Stress analysis of a rack gear on sea wave power plant design in Bangka Island

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Abstract. Bangka Island is one of the islands in Indonesia which has the potential of marine energy resources. One of the energies is ocean waves that can be used as an alternative to renewable energy in the design of mini power plants. The mechanic system flow that can be applied is sea wave drives float and then it drives a transmission element. Element transmission will rotate the generator that connected by a shaft. The element transmission that used in the plants is rack and pinion gear. This research conducted static analysis software using the von Mises and safety factor method on rack and pinion gear. Based on research data, wave data at the headland of a bonded coast in Central Bangka Regency in January 2019 with a maximum wave height of 1.220 m and a minimum of 0.285 m. The force assessment that occurs on the buoy is based on the wave force with a maximum wave height of 287.19 N and the buoyancy force. From the highest height the maximum force obtained at the buoy is 689.54 N and vice versa the weight of the buoy mass. From the analysis using Autodesk Inventor software, it was found that the maximum stress that occurs in pinion gears is 53.14 MPa smaller than the yield strength material and the safety factor that occurs a minimum of 6.59 is greater than the safety factor allowed so that the rack and pinion gear can accept the force exerted by the waves.

1. Introduction
Increasing population, human need for electrical energy is increasing. The existence of fossil fuel sources as the main energy source of electricity is increasingly depleting so that it requires energy sources from new and renewable energy. Many new and renewable energy sources can be developed, one of which is energy from ocean energy. There are 2 types of waves that can be converted into wave energy, namely ocean waves and sea winds [1]. This is due to the relatively independent source of wind and wave power, which is largely driven by waves, not by local wind. Wave energy has a promising prospect because the highest wave energy density is around 4 to 30 times greater than wind [2][3]. However, the utilization of wave energy technology development is still far away and well tested so that the contribution made is not significant to the more renewable electricity supply before 2020[4].

To extract electrical energy from wave energy using Wave Energy Converters (WEC) which are not harmful to the environment [5]. Different types of Wave Energy Converters depend on locations with wave periods of 2-25 s [6]. The buoy is one of the Wave Energy Converter that can be used in accordance with sea conditions and to improve the efficiency of energy extraction [3].

One of the provinces that have the potential of ocean waves to develop new and renewable energy in Indonesia is the Bangka Belitung Islands province. Wave height in the waters of Bangka Belitung, in
December 2018 - April 2019 with calm to moderate classification with wave height ranging from 0.1-1.25 m[7][8] and period of wave are 1.12 – 3.97 s.

2. Methodology

2.1. Principle of PLT Gel

The working principle of wave power plants (PLT Gel) is to utilize the motion of ocean waves experienced by buoys. The float drives the rack and pinion gear connected by the lever which rests on a fixed frame. Rack and pinion gear rotate the driving shaft of the electric generating motor[9] as shown in figure 1.

2.1.1. The dimension of the buoy. The size of the buoy in this study is assumed to be 200x700x1050 mm and ignores the buoyed weight with geometry as shown in figure 2.

![Figure 1. Sea wave power plant design using rack and pinion gear [9][10].](image1)

![Figure 2. Dimension and geometry of buoy[10].](image2)

2.1.2. Specification of link. Link material is assumed to be carbon steel with dimensions of Ø100 x 2500 mm with shape as shown in figure 3.

![Figure 3. The geometry of link[10].](image3)

2.1.3. Specification of rack gear. To continue the wave force and motion into straight motion and rotational motion, this study uses a rack and gear pinion transmission element with specifications as in figure 4 and table 1.

![Figure 4. The geometry of rack and pinion gear.](image4)
Table 1. Dimension parameters considered on rack gear.

| Parameters                        | Notations | Values               |
|-----------------------------------|-----------|----------------------|
| Modul                             | \( m \)   | 10 mm                |
| System of gear teeth              | -         | \( 14\frac{1}{2} \) Full-depth involute system |
| Material                          | -         | Steel, carbon        |
| Ultimate tensile strength         | \( \sigma_u \) | \( 420 \frac{N}{mm^2} \) |
| Yield strength                     | \( \sigma_y \) | \( 350 \frac{N}{mm^2} \) |
| Mass density                      | \( \rho \)  | \( 7850 \frac{kg}{m^3} \) |
| Pressure angle                     | \( \phi \)  | \( 14\frac{1}{2} \) |
| Tooth thickness                    | \( b \)   | 15.71 mm             |
| The length of the rack gear       | \( D_p \)  | 2000 mm              |
| Number of the rack gear teeth     | \( T_p \)  | 63 teethes           |
| The pitch diameter of the pinion  | \( D_p \)  | 200 mm               |
| Number of pinion teeth            | \( T_p \)  | 20 teethes           |

2.2. Parameter Considered

2.2.1. Parameter of sea wave. Wave parameters consist of a crest, trough, wavelength (L or \( \lambda \)), wave height (H), wave period (T)[11].

![Figure 5. Schematic of wave sea][6]

2.2.2. Data of sea wave. Data collection is based on wave height data in January 2019 obtained from the Meteorology, Climatology and Geophysics Agency (BMKG) with a coastal location in Berikat, Central Bangka Regency, Bangka Belitung Islands Province with wave height in January 2019 fluctuating with a minimum wave height of 0.285 m and maximum wave height of 1.22 m[9][10] as shown on the graph in figure 4.
Wave Period and wavelength. The wave assumptions that occur are linear waves because they can be applied to engineering problems with reasonable accuracy[6]. The wave calculation is affected by the wave height (H) wavelength (λ), and wave period (T) [12]:

\[ T = 3.55\sqrt{H} \]
\[ \lambda = 5.12T^2 \]  

(1)  
(2)

2.2.3. Power wave dan wave force. Power wave (P\text{wave}) is produced based on the density of seawater (ρ = 1030 kg / m³), gravity (g), wave height (H) and period (T). While the wave force (F\text{wave}) generated from the wave depends on the wave power ((P\text{wave}), wavelength (λ) and the wave period (T)[13].

\[ P_{\text{wave}} = \frac{\rho g^2 H^2 T}{32\pi} \]  
\[ F_{\text{wave}} = \frac{P_{\text{wave}} T}{\lambda} \]  

(3)  
(4)

From the graphic as shown on Figure 8, the maximum wave force is 287.19 N at 1.22 m of wave height.

2.2.4. Buoyancy force. The buoyancy force on a buoy is influenced by the density of seawater (ρ), gravity (g) and the volume of buoy submerged in water (V)[13][14] assuming the volume of buoy submerged is 0.5 buoy height.
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\[ F = \rho g V \quad (5) \]
\[ F = 689.54 \, N \quad (6) \]

2.2.5. \textit{Gravity}. It is assumed that the buoy mass is so that the buoy gravity is ignored.

3. \textbf{Result and Discussion}

3.1. Forces on buoy

The total force on the buoy is influenced by the wave force, buoyancy force and buoyancy gravity as shown in figure 9.

\[ F_{\text{generated}} = F_{\text{wave}} + F_{\gamma} + F_{\text{massa}} \quad (7) \]

From the graphic results in Figure 10, the maximum force generated is 976.73 N at a wave height of 1.22 m which is used as a reference for the next static calculation.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure9.png}
\caption{Freebody diagram of buoy.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure10.png}
\caption{Graphics of force generated.}
\end{figure}

3.2. \textit{Force on rack and pinion gear}

The force that occurs on the link is assumed to be a static force with the freebody diagram in Figure 11 with the condition of the link angle of 35° to sea level by calculating the forces on the link as follows:

\[ F_n = \frac{F_{\text{generated}} X_{n1}}{\cos \alpha_{n2} X_{n2}} \]

\[ \sin \alpha_{n2} X_{n2} \quad (8) \]
Figure 11. Free body diagram of system.

Figure 12. The maximum load on maximum wave.

Table 2. Parameters considered of free body diagram system.

| Parameters                                      | Notations | Values |
|-------------------------------------------------|-----------|--------|
| High wave                                       | Hwave     | 1.22 m |
| Support on pin                                  | A         | -      |
| The horizontal length of generated force (F_{generated}) to support A | X_{a1}    | -      |
| The vertical length of generated force (F_{generated}) to support A | Y_{a1}    | -      |
| The angle between link and buoy                 | \alpha_{a1} | -      |
| The horizontal length of rack gear force (F_{generated}) to the center of the pinion gear | X_{a2}    | -      |
| The vertical length of rack gear force (F_{generated}) to the center of the pinion gear | Y_{a2}    | -      |
| The angle between the rack gear and horizontal axis | \alpha_{a2} | -      |

From the results of the graph in Figure 12, obtained at a wave height of 1.22 m, the maximum force that occurs in rack gear is 4906.06 N or 4.91 kN at wave height 0 m and the minimum force on rack gear is 4.01 kN at wave height 1.22 m.

3.3. Modelling

Analysis using Autodesk Inventor Version 2019.4 software with the type of study static analysis with parameters as in Table 3 with constraints and mesh as shown in Figure 13.
Table 3. Parameters considered of stress analysis.

| Parameters                                      | Notations | Values          |
|-------------------------------------------------|-----------|-----------------|
| Mass                                            | m         | 13.85 kg        |
| Support on pin                                  | A         | -               |
| Detect and Eliminate Rigid Body Modes           | -         | No              |
| Separate Stresses Across Contact Surfaces       | -         | Yes             |
| Motion loads analysis                           | -         | No              |
| 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°             |
| Axial force on rack gear                        | $W_a=F_{generated}$ | 4906.06 N=4.91 kN |
| Pin constraint                                  | A         | -               |
| Frictionless constraint                         | B         | -               |

Figure 13. Modelling, load, and constraints.  
Figure 14. Mesh model.

3.4. Static analysis of rack and pinion gear

3.4.1. Von mises. The stress that occurs on teeth gears is compared to the allowable stress on the material based on yield strength. For ductile material, static stress analysis uses the Von Mises Stress method [15]. From the simulation results, the graph as shown in Figure 6 states that the maximum stress occurs at 53.14 MPa in a teeth’s pinion gear. This analyses that the stress that occurs is smaller than the material yield strength.

Figure 15. Von mises stress analysis.
3.4.2. **Safety factor.** The safety factor that occurs in the rotating shaft must be more than $1.5 - 2$[16] so that the design is safe. Safety factor minimum on gear is 6.59 and the maximum safety factor is 15 mm. Both safety factors are on the pinion gear. From the results of the analysis of safety factors, both rack and pinion gear satisfy safety factor.

![Safety factor analysis](image)

**Figure 16.** Safety factor analysis.

4. **Conclusion**

From the analysis using Autodesk Inventor 2019 software, it was found that a rack and pinion gear with carbon steel material with a yield strength of 350 MPa was able to withstand force from sea wave and buoy force on the Bangka Belitung sea.

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