be categorized to two classes. The material of the first class is advanced composite material. The examples of the first class are graphite and carbon-fibre. The high strength-to-weight ratio is the major characteristic of this class. The flywheel of the second category commonly has the main structural made of steel. The flywheel from this class is like the conventional flywheel (slow rotation, large diameter etc.) but has a better performance. The second parameter in designing flywheel is the geometry of the flywheel. The geometry such as shape or specific design of the flywheel will influence its rotational speed. Thus, the stored kinetic energy and the specific energy produced will be also affected [9]. There is a characteristic that affect the specific energy produced such as shape factor [8]. Different flywheel geometry gives different shape factor. Furthermore, the specific energy produced also different depends on the geometry of the flywheel.

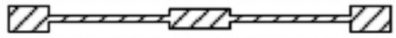
Flywheel geometry	Cross sectional/pictorial view	Shape factor K_s
Flat unpierced disc		0.61
Thin rim		0.50
Rim with web		0.40
Flat pierced disc		0.31

Table 1: The geometry of flywheel and shape factor.

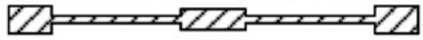
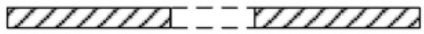
Flywheel geometry	Cross sectional/pictorial view	Specific energy E_{sp}
Thin rim		
Rim with web		
Flat unpierced disc		
Flat pierced disc		worst

Table 2: The performance of specific energy produced by different geometry of flywheel.

Maximum tangential stress for cylindrical shaped flywheel is given by,

$$S_m = \frac{3+\upsilon}{9}\rho\omega^2 r^2 \qquad (5)$$

Where υ is Poisson's ratio. From Eq. (5), the specific energy density is given by,

$$E_{specific} = \frac{2S_m}{\rho(3+\upsilon)} \qquad (6)$$

2.7 Bearing

Bearing is an important component for spinning rotor as a lubrication. Two types of bearing are commonly used in spinning rotor. They are magnetic bearing and ball bearing. Several aspects need to be considered to utilize to the system. They are such as life cycle, losses, weight, and cost. The significant of utilizing magnetic bearing is the rotor has a potential of spinning with high-speed rotation. However, the high-speed spinning rotor will cause a large disparity for induced vibration. Anyway, the ball bearing is highly advantage in material. In term of weight, the ball bearing is more advance compared to magnetic bearing due to relatively low losses generated caused by drag [9].

CHAPTER 3

METHODOLOGY

3.1 Process flow chart

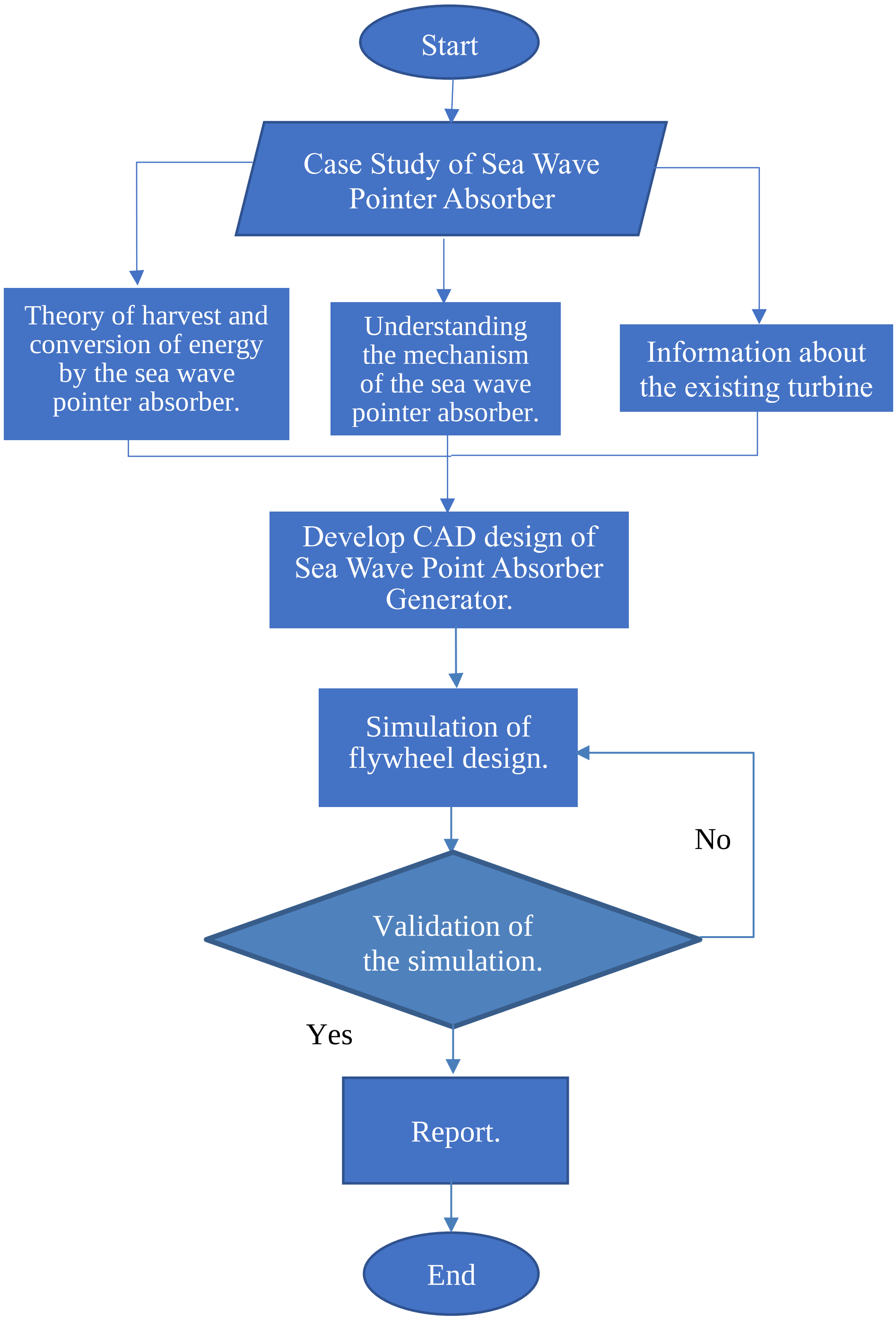


Figure 7: Project flowchart

Figure above shows the flow chart of the project. The project begins with the case study of sea wave pointer absorber. This process is done to achieve more understanding about the theory energy harvesting and conversion and working mechanism of the sea wave point absorber. The information related to generator also studied for this project. The project is then followed by the CAD design of sea wave point absorber generator. SOLIDWORKS software is chosen for the development of the generator design. After the sea wave point absorber generator design has been generated, the simulation is conducted on different geometries and materials of the flywheel using ANSYS software. Two types of simulation have been run which are Static Structural analysis and Explicit Dynamic analysis [10]. The results from the simulation will be validated. Simulation will be checked again if the results are not as expected. After that, improvement of design and simulation may be performed based on the generator performance. The project is then proceeded to report if no issues on the processes before.

3.2 Case study

Case study about sea wave point absorber is crucial for this project. Journals and research papers are referred to gain more understanding on the device itself. Further information such as wave energy converter (WEC) types, modes of operation, wave energy conversion, flywheel design and bearing used have been mentioned in Chapter 2: Literature Review.

3.3 Design of sea wave point absorber generator

The design of generator is constructed using CAD software which is SOLIDWORKS. The design of the generator consists of several components. The list of the CAD components can be referred to Table 3. They are such as shaft, flywheel, casing, motor, lid and bearing. The generator is fully sealed to make sure no water can enter the system, so that the flywheel can rotate smoothly. Thus, the generator performance can be maintained.

CAD Parts.	• Case. • Bearing.

	• Lid. • Flywheel. • Shaft. • Motor.

Table 3: CAD parts of generator

For this project, the flywheel geometry will be the manipulated variable. Thus, three different geometries of flywheel are generated. They are such as rectangular cross-sectional geometry, triangular cross-sectional geometry, and rim cross-sectional geometry (Figure 8). All CAD parts are drawn except bearings. The bearings are imported from Toolbox in Design Library in SOLIDWORKS Assembly. The type of bearing selected is radial ball bearing with 83 mm outer diameter and 30 mm inner diameter. The radial ball bearings are inserted below the lid and top of the motor of the generator (Figure 9). The assembly of the generator can be referred in Figure 10.

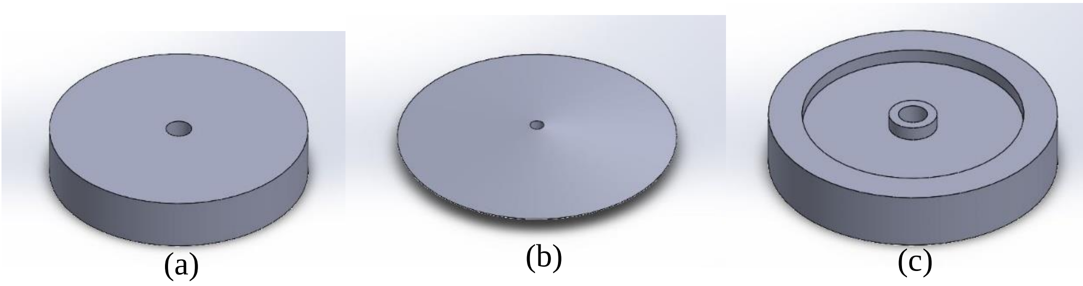


Figure 8: Different geometries of flywheel. (a) Rectangular cross-sectional, (b) Triangular cross-sectional and (c) Rim cross-sectional.

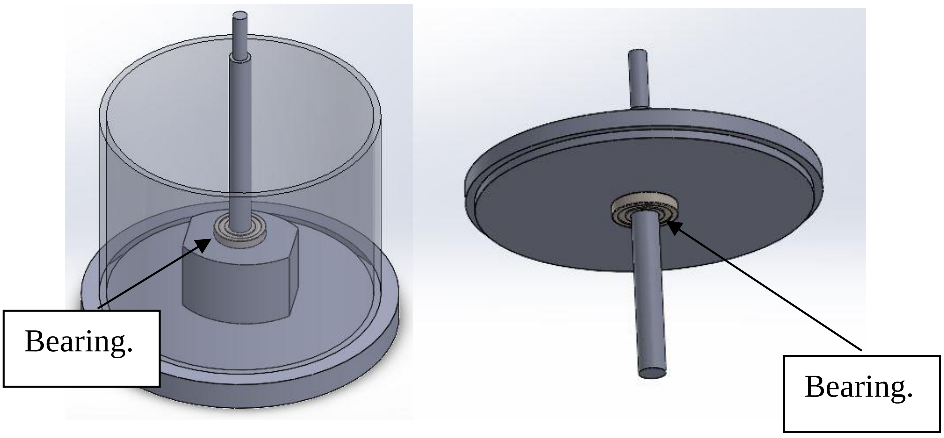


Figure 9: Position of ball bearings in the assembly.

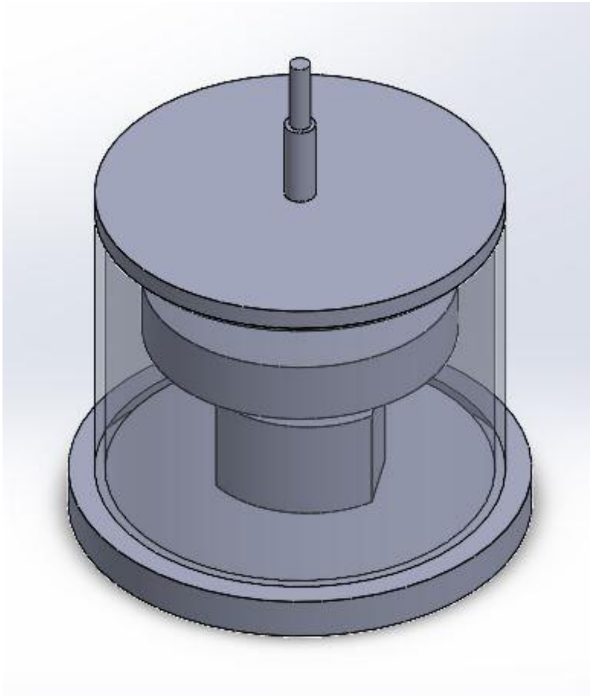


Figure 10: Assembly of the generator.

3.4 Simulation

Two software which are SOLIDWORKS and ANSYS are used for the simulation. Motion analysis is conducted using SOLIDWORKS. Meanwhile, two types of simulation are generated using ANSYS Workbench. They are such as Static Structural Analysis and Explicit Dynamic Analysis. The utilization of Static Structural Analysis is to determine the finite element analysis such as equivalent stress and equivalent elastic strain. Explicit Dynamic Analysis is employed to determine the Kinetic Energy in the flywheel [10].

The simulations are then validated. This is to make sure the results of the simulation suit the expectation of the supervisor. If the results are not accepted, the simulation will be reviewed again. There will be change in boundary condition or steps in doing the simulation again.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Sea wave point absorber generator

As stated in Chapter 3: Methodology, the sea wave pointer absorber must be fully sealed. The reason is to make sure the water cannot enter the system. The drag from water will cause implication for the flywheel performance. As the generator is fully sealed, the flywheel will face minimum drag as the absence of additional drag from the water. Thus, the flywheel can rotate smoothly and longer.

The type of bearing that often used in generator that consist of flywheel is usually magnetic bearing and ball bearing. For this project, ball bearing is chosen to be part of the system. This is because the flywheel will rotate continuously due to simple harmonic motion of the wave. The ball bearing has longer life cycle compared to magnetic bearing. Besides that, the weight of the ball bearing is much low compared to the magnetic bearing. Thus, it will produce lower drag compared to the utilization of magnetic bearing as lubricants. Furthermore, the performance of magnetic bearing will decrease by time. Hence, the magnetic bearing need to be replaced more frequent compared to long lasting ball bearing. Thus, the maintenance of using magnetic bearing will be higher compared to ball bearing.

The generator of sea wave point absorber is fully submerged. There is an air space in the generator since it is fully sealed. Since that, the buoyant force will produce upward force. The additional weight will be attached to the generator enough for the buoy of sea wave point absorber.

4.2 Flywheel

4.2.1 Finite element analysis

Angular velocity = 100 rpm

Material: Gray Cast Iron.

Geometry (cross-sectional)		Rectangular	Triangular	Rim
Equivalent Stress (Pa)	Min	3029.1	5881.9	1258.3
	Max	14154	14154	9157.4
Equivalent Elastic Strain (m/m)	Min	2.7730E-08	5.61340E-08	2.3056E-08
	Max	1.2999E-07	1.2917E-07	8.3803E-08

Table 4: Result of finite element analysis for gray cast iron material.

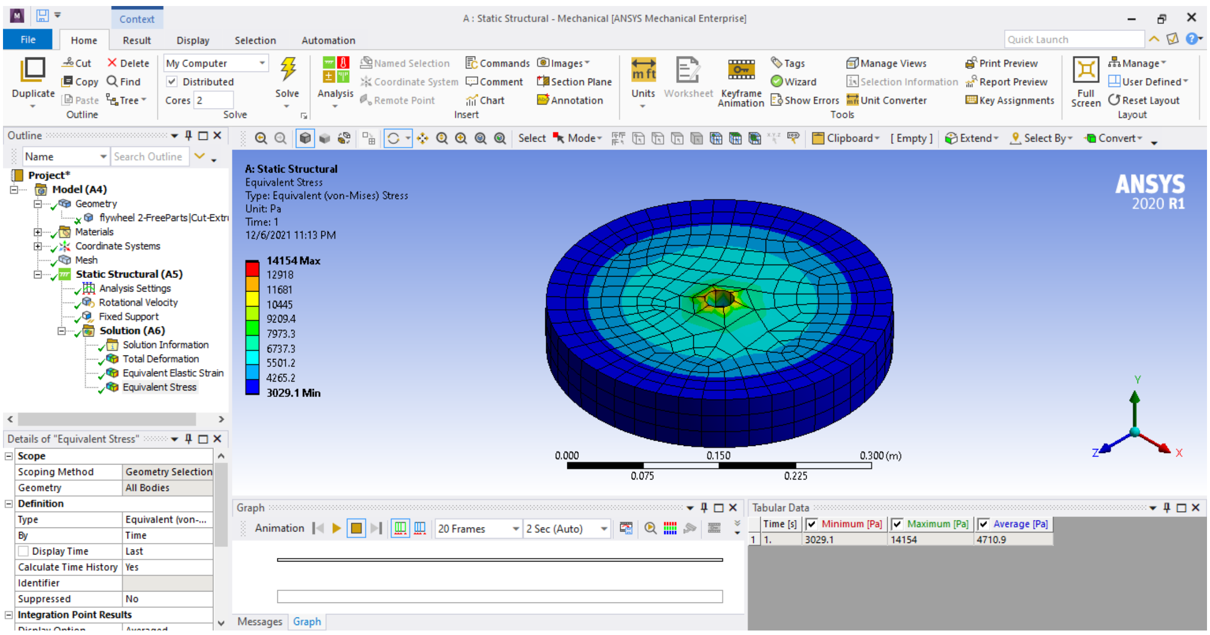


Figure 11: Equivalent stress distribution for Rectangular Cross-Sectional for gray cast iron material.

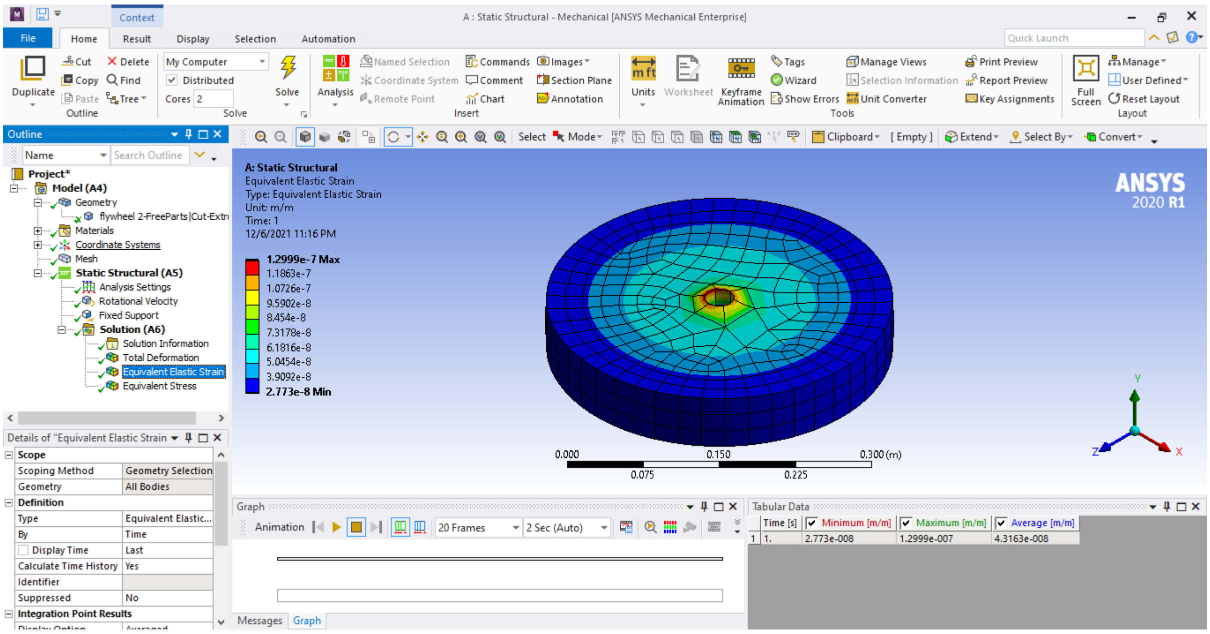


Figure 12: Equivalent elastic strain distribution for Rectangular Cross-Sectional for gray cast iron material.

The colour of the contour represents the amount of equivalent stress acts on the flywheel. The amount of equivalent stress increasing from blue colour to red colour. Based on Figure 11, it can be seen that the highest equivalent stress (14154 Pa) is at the center of the flywheel, meanwhile the lowest equivalent stress is 3029.1 Pa at near the edge of the flywheel. The colour of the contour can also be applied for equivalent elastic strain. The amount of equivalent elastic strain increasing from blue colour to red colour. Based on Figure 12, it can be seen that the highest equivalent elastic strain (1.2999E-7 m/m) is at the center of the flywheel, meanwhile the lowest equivalent stress is 2.773E-8 m/m at near the edge of the flywheel.

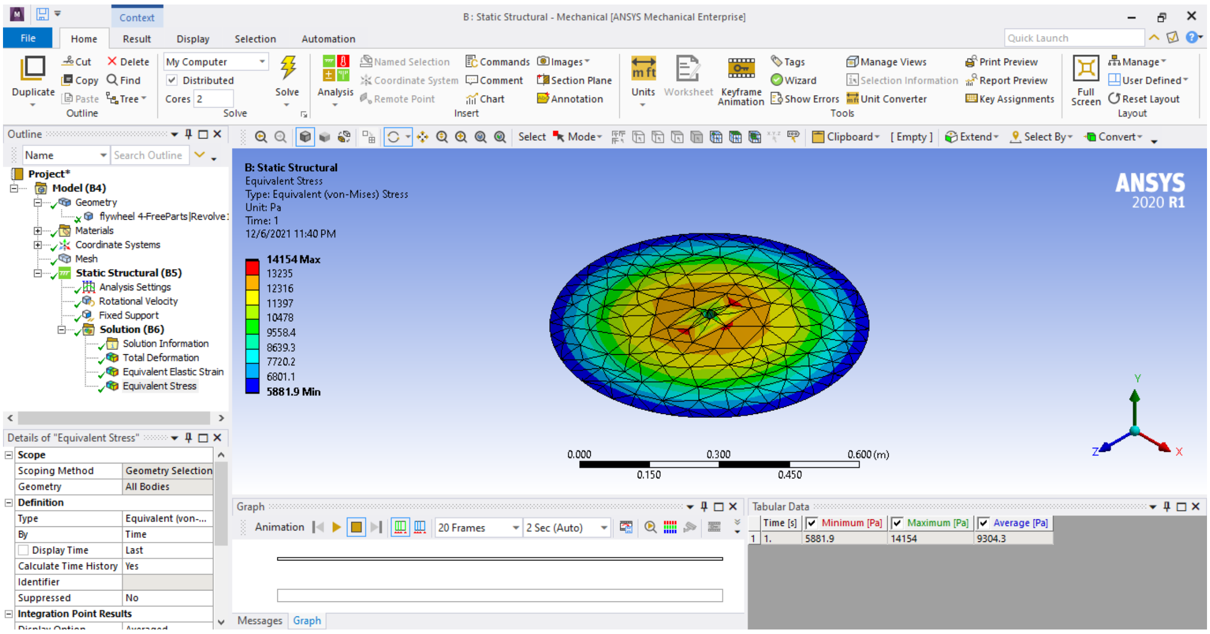


Figure 13: Equivalent stress distribution for Triangular Cross-Sectional for gray cast iron material.

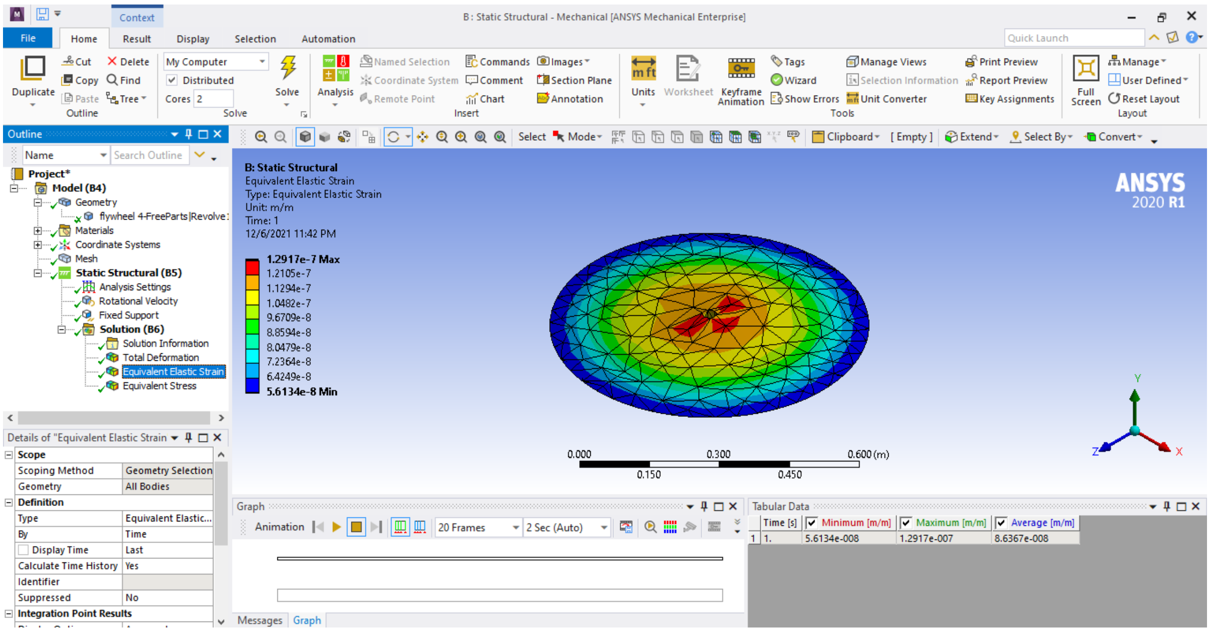


Figure 14: Equivalent elastic strain distribution for Triangular Cross-Sectional for gray cast iron material.

Based on Figure 13, it can be seen that the highest equivalent stress (14154 Pa) is at the center of the flywheel, meanwhile the lowest equivalent stress is 5881.9 Pa at near the edge of the flywheel. The colour of the contour can also be applied for equivalent elastic strain. The amount of equivalent elastic strain increasing from blue colour to red colour. Based on Figure 14, it can be seen that the highest equivalent elastic strain (1.2917E-7 m/m) is at the center of the flywheel, meanwhile the lowest equivalent stress is 5.6134E-8 m/m at near the edge of the flywheel.

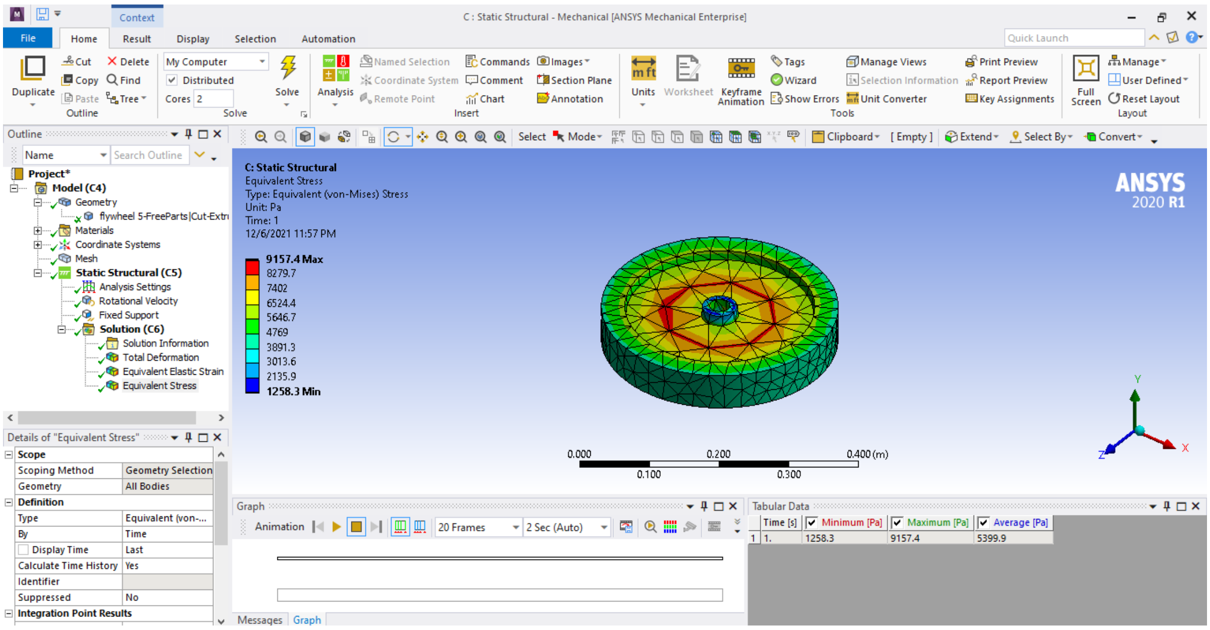


Figure 15: Equivalent stress distribution for Rim Cross-Sectional for gray cast iron material.

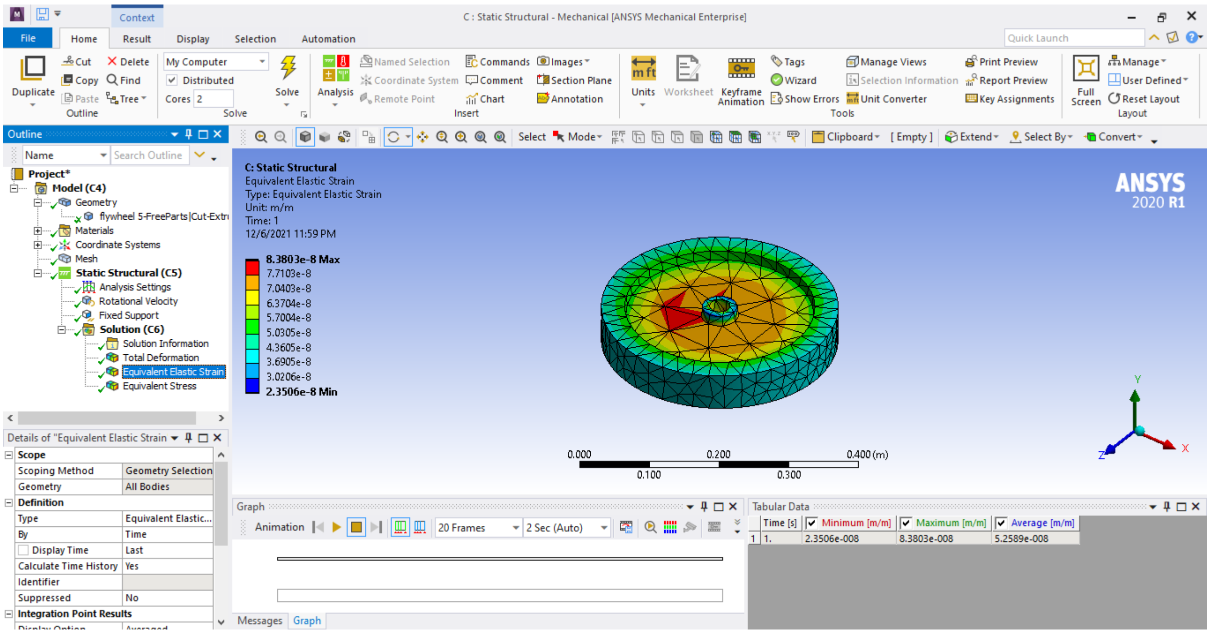


Figure 16: Equivalent elastic strain distribution for Rim Cross-Sectional for gray cast iron material.

Based on Figure 15, it can be seen that the highest equivalent stress (9157.4 Pa) is at the center of the flywheel, meanwhile the lowest equivalent stress is 1258.3 Pa at near the edge of the flywheel. The colour of the contour can also be applied for equivalent elastic strain. The amount of equivalent elastic strain increasing from blue colour to red colour. Based on Figure 16, it can be seen that the highest equivalent elastic strain (8.3803E-8 m/m) is at the center of the flywheel, meanwhile the lowest equivalent stress is 2.3056-8 m/m at near the edge of the flywheel.

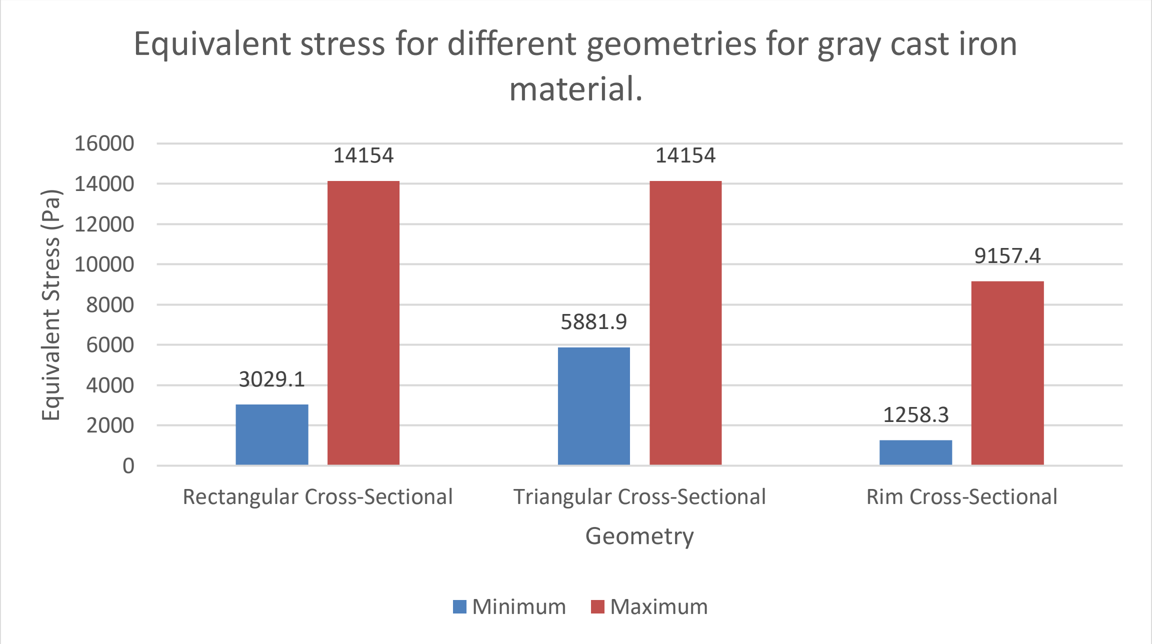


Figure 17: Equivalent stress for different geometries for gray cast iron material.

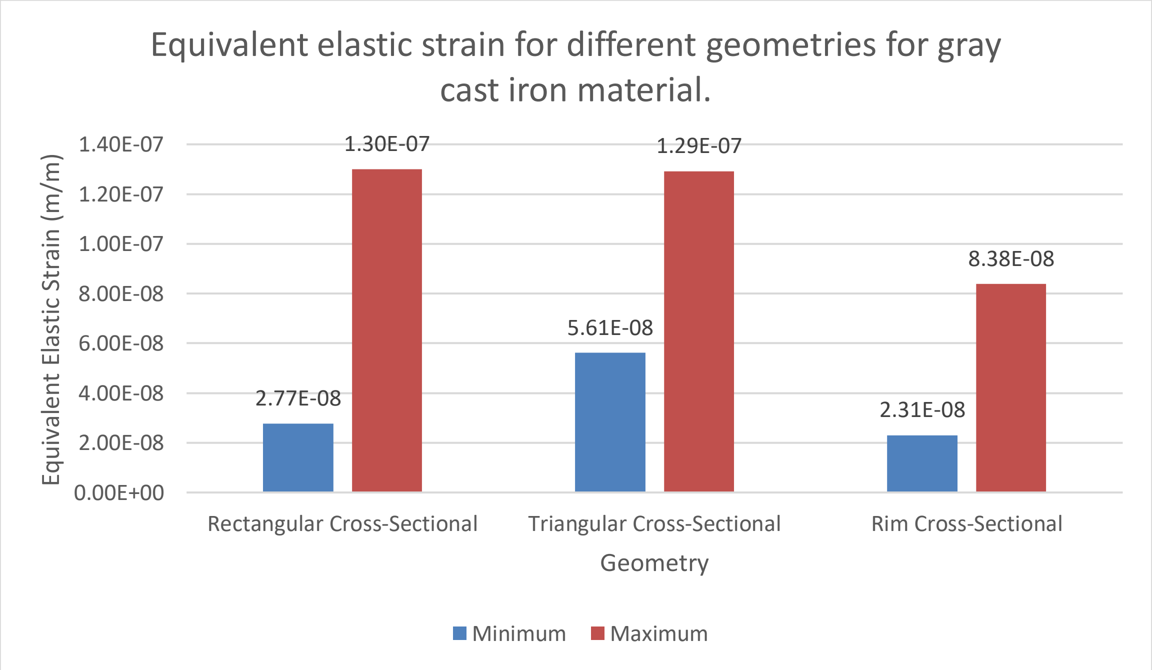


Figure 18: Equivalent elastic strain for different geometries for gray cast iron material.

Based on the chart of equivalent stress for different geometries for gray cast iron material (Figure 17), minimum (1258.3 Pa) and maximum equivalent stress (9157.4 Pa) acts on rim cross-sectional geometry of flywheel is the lowest compared to rectangular cross-sectional geometry and triangular cross-sectional geometry. From the comparison between rectangular cross-sectional geometry and triangular cross-sectional geometry, the maximum equivalent stress acts on the flywheel for both geometries is the same (14154 Pa), but the minimum equivalent stress for triangular cross-sectional (5881.9 Pa) is much higher compared to rectangular cross sectional (3029.1 Pa).

From equivalent elastic strain for different geometries for gray cast iron material (Figure 18), rim cross-sectional geometry of flywheel experiences the lowest minimum (2.31E-8 m/m) and maximum equivalent elastic strain (8.38E-8 m/m) compared to other two geometries. Based on the comparison between rectangular cross-sectional geometry and triangular cross-sectional geometry, the maximum equivalent elastic strain for triangular cross-sectional (1.29E-7 m/m) is a little bit lower compared to rectangular cross-sectional geometry (1.30E-7 m/m). Meanwhile, the minimum equivalent elastic strain for triangular cross-sectional (5.61E-8 m/m) is much higher compared to rectangular cross-sectional geometry (2.77E-8 m/m).

Material: Epoxy Glass.

Geometry (cross-sectional)		Rectangular	Triangular	Rim
Equivalent Stress (Pa)	Min	1194.3	2428.4	291.58
	Max	5056.6	5031.2	3440.8
Equivalent Elastic Strain (m/m)	Min	1.46740E-08	3.3361E-08	1.2267E-08
	Max	7.0079E-08	6.9672E-08	5.0557E-08

Table 5: Result of finite element analysis for epoxy glass material.

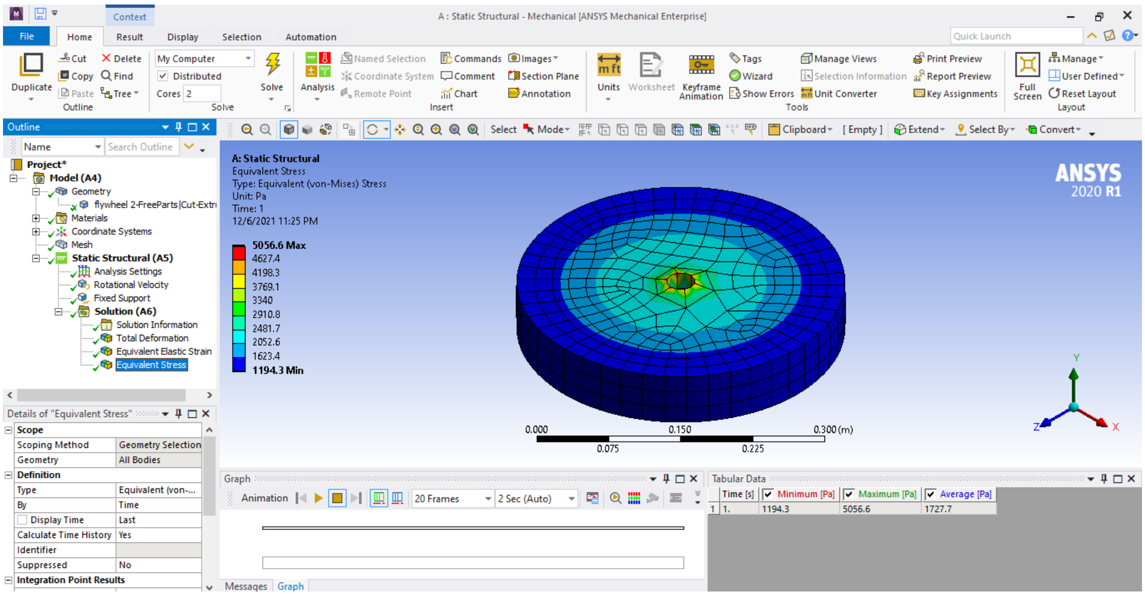


Figure 19: Equivalent stress distribution for Rectangular Cross-Sectional for epoxy glass material.

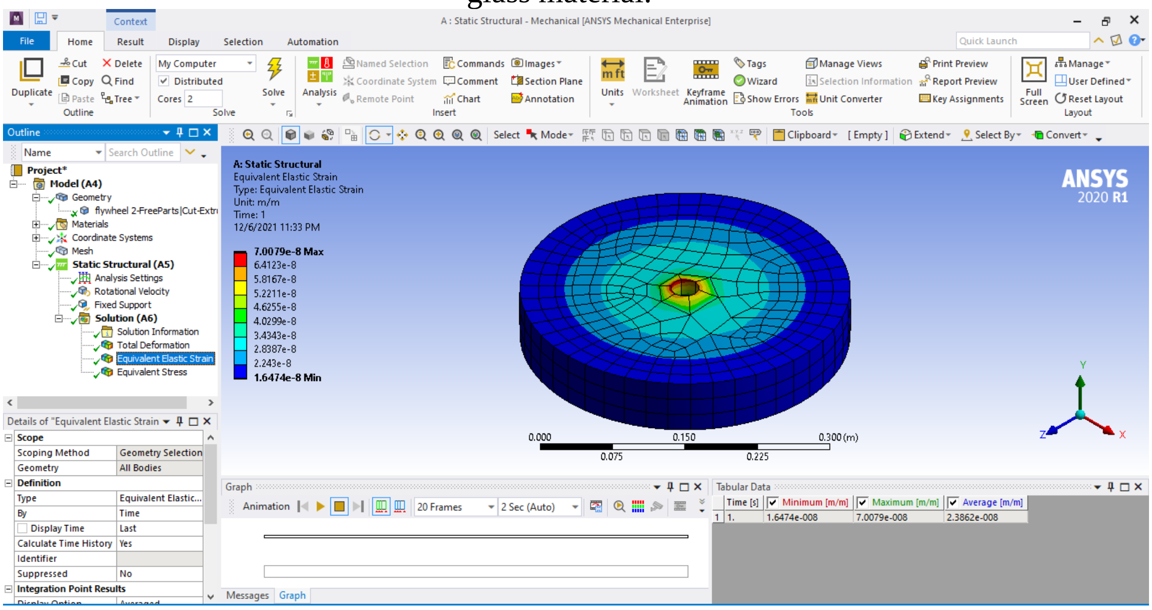


Figure 20: Equivalent elastic strain distribution for Rectangular Cross-Sectional for epoxy glass material.

Based on Figure 19, it can be seen that the highest equivalent stress (5056.6 Pa) is at the center of flywheel, meanwhile the lowest equivalent stress is 1194.3 Pa at near the edge of the flywheel. The colour of the contour can also be applied for equivalent elastic strain. The amount of equivalent elastic strain increasing from blue colour to red colour. Based on Figure 20, it can be seen that the highest equivalent elastic strain (7.0079E-8 m/m) is at the center of the flywheel, meanwhile the lowest equivalent stress is 1.4674E-8 m/m at near the edge of the flywheel.

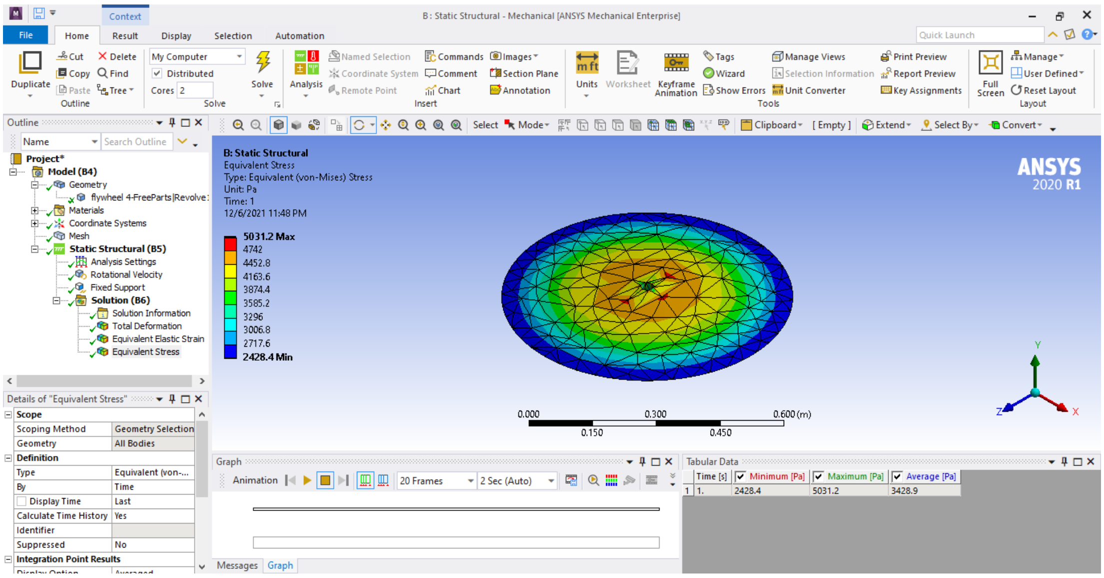


Figure 21: Equivalent stress distribution for Triangular Cross-Sectional for epoxy glass material.

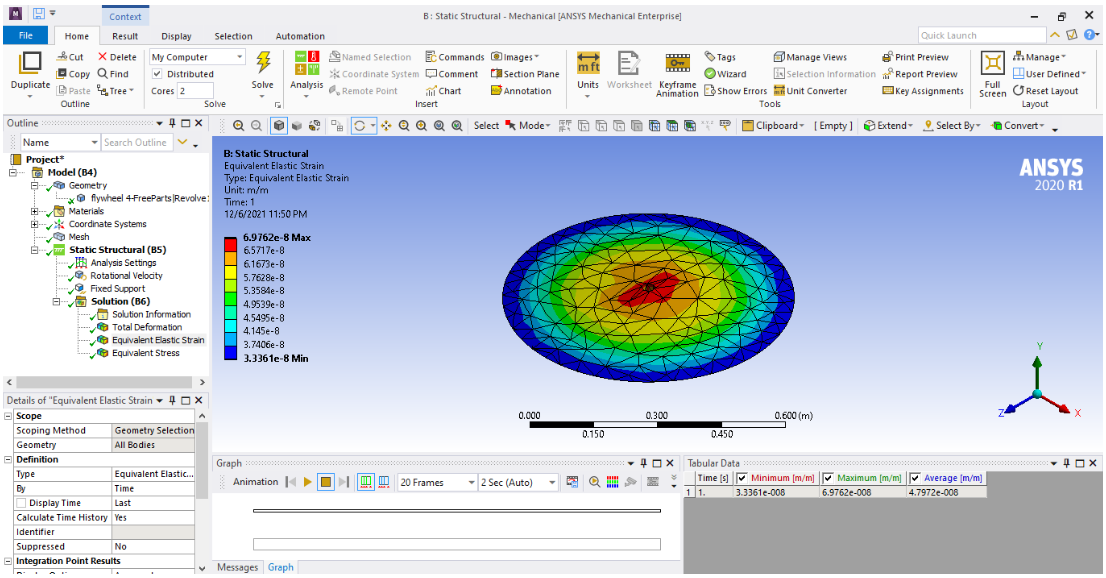


Figure 22: Equivalent elastic strain distribution for Triangular Cross-Sectional for epoxy glass material.