

# A Wave Energy Generation Device using Impact Force of a Breaking Wave Based Purely on Gear Compounding

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**Abstract:-** The exploration of alternative energy sources has become a primary concern of mankind even though fossil fuels are still the leader in the energy sector. Ocean wave energy as one of the promising alternatives, extensive research and development activities are happening around the world to explore new methods and to improve the existing methods.

Among the existing plethora of technologies for harnessing renewable energy, the ones developed for wave energy have the lots of potential to be a major contributor to the amount of renewable energy produced. Almost all of these systems which use ocean waves to generate energy are void of pollution, that is to say that these systems do not produce any substances as side products that would harm the marine environment or the atmosphere in any way. With the rapidly decreasing amount of available fossil fuels and an even more expeditiously increasing population, and therefore and exceeding demand and consumption rate, it's not long before the earth is going to be devoid of these precious resources. The need for more efficient technologies to harvest these available resources of renewable energies is more than ever. Although, there are numerous wind and solar farms built across the earth they are not enough adequate enough to suffice the need of 7.7 billion people around the globe. Water bodies cover around 70% of earth's surface and these have immense potential for producing humungous amount of renewable energy. A shabby assessment shows that there is about 8,000-80,000 TWh/yr of wave energy present in the oceans. This enormous myriad of energy is enough to alleviate the problem of energy from the world.

**Keywords:-** Ocean Waves, Renewable Energy, Wave Energy Convertors.

## I. INTRODUCTION

Since long wave energy has been considered to be one the most reliable and feasible sources of renewable energy. Wave energy generators or convertors refer to the broad spectrum of devices that are used to convert wave power to electricity. There is a plethora of such devices that currently exist on paper as well as in actual practice installed in oceans, all under investigation for their feasibility and efficacy. Most of these devices are meant to

be installed at a considerable distance from the mainland so as to utilize the undulating sea waves.

Furthermore, these devices are designed to use the energy of the non-breaking waves i.e. the undulating up and down motion of the water level, which occur far away from shore, which in return increases the maintenance cost of the system or device. This paper aims to demonstrate a device that makes use of the impact force of the breaking waves. Since this device will use breaking waves, which are available much closer to the shore than non-breaking waves, the maintenance and installation charges operations are much more economical. Furthermore, the device is based purely on highly efficient gear compounding, thus has multiple output points. And since the energy source i.e. is the waves are not a constant force, the device has been designed to operate keeping in mind the intermittent nature (both time-wise and force wise) of the breaking waves.

### A. Challenges faced

#### ➤ Resource Assessment

Wave energy is highly variable in frequency and force. The frequency of the waves is generally very low and the force of the waves varies over a wide range (from low to very high). Unlike tidal energy, motion of waves do not have a constant direction. They change their direction slightly throughout the day. To maximize the efficiency, we need a dynamic apparatus capable of changing direction in accordance with the waves.

#### ➤ Maintenance and Training

Regular checking and replacement of damaged parts is required. A trained person is needed for all these activities.

### B. Focus

The "Oscillating wave energy convertor" (OWEC) device comprises of pendulum mechanism that converts wave energy into mechanical energy and energy storage mechanism where the mechanical energy is transferred quantitatively to generator.

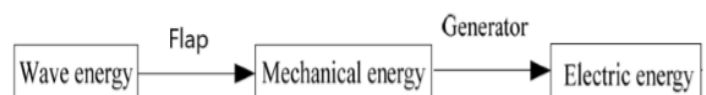


Fig 1

**II. GOVERNING EQUATIONS**

Like other waves, ocean waves are caused by the disturbance in medium. This disturbance is due to the wind blowing over the surface of ocean which transfers energy. This energy transfer could be seen as a hump in the medium. In an ocean instead of water energy is travelling at the speed of wave. In deep sea a resting object moves in a perfect circle. The diameter of the circle is equal to the wave height. Fig. 1 illustrates the wave particle motion in deep water. The circular motion of the particles diminishes near the bottom of sea bed.

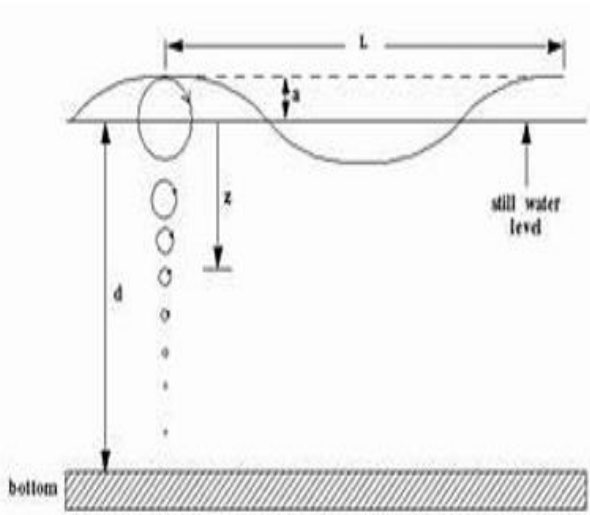


Fig. 2:- Wave particle motion in deep water [1]

Wave length determines the size of the orbits of molecules within a wave and the water depth determines the shape of orbits. In deep sea, wave particles move without the loss of any energy. In shallow water the water particles lose their energy due to the frictional with bottom. In this region wave particles move in elliptical form. Just near shore the effect of bottom friction increases so much that the crest starts moving faster than its supporting base and a wave break.

**A. Wave Energy**

The calculation of wave energy is very important in designing a particular wave energy converter. This factor helps us in determining the size of wave energy converter. One important parameter involve in wave energy calculation is wave velocity.

**B. Wave velocity**

There are two measures for wave velocity. The phase velocity and group velocity.

➤ **Phase velocity**

Phase velocity is the velocity of an individual wave. For deep water

Where 
$$v = \sqrt{\frac{g\lambda}{2\pi}}$$

So, 
$$\lambda = \frac{gT^2}{2\pi}$$

$$v = \frac{gT}{2\pi}$$

Where g is the acceleration due to gravity, λ is the wavelength and T is the time period of wave. The group velocity is the velocity of the packet of waves. In deep water the group velocity is half of the phase velocity.

➤ **Group velocity**

The group velocity is the velocity of the packet of waves. In deep water the group velocity is half of the phase velocity.

$$c_g = v / 2$$

In deep water the velocity of the waves remains constant. As the wave reached in shallow water the velocity of wave start decreasing. In shallow water, the frictional force acting on the wave decreases the wave velocity. The wave velocity in shallow water is given by

$$= 3.1\sqrt{d}$$

Where, v is  $v = \sqrt{gd}$  speed (in meters per second), g is the acceleration due to gravity, and d is the depth of the water (in meters). The period of a wave remains unchanged regardless of the depth of water through which it is moving.[3]

After getting the velocity of wave average velocity can be calculated as

$$V_{avg} = \frac{\int_a^b v dh}{\int_a^b dh}$$

Where, a and b are velocity of water at h=a and h=b respectively.

Hence average pressure and average force on the flap can be given by

$$P_{avg} = \frac{1}{2} * \rho * V_{avg}^2$$

$$F_{avg} = P_{avg} * A$$

This leads to torque and power on shaft as

$$T = F * x_{cp}$$

$$Power (p) = T * \omega$$

### III. GEAR MECHANISM WITH SPRING AS ENERGY STORING DEVICE

The structure composing of power generation device and energy conversion process are shown in Fig.3. This device is mainly composed of pendulum, energy storing mechanism and power generator. Because of intermittency and randomness of wave motion, the output power of generator is not stable and the energy conversion efficiency is low if the pendulum is directly connected to power generator. For this reason, the energy storing mechanism proposed in this paper is placed between pendulum and generator.

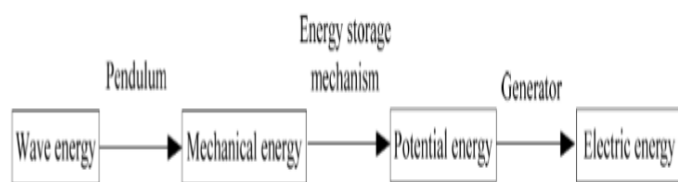


Fig. 3:- Diagram of structure composing and energy conversion process

The structure diagram of energy storing mechanism is shown in Fig. 4, and the working principle of wave energy generator device is described below. The wave energy is changed into mechanical energy through pendulum swing under the action of wave movement, and then the mechanical energy is input into energy storing mechanism by input shaft. Because of unidirectional transmission of one-way bearing A and B, the torque only transmits from large gear of first stage to large gear of second stage when input shaft rotates in forward direction, while the small gear of first stage idles; when input shaft rotates in reverse direction, the torque transmits from small gear of first stage, to medium gear, till small gear of second stage, while the large gear of first stage idles. As a result, when the swing motion of pendulum transmits to middle shaft, the teeth uncompleted gear fixed to middle shaft only rotates in reverse direction. In the process of teeth uncompleted gear rotating and engaging with rack, the energy storing spring is compressed and the mechanical energy is converted into potential energy of spring. As soon as the missing teeth parts of teeth-uncompleted gear rotate into meshing area with rack, the teeth-uncompleted gear is out of contact with rack, resulting in the potential energy being stored in spring to be released and causes the rotation of output gear. The rotation of output gear is transmitted to output shaft, and then the energy is imported quantitatively into generator, finishing a cycle of energy conversion.

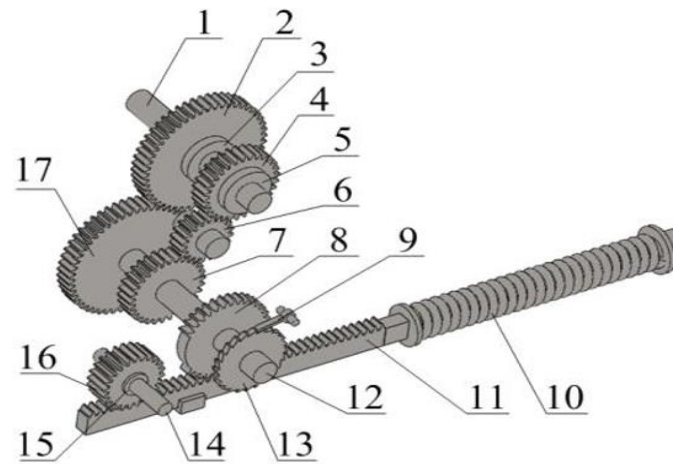


Fig 4:- Diagram of energy storing mechanism model

1.input shaft; 2 large gear of first stage; 3 one-way bearing A; 4 small gear of first stage; 5 one-way bearing B; 6 medium gear; 7 small gear of second stage; 8 teeth-uncompleted gear; 9 pawl; 10 energy storing spring; 11 rack; 12 middle shaft; 13 ratchet; 14 output shaft; 15 one-way bearing C; 16 output gear; 17 large gear of second stage.

➤ *Problem Associated*

Adding a spring will simply increase one stage of power transmission which will again cause some mechanical losses as we are storing and releasing energy via a spring. In return stroke it comes back to its original position only due to its weight and at the same time, it has to compress the spring as well. Therefore, in return stroke we will get comparatively very low power.

➤ *Compact Gear Mechanism*

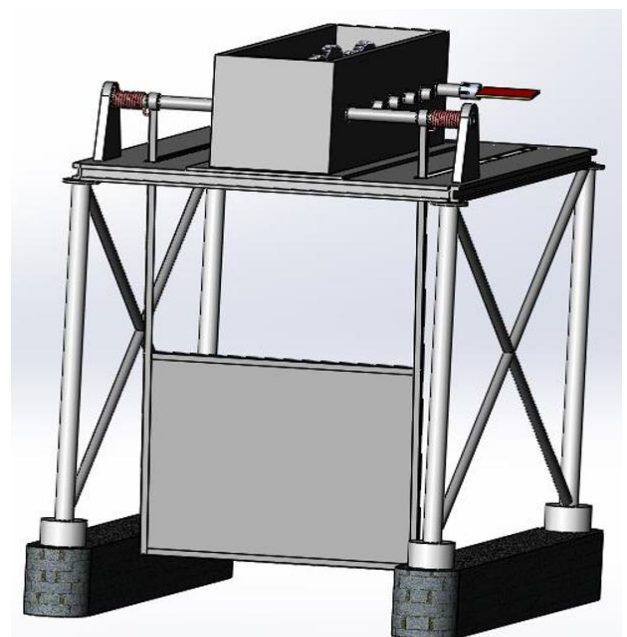


Fig 5

This system looks quite similar to our second mechanism where we had coupled gear to oscillating link. But here we made slight modification by placing gear on same shaft about which the flap is oscillating. So, we have eliminated the problem of toggling of linkages. we have also placed one way bearing between gear and first shaft. There are two gears on first shaft. Bigger one rotates only in forward stroke and smaller one rotates only in reverse stroke due to one way bearing. This time we can get rotational output in both the stroke that too in same direction. We have also attached two torsional springs i.e. one on each side of flap. When the wave strikes the flap, springs will store some amount of energy along with rotational power output and this rotation can be converted to electrical power via a generator. In return stroke flap will come back to its original position due to its self-weight and spring since spring will release its stored energy.

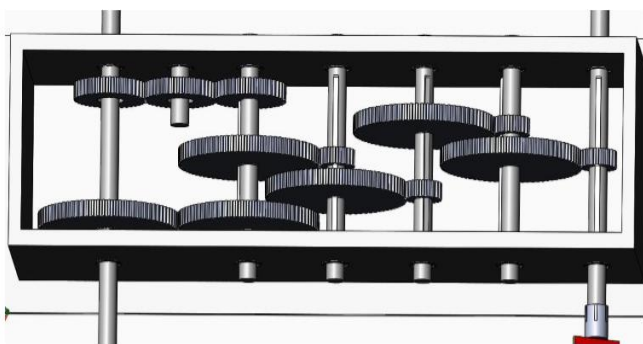


Fig 6:- Gear box with compound gear train

Flap provides rotational speed of 18 rpm only. To amplify rotational speed to 3000 rpm so that we can get 50HZ power supply we have two choices i.e. compound gear train or epicyclic gear train. In compound gear train we can use 4-stages of compounding with speed ratio of 4 in each stage (as shown in Fig 6). So we can easily reach 3000 rpm including all the mechanical losses. In epicyclic gear train (not shown here) first of all we can increase speed by 4-times using simple gear train then we can use 3-staged compound epicyclic gear train with gear ratio of 4 in each stage. Only benefit of using epicyclic is that we can reduce number of shafts and hence the length of gear box.

**IV. CALCULATIONS**

*A. Flap Design*

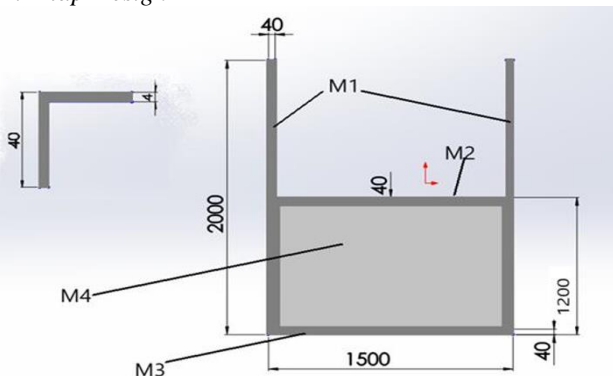


Fig 5:- Flap geometry

➤ *Mass Calculations of Flap (M) [Referring to fig 5]*

$$\begin{aligned}
 M_1 &= \text{Volume} * \text{Density} \\
 &= 2 * \{[(4 * 0.4) + (3.6 * 0.4)] * 200 * 7.0\} \\
 &= 9.484 \text{ Kg} \\
 M_2 &= [(3.04 * 150) * 7.8] / 1000 \\
 &= 3.556 \text{ Kg} \\
 M_3 &= 3.556 \text{ Kg} \\
 M_4 &= [(120 * 150) * 0.5 * 7.8] / 1000 \\
 &= 70.2 \text{ Kg} \\
 M_{\text{Total}} &= M_1 + M_2 + M_3 + M_4 \\
 &= 86.79 \text{ Kg}
 \end{aligned}$$

*B. Centre of Mass Calculation(xcm)*

$$\begin{aligned}
 \bar{x} \text{ cm} &= \{ (M_1 * 1) + (M_2 * 0.8) + (M_3 * 2) + (M_4 * 1.4) \} / M_{\text{Total}} \\
 &= \{ (9.484 * 1) + (3.556 * 0.8) + (3.556 * 2) + (70.2 * 1.4) \} / 86.79 \\
 &= 1.356 \approx 1.36 \text{ m}
 \end{aligned}$$

*C. Mass Moment of Inertia Calculation (I)*

$$\begin{aligned}
 I &= I_1 + I_2 + I_3 + I_4 \\
 &= (M_1 * L_{12} / 3) + (M_2 * L_{22}) + (M_3 * L_{32}) + \{ (M_4 * L_{42} / 12) + (M_4 * r_2^2) \} \\
 &= (9.484 * 22 / 3) + (3.556 * 0.82) + (3.556 * 22) + \{ (70.2 * 1.22 / 12) + (70.2 * 1.42) \} \\
 &= 175.16 \text{ Kg-m}^2
 \end{aligned}$$

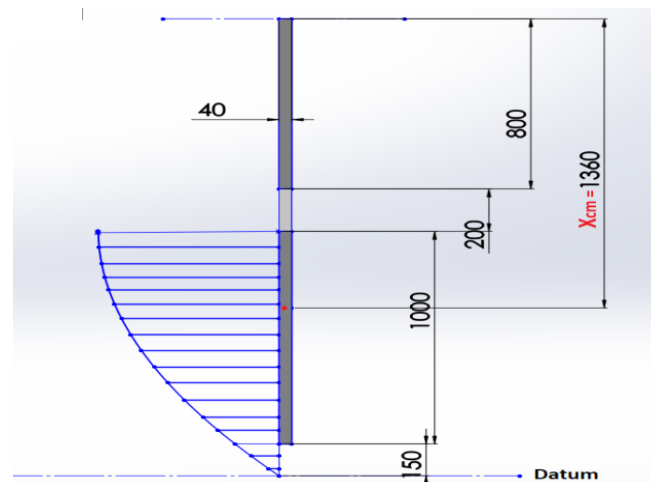


Fig 8:- Side view of flap

*D. Average Velocity (Vavg) [referring to Fig 6]*

$$\begin{aligned}
 V_{\text{avg}} &= \frac{\int_{0.15}^{1.15} v \, dh}{1.15 - 0.15} \\
 &= \frac{2/3 * \sqrt{g} [1.153/2 - 0.153/2]}{[1.15 - 0.15]} = 2.4537 \text{ m/s}
 \end{aligned}$$

*E. Average Pressure (Pavg)*

$$\begin{aligned}
 P_{\text{avg}} &= 1/2 * \rho * V_{\text{avg}}^2 \\
 &= 3103.1 \text{ Pa}
 \end{aligned}$$



**F. Average Force (Favg)**

$$F_{avg} = P_{avg} * A$$

$$= 3010.3 * 1.5 * 1$$

$$= 4515.5 \text{ N}$$

**G. Calculation of  $x_{cp}$  at  $\theta_{max}$**

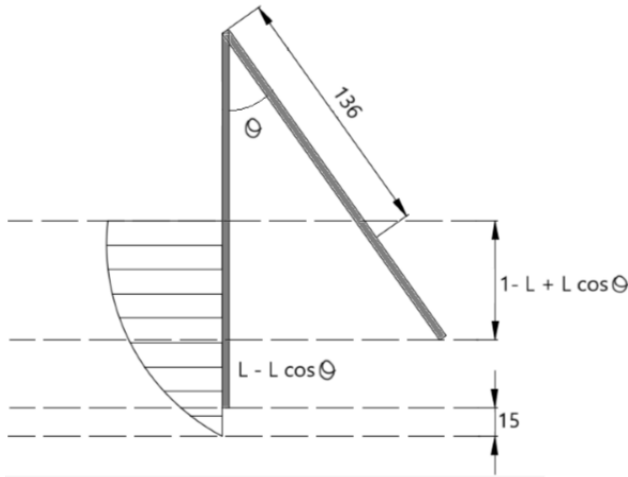


Fig 9:- velocity at any inclined position

$$P_2 = \frac{1}{2} * \rho V^2 = \frac{1}{2} * \rho g h$$

$$= \frac{1}{2} * 1000 * g * (0.15 + L - L \cos \theta)$$

$$= \frac{1}{2} * 1000 * g * (0.15 + 2 - 2 \cos \theta)$$

$$= 3031 \text{ KPa}$$

$$P_1 = \frac{1}{2} * \rho g h$$

$$= \frac{1}{2} * 1000 * 9.81 * 1.15$$

$$= 5640 \text{ KPa}$$

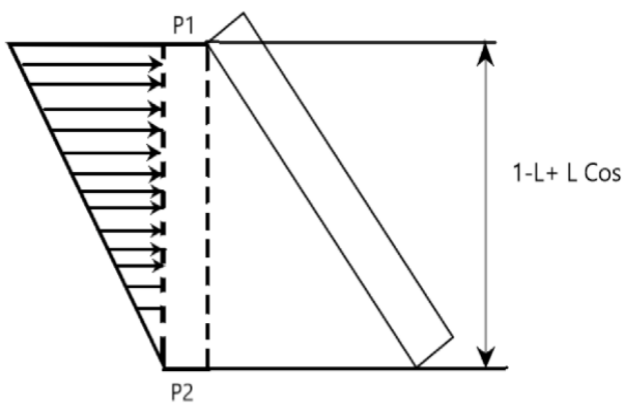


Fig 10:- Pressure profile at inclined position

( Where, P2 and P1 are the pressures on the flap at 0° and  $\theta^\circ$  respectively)

Assuming  $35 \leq \theta \leq 45$

$$P_2 = 3031 \text{ N/m}^2 \quad P_1 = 5640 \text{ N/m}^2$$

$$P_2 - P_1 = 2609 \text{ N/m}^2$$

$$x_{cp} =$$

$$x_{cp} =$$

$$= 0.239 \approx 0.24 \text{ m}$$

$$x_{cp} = 0.24 \text{ m}$$

$$x_{cp} = 1.24 \text{ m}$$

$$V_{avg} = \frac{\int_{0.618}^{1.15} \sqrt{gh} dh}{\int_{0.618}^{1.15} dh}$$

$$P_{avg} = \frac{1}{2} \rho V_{avg}^2$$

$$= \frac{1}{2} * 1000 * 1.4^2$$

$$= 980 \text{ N/mm}^2$$

$$F_{avg} = P_{avg} * \text{Area}$$

$$= 980 * (0.532 * 1.5)$$

$$= 782 \text{ N}$$

**H. Maximum power available (Pmax)**

$$P_{max} = 4515.5 * 2.4537 = F * V$$

$$= 11079.6 \text{ Watt}$$

$$= 11.08 \text{ KW}$$

**I. Torque Available ( $\tau$ )**

$$T = F * x_{cp}$$

$$= 4515.5 * x_{cp}$$

$$P_1 = \frac{1}{2} * \rho V^2$$

$$= \frac{1}{2} * 1000 * g * 1.15$$

$$= 5640.75 \text{ N/mm}^2$$

$$P_2 = \frac{1}{2} * \rho V^2$$

$$= \frac{1}{2} * 1000 * g * 0.15$$

$$= 735.75 \text{ N/mm}^2$$

$$x_{cp} = \frac{\{P_2 * 0.5\} + \{ (P_1 - P_2) / 2 * 1/3 \}}{P_2 + 1/2(P_1 - P_2)}$$

$$= 0.3718 \text{ m}$$

$$\text{Torque } (\tau) = (0.3718 + 1) * 4515.5$$

$$= 6194.36 \text{ Nm}$$

➤ **Spring design**

To get the value of K and  $\theta_{max}$

Velocity will not change with one-meter travel of flap so assuming

V = Constant

Wave period = 5.5 seconds

**J. Average Angular Velocity ( $\omega_{avg}$ )**

$$\Delta PE = \Delta KE$$

$$Mg * X_{cm} * (1 - \cos \theta) + \frac{1}{2} K \theta^2 = \frac{1}{2} I \omega^2$$

$$\Delta PE = [86.79 * 9.81 * 1.36 (1 - \cos 40)] + [\frac{1}{2} * 300 * 40 * (\pi/180)] = (\frac{1}{2} * 175.2 * \omega^2) 271 + 105$$

$$\Delta KE = \frac{1}{2} * 175.2 * \omega^2$$

$$\omega = 2.07 \text{ rad/s}$$

$$N = 2.07 * 60 / (2\pi) = 19.78 \text{ rpm}$$

$$\omega = \frac{[\{ (P_2 * L_2 * B * X_2) + (\frac{1}{2} (P_1 - P_2) * L_1 * B * X_1) \}]}{P_2 * B * L_2 + \frac{1}{2} (P_1 - P_2) * B * L_1}$$

$$+ \alpha * \frac{[\{ (3031 * 0.532 * 0.532) + (\frac{1}{2} * 0.532 * 2609 * 0.532 / 3) \}]}{t}$$

$$= 0 + \frac{(3031 * 0.532) + (\frac{1}{2} * 0.532 * 2069)}{t}$$

$$(\tau/I) * t = (mg * X_{cm} * \sin\theta + K * \theta) * t / 175.2$$

$$t_2 = 0.38 \text{ s}$$

$$t_1 = L * \sin \theta / V = (2 \sin 40) / 2.45$$

$$= 0.525 \text{ s}$$

$$\omega_{avg} = (\omega_1 * t_1 + \omega_2 * t_2) / (t_1 + t_2)$$

$$= 17 * 0.525 + 19.78 * 0.38 / 0.525 + 0.38$$

$$= 18.16 \text{ rpm}$$

**K. Stiffness of spring (K)**

Considering equation

$$\Sigma M_0 = 0$$

$$F * X_{cp} = (mg * X_{cm} * \sin \theta) + K * \theta$$

$$782 * 1.24 = (86.79 * 9.81 * 136 * \sin 40) + k (40 * \pi / 180)$$

$$970 = 744.29 + (k * 0.698)$$

$$K = 322 \text{ Nm/rad}$$

**L. DESIGN OF GEARS**

➤ *Shaft design*

Material: C-40 Steel

$$\sigma = 324 \text{ N/mm}^2$$

Factor of safety = 2

$$\sigma_d = 324 / 2 = 162 \text{ N/mm}^2$$

$$= \sigma_d / 2 = 81 \text{ N/mm}^2$$

Where  $\sigma_d$  is design stress and  $\tau$  is the shear stress From shear stress formula

$$\tau = 16 T / \pi D^3$$

$$d = \left( \frac{16 T}{\pi \tau} \right)^{1/3}$$

$$d = \left( \frac{16 * 6194 * 1000}{\pi * 81} \right)^{1/3} \quad 73 \text{ mm}$$

$$d \approx 75 \text{ mm}$$

Where d is the diameter of shaft

➤ *Gear design*

$$W = 18 \text{ rpm}$$

$$\tau = 6194 \text{ N-m} = 6194 * 103 \text{ N-mm}$$

Steel C-45, case hardened  $\sigma = 353 \text{ N/mm}^2$

Factor of safety: 2

$$\sigma_d = 353 / 2 = 176.5 \text{ N/mm}^2$$

$$\text{BHN} = 300 \quad K = b/m = 10$$

$$b = 10 \text{ m}$$

$$Z_1 = 20, Z_2 = 40, Z_3 = 80$$

Since both pinion & gear are made of same material, hence we design for pinion  $Z_1 = 20$

$$y = \left( 0.154 - \frac{0.912}{Z} \right)$$

$$= \left( 0.154 - \frac{0.912}{20} \right)$$

$$= 0.1084$$

$$Y = \pi * y = \pi * 0.1084$$

$$= 0.3404$$

$$C_v = \frac{3.05}{3.05 + V}$$

$$= \frac{3.05}{3.05 + 1.4}$$

$$= 0.685$$

$$m = (2 * mt / \sigma_d * C_v * k * Y_z)^{1/3}$$

$$= (2 * 6194 * 1000 / 177 * 0.685 * 10 * 0.304 * 20)^{1/3}$$

$$= 11 \text{ mm}$$

$$d_1 = m * Z_1 = 11 * 20 = 220 \text{ mm}$$

$$d_2 = m * Z_2 = 11 * 40 = 440 \text{ mm}$$

$$d_3 = m * Z_3 = 11 * 80 = 880 \text{ mm}$$

**V. ANALYSIS**

SOLIDWORKS software has been used for design and simulation.

➤ *Material properties*

AISI 4340 annealed steel has been used as a flap material and properties of this material is given below in fig 11.

Property	Value	Units
Elastic Modulus	2.05e+011	N/m <sup>2</sup>
Poisson's Ratio	0.285	N/A
Shear Modulus	8e+010	N/m <sup>2</sup>
Mass Density	7850	kg/m <sup>3</sup>
Tensile Strength	745000000	N/m <sup>2</sup>
Yield Strength	470000000	N/m <sup>2</sup>
Thermal Expansion Coefficient	1.23e-005	/K
Thermal Conductivity	44.5	W/(m-K)

Fig 11:- Material properties

Selected material has high yield strength of 470Mpa to prevent bending of flap and it also offer high toughness which is advantageous for impact loading of flap by ocean wave.

➤ *Modelling*

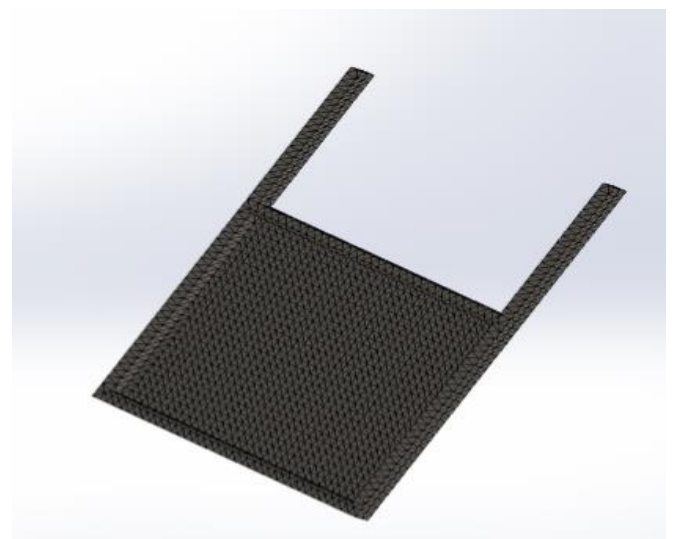


Fig 12:- Meshing of flap

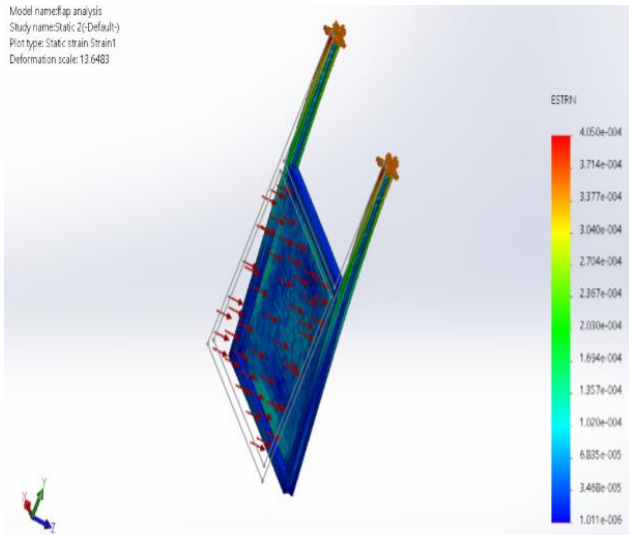


Fig 12:- Boundary condition

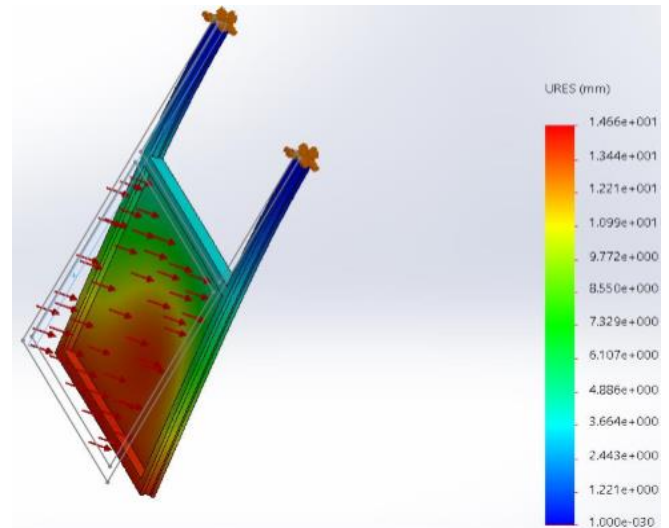


Fig 15:- displacement of flap

➤ Stress and strain calculation

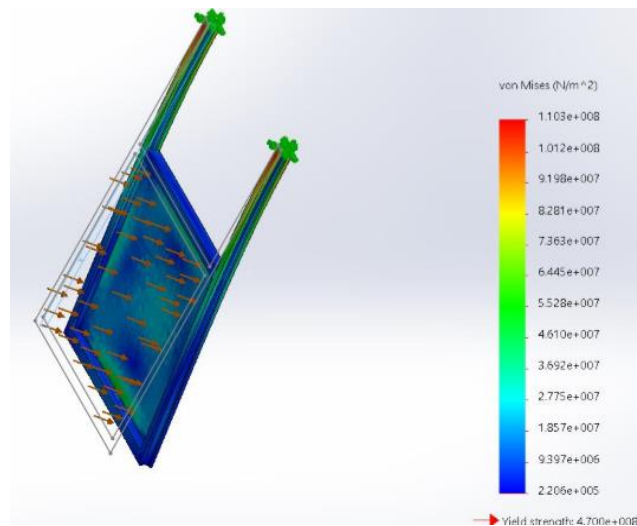


Fig 13:- Stress developed on flap

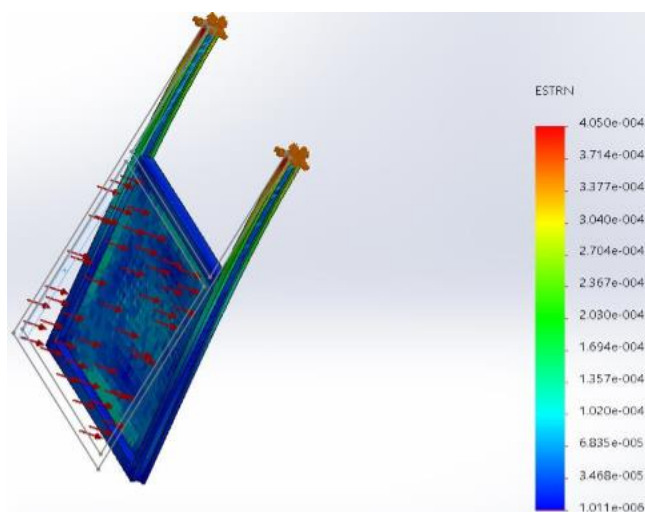


Fig 14:- strain developed on flap

The analysis shows that maximum value of stress developed is 110Mpa which is well below the yield limit of material (470 Mpa).

Strain and displacement analysis shows that maximum displacement of flap will be 14mm only which is quite acceptable value such a big structure.

**VI. CONCLUSION**

After studying the various journals on wave energy utilization it has been observed that only limited countries in the world have the technology for conversion of wave energy in the electrical energy. The major reason behind it is the challenges faced due to fluctuation of wave, intermittency, high and low tides availability etc.

In India, the Vizhinjam wave energy plant, based on Oscillating Water Column (OSC) was decommissioned in the year 2000 due to inability in meeting the target requirements. As India has huge availability of wave energy due to longer coastal area, there is a great opportunity for fulfilment of demand, but it requires extensive research and investment.

We have developed Oscillatory Wave Energy Converter (OWEC), which is capable of generating 7.4 KW/m width of flap, with theoretical efficiency of about 59 percent. This OWEC helps us to reduce facility installation costs, increases stability, and facilitates maintenance, rather than the existing technologies installed on the sea or the ocean floor. Lots of big cities and harbors next to the ocean can harness the power of the waves for their consumption. Also this will reduce dependency on foreign companies for fossil fuels, if energy from wave power can be extracted up to its maximum. Underwater cable not required; the energy is transferred from the unit installed onshore to units installed on land directly.

Design of Oscillatory Wave Energy Converter can be improved further more to increase the efficiency. Also there is need of further more study and research.

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