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Analysis and Optimization of a Small-Scale Oceanic Wave Energy Converter

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Abstract: Recently, there has been a rise in awareness of ocean wave energy as a potential source of useful energy. Basically, a wave energy converter is a device that converts mechanical energy from ocean waves into electrical energy. This research is about to analyses and optimize the previous small-scale oceanic Wave Energy Converter (WEC) project that is planned to run the generator at 600 rpm and generate about 12kW of electrical power per day. This research was based on analysis and safety considerations in WEC design, such as gear failure analysis, shaft analysis, bearing analysis, buoyancy force, and component optimization. Static analysis is performed on components such as connectors, buoys, and platforms. The results of static analysis of key components, such as gears, shaft bearings, buoy connectors, and platforms, surpass the safety factors that meet the requirements. Shape optimization is also done to reduce the weight of the machine to increase efficiency and ensure that the new design of components is in accordance with the standards. The total weight of the Small-Scale Ocean Wave Energy Converter was successfully reduced by 39.53 %, from 1068.10 kg to 645.83 kg.

Keywords: Wave Energy Converter (WEC), Static Analysis, Shape Optimization

1. Introduction

Wave energy is a future sustainable electrical power generation source that is both environmentally friendly and rapidly increasing. Wave energy, unlike other renewable energy sources, can provide electricity all year. With a total coastline of 4,675 kilometres, based on data in 2019 Malaysia has a lot of potential to use wave energy, especially along the coast and on the islands. The purpose of this research is to analyse and optimize a wave energy converter designed by [1].

According to previous research, there are some problems and shortcomings in the design of the machine. For instance, the weight of the machine exceeds the specified weight, there are unreported mechanisms that can damage the mechanism system, and buoyancy was not considered by the author.

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Analyses and optimization should be conducted regarding the buoyancy system, crank mechanism, single direction mechanism, and gearbox mechanism, based on strength, safety, size, and weight. Then, using SolidWorks software, new optimize 3D models can be developed and simulated.

The objective of this project is to analyse and optimize the previous oceanic wave energy converter design in terms of its component's strength, safety factor, weight, geometry size and material so that it can become more efficient and meeting the sustainable design criteria.

2. Literature Review

Several software has been used to perform static analysis and shape optimization to analyze and optimize the WEC, as well as Microsoft Excel to assist with calculation and documentation in conducting this research.

2.1 Studies on Previous Design

The WEC design is divided into three main sub-assemblies, crank mechanism, motion transfer, and gearbox. The crank mechanism transfers the motion of sea waves from translational to rotational motion. The motion transfer mechanism receives the rotating motion and maintains the rotational in one direction even though the crank mechanism moving up and down according to ocean waves repeatedly. Lastly, gearbox is used to increase the rotation speed until it reaches the minimum speed required of the generator. Figure 1 shows the full design of the wave energy converter.

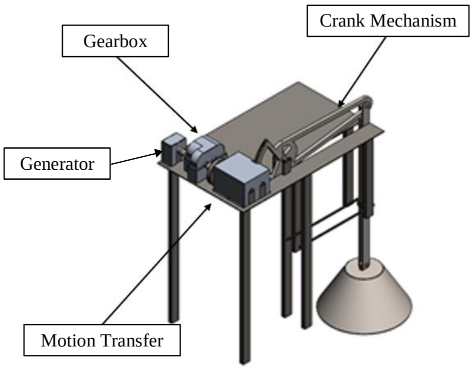


Figure 1: Full Design Wave Energy Converter [1]

2.2 Studies of SolidWorks Simulation

SolidWorks is a software program that allows the user to perform finite element analysis (FEA), creates 2D or 3D designs, and conduct product data management. The parametric design generates three types of files as a part, an assembly, and a drawing. SolidWorks Add-In products also have a wide variety of functionality, such as Photo View 360, Scan To 3D, Motion in SolidWorks, Routing, Simulation, and Toolbox [2]. In general, a study can be completed by following procedures such as creating a new study by defining the type and options of analysis, defining the parameters, defining component contacts and contact sets, defining material properties, defining restraints and loads, mesh, run the study and view results. Figure 2 shows the procedure for conducting simulation [3].

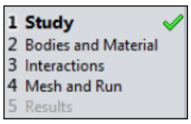


Figure 2: Procedure for Conducting Simulation [2]

2.3 Studies on Static Analysis in SolidWorks

In SolidWorks, static studies have given tools for analyzing linear stress on parts and assemblies which are loaded by static loads. SolidWorks has developed a tool which calculates displacement, force, strain and stress in a part or assembly with an applied external load (force, torque, pressure, gravity, and temperature), as well as predefined material and constraint [2]. In simple terms, static studies investigate the region of material breakdown where stresses surpass a specified limit and can aid in avoiding material failure due to high stress. The static study on SolidWorks can produce a variety of plot results, such as stress plots, factor of safety, and shape optimization. The stress plot is used to analyze the distribution of different types of stress over or within the body curve. The factor of safety plot analyzes the design's safety at each node using the failure criterion, material properties, and maximum stress. Shape optimization analysis is to obtain the best use of material for a body.

2.4 Studies on Shape Optimization in SolidWorks

Design optimization can increase the value of a product by improving its performance within its operating environment, and by reducing the cost of producing it by reducing the amount of material used to make it [4]. Optimization study is defined by goals or objective functions, as well as design variables, and constraints. For example, it can vary the dimensions of a body to minimize the amount of material while constraining stresses so that they do not exceed a specified limit. The aim of the current study is to reduce the weight and shape of the connector and platform model in an optimum condition without affecting the durability of a model designed.

2.5 Studies on Buoyancy Force

The buoyant force on an object can be calculated using the Archimedes principle. The pressure exerted by the fluid in which an object is immersed causes the buoyant force. Because the pressure of a fluid increases with depth, the buoyancy force always points upwards. The submerged volume fraction of a floating body is equal to the ratio of the body's density to the density of the fluid. When the density ratio is equal or greater than one, the floating body becomes completely submerged. Being able to float on the surface of a liquid when the average density of the body is less than that of the liquid. [5].

3. Results and Discussion

This section discusses the result of the simulation by using SolidWorks and Ansys Software. The main part of this study is the Gearbox and the Clutch mechanism that supports the rotating and rotating parts with it to transmit motion at a certain torque and speed. The static analysis of the respective component is instead determined by calculating the safety factor in terms of structure and joint. Microsoft Excel is used to assist in calculations such as gear failure, shaft failure, and buoyancy.

3.1 Overview of the Overall System of Small-Scale Wave Energy Converter

A wave energy converter is made up of three main components, a crank mechanism, motion transfer, and a gearbox. Most structures are made from AISI 316 stainless steel, which is corrosion resistant and resistant to chloride. Figure 4 shows the wave energy converter operating system. Appendix A contains data on the machine shaft's rotational direction as well as the amount of force, speed, and torque generated.

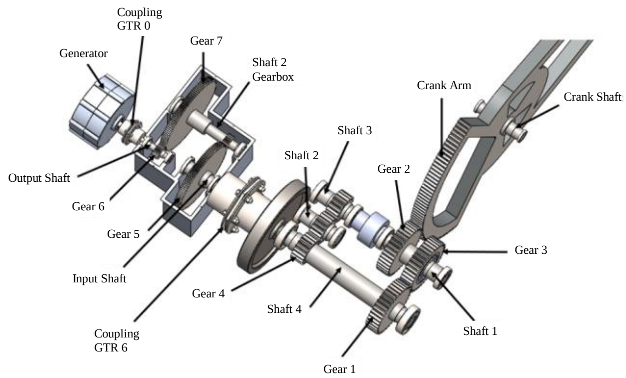


Figure 4: Wave Energy Converter Operating System

3.2 Gear Failure Analysis

Steel Grade 2 AISI 1040 Hot-Rolled, Through-Hardened was selected. The reason why is that its yield strength is big enough to sustain the strength acting upon it. For gears, set the material to be able to sustain Brinell Hardness 320 HB to 380 HB. Tables 1 and 2 show the result of gear analysis.

Table 1: Gear Analysis for Set 1, Set 2 Clutch, and Set 1 Clutch

Parameters	Gear Analysis Set 1		Gear Analysis Set 2 Clutch		Gear Analysis Set 1 Clutch	
	Gear Arm	Gear 2	Gear 4	Gear 4	Gear 3	Gear 1
Ratio	5		1		1	
No. Teeth	200	40	20	20	40	40
Speed (rpm)	3.8	18.8	18.8	18.8	18.8	18.8
Torque (Nm)	3364.8	673.0	673.0	673.0	673.0	673.0
F_t (N)	4206.0	4206.0	4206.0	4206.0	4206.0	4206.0
F_r (N)	1530.9	1530.9	1530.9	1530.9	1530.9	1530.9
Brinell Hardness (MPa)	320.0	320.0	320.0	320.0	320.0	320.0
Gear Bending Strength S_t (MPa)	338.0	338.0	338.0	338.0	338.0	338.0
Contact Material Strength S_C (MPa)	1008.2	1008.2	1008.2	1008.2	1008.2	1008.2
Bending Stress σ (MPa)	88.4	113.7	56.9	57.1	106.2	106.5
Bending Factor safety S_F	4.39	3.52	6.84	6.81	3.66	3.65
Pitting resistance (contact stress) σ_c (MPa)	230.2	528	482.0	483.0	658.7	659.6
Safety factor S_H pitting failure	4.89	2.21	2.42	2.42	1.77	1.77

Table 2: Gear Analysis for Set 1 Gearbox and Set 2 Gearbox

Parameters	Gear Analysis Set 1 Gearbox		Gear Analysis Set 2 Gearbox	
	Gear 5	Gear 6	Gear 7	Gear 6
Ratio	5.45		6	
No. Teeth	109	20	120	20
Speed (rpm)	18.8	102.2	102.2	613.1
Torque (Nm)	673.0	123.5	123.5	20.6
F_t (N)	3087.0	3087.0	514.5	514.5
F_r (N)	1123.6	1123.6	187.3	187.3
Brinell Hardness (MPa)	340.0	380.0	320.0	320.0
Gear Bending Strength S_t (MPa)	352.0	380.1	338.0	338.0
Contact Material Strength S_C (MPa)	1056.4	1152.8	1008.2	1008.2
Bending Stress σ (MPa)	246.8	302.7	84.0	99.6
Bending Factor safety S_F	1.64	1.53	4.89	4.37
Pitting resistance (contact stress) σ_c (MPa)	505.5	503.7	282.4	689.0
Safety factor S_H guarding against pitting failure	2.37	2.85	4.44	2.01

3.3 Shaft Analysis

The material for shaft is 1020 CD steel has value S_{ut} = 470 MPa and S_y = 390 MPa. This material (1020 CD) steel was chosen for shaft because it is a medium low hardenability[6]. Other than that, it is generally supplied in the cold drawn. Table 3 shows the results of Shaft Analysis.

Table 3: Results of Shaft Analysis

	Shaft 1		Shaft 4		Shaft 3	Shaft 2	Input Shaft	Shaft 2 Gearbox		Output Shaft
	A	B	A	B				A	B	
Material	1020 CD									
M_a (Nm)	*253.2*	288.5	399.7	251.58	268.0	272.6	77.8	15.2	101.1	10.7
T_a (Nm)	*673.0*	-673.0	673.0	-673.0	673.0	673.0	673.0	123.5	-123.5	-20.6
S_e' (MPa)		*235.0*		235	235.0	235.0	235.0		235.0	235.0
S_{ut} (MPa)		*470*		470	470	470	470		470	470
S_y (MPa)		*390*		390	390	390	390		390	390
Minimum Diameter (mm)	47.0	49.0	49.0	46.0	48.0	48.0	40.0	23.0	32.0	16.0
S_e (MPa)	158.1	154.3	152.0	152.0	156.2	156.2	158.1	167.5	156.2	173.2
σ_a' (MPa)	46.4	84.1	46.9	29.54	44.7	47.3	17.5	11.9	97.3	22.2
σ_m' (MPa)	123.4	56.0	60.4	60.41	82.1	89.9	144.1	92.2	14.1	44.0
n_f (MPa)	1.80	1.51	2.29	3.10	2.17	2.03	2.40	3.75	1.54	4.51
n_y (MPa)	2.30	2.79	3.63	4.34	3.08	2.85	2.42	3.75	3.51	5.90

3.4 Bearing Analysis

Assume that the wave energy converter life span for 5 year and 24 hours per day. Table 4 shows the results of bearing selection at shaft.

Table 4: bearing Selection at Shaft

	Force Bearing C_{10}(A) (N)	Type Bearing A	Force Bearing C_{10}(B) (N)	Type Bearing B
Shaft 1	20122.8	6207	16566.1	6207
Shaft 3	15234.6	6207	21104.6	6207
Shaft 2	13371.2	NU 1008	18443.6	NU 1008
Shaft 4	34203.4	6308	21463.4	6308
Input Shaft	6173.7	61907	7645.7	61907
Shaft 2 Gearbox	2343.2	NU 204 ECP	19192.2	61907
Output	3171.5	6202	4065.1	6202

3.5 Inertia Force

Inertial force is the opposite in direction to an accelerating force acting on a body. To calculate the inertial force, it must calculate the total torque produced by the clutch mechanism, gearbox, and generator. The total torque on the crank arm gear in this mechanism is 1465.34 Nm and the total of inertia force required to run the thorough system is 1221.12 N

3.6 Buoyancy Force

The Archimedes principle can be used to calculate the buoyant force on an object. The buoyancy force is calculated directly in this design by using the inertia force, connector weight, and buoy weight.

$$Buoyancy\ Force, F_B = Weight\ of\ Object + Force\ Inerta$$

$$Buoyancy\ Force, F_B = \left(8027\, {}^{kg}/_{m^3}\right) \times (9.81\, {}^{m}/_{s^2}) \times (0.202\, m^3) = 15915.06\, N$$

$$Weight\ Object, w_{buoy} = \left(\rho_{AISI\ 316}\, g\, V_{buoy}\right) + \left(\rho_{AISI\ 316}\, g\, V_{Connector}\right) + Force\ Inertia$$

$$w_{Object} = \left(8027\, {}^{kg}/_{m^3} \times 9.81\, {}^{m}/_{s^2} \times 0.013\, m^3\right) + \left(22.17kg \times 9.81\, {}^{m}/_{s^2}\right) + 1221.12\, N$$

$$w_{Object} = 2462.29\, N$$

$$F_B = w_{Object}$$

$$15915.06\, N > 2462.29\, N$$

The buoy's weight is less than the buoyancy force, which means the buoy can float and transfer sea wave motion to the crank mechanism.

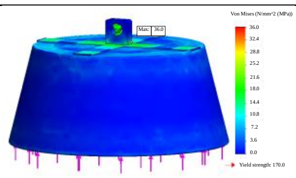
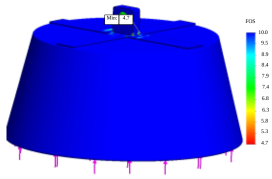
3.7 Static Analysis

Static analysis is intended to determine parts, connections, and components' safety factors simultaneously. In static analysis, displacement, reaction force, strain, and stress are calculated in a part or assembly with an external load. Static analysis involves several components, including a connector, buoy, and platform. To perform static analysis, several details must be specified, including materials, fixtures, force inertia to move the crank mechanism and external loads.

3.7.1 Static Analysis of Buoy

Buoys are important in this design because they transfer the motion of sea waves to the crank mechanism. The force acting on the buoy is 2462.29 N. Table 5 shows the results of Maximum Von Mises Stress and Safety Factor.

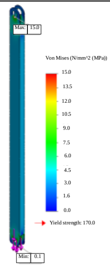
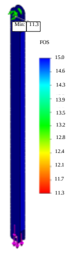
Table 5: Results of Maximum Von Mises Stress and Safety Factor for Buoy

Type of Analysis	Maximum	Results
Maximum Von Mises Stress	36 MPa	
Safety Factor	4.7	

3.7.2 Static Analysis of Connector

For the static analysis, the external load with force inertia applied to the connector is 2462.29 N. Table 6 shows the results of Maximum Von Mises Stress and Safety Factor.

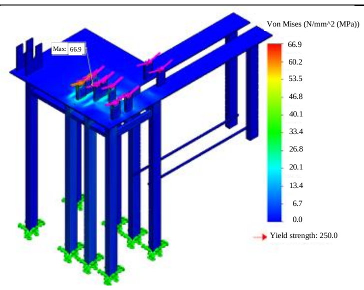
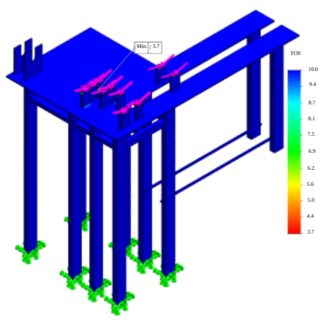
Table 6: Results of Maximum Von Mises Stress and Safety Factor for Connector

Type of Analysis	Maximum	Results
Maximum Von Mises Stress	15 MPa	
Safety Factor	11.3	

3.7.2 Static Analysis of Platform

The platform is the framework in which the clutch mechanism, gearbox, and generator operate. Platform is also an important component in this system. Table 7 shows the results of Maximum von Mises Stress and Safety Factor.

Table 7: Results of Maximum von Mises Stress and Safety Factor for Platform

Type of Analysis	Maximum	Results
Maximu Von Mises Stress	66.9 MPa	
Safety Factor	3.7	

3.8 Shape Optimization

Shape optimization refers to the volume that must be reduced, as well as the dimensions that must be modified and the stress limits that are behaviour constraints. Before performing shape optimizations, several details must be provided, including materials, fixtures, external loads, goals and constraints, and manufacturing control. Colour codes are used to indicate the availability of parts for removal on the platform. Yellow indicates the part is critical and must be saved, whilst the purple colour indicates that it is safe to remove. Shape optimization involves several parts such as platforms and connectors.

3.8.1 Shape Optimization of Connector

The connector's initial mass is 90.36 kg. The new design's mass is decreased to 22.17 kg after reshaping, representing a 75.55 percent reduction in mass on the connector, with a safety factor of 11.3. Figure 5 shows the result of shape optimization of connector.

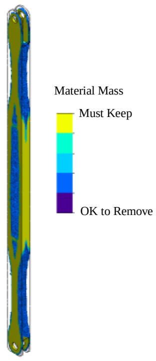


Figure 5: Result of Shape Optimization of Connector

3.8.2 Shape Optimization of Platform

The platform's initial mass is 659.64 kg. The new design's mass is decreased to 381.64 kg after reshaping, representing a 42.14 percent reduction in mass on the platform, with a safety factor of 3.7. Figure 6 shows the result of shape optimization of the platform.

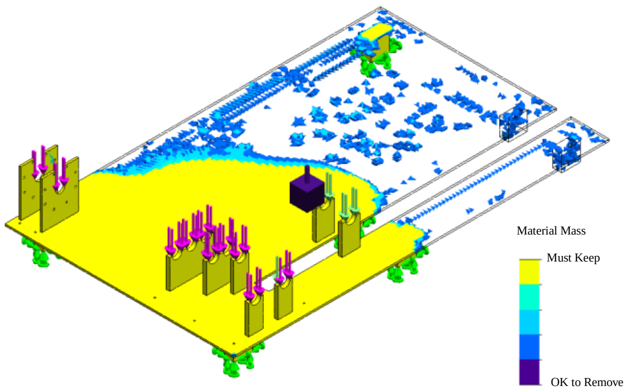


Figure 6: Result of Shape Optimization of Platform

3.9 Weight of Product

The overall mass of the device is 671 kg, which was calculated using SolidWorks software, the SKF bearing, the Tsubaki Cam Clutch, and the Elastomeric Coupling. The weight of the previous Small Scale Oceanic Wave Energy Converter is 1068.10 kg. After analysis and optimization, the new (WEC) weight is reduced to 645.83 kg, reflecting a 39.53 percent reduction in the machine.

4. Conclusion

This project's objectives have been achieved. The total weight of the Ocean Wave Energy Converter was successfully reduced by 39.53%, from 1068.10 kg to 645.83 kg. Based on shape optimization, mass reductions had been made to the connector and platform. Analysis of gear, shaft, and bearing components has shown gear failure analysis results above the required factor safety.

Acknowledgement

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