Investigation in a Ocean Wave Energy Converter with a Flywheel

A Thesis Presented

by

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Abstract of the Thesis

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A wave energy converter with a flywheel has been investigated and three conceptual designs of power take-off system have came up of which the third generation conceptual design has been built as a prototype for test. Among variable types of wave energy converters, Salter's Duck can convert wave energy to mechanical energy with high efficiency up to 90%. Salter's Duck moves in two directions as waves come and a power take-off system should be designed connected with Salter's Duck for converting mechanical energy to electrical energy. Considering the intermittent energy input, a flywheel energy storage system is included in the power take-off system. The prototype built based on the third generation conceptual design is able to capture energy in both directions which means no matter Salter's Duck moves up or moves down increasing the energy conversion efficiency. Three groups of tests are carried out under the conditions of different power input and different number of flywheels to demonstrate that flywheels can smooth the power output. The results from tests can be referred to for building real model in the future.

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Acknowledgments

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Chapter 1:Introdution

Waves Feature

Ocean waves is caused by wind blowing over the surface of ocean[1] and can continuously generate as long as the consistency and force of wind is enough. Waves motion exists everywhere in ocean waves which is formed by the periodic movement of water particles away from balancing position by the external force. One particle movement will drive other particles move due to fluid continuity resulting in waves propagation, thus periodicity of time and space is main feature of waves motion. Actual waves movement is expected to be more complicated and cannot be viewed as strict periodicity, however, motion of waves can be simplified as sinusoidal motion for convenient analysis which is described by sinusoidal functions as Figure 1.

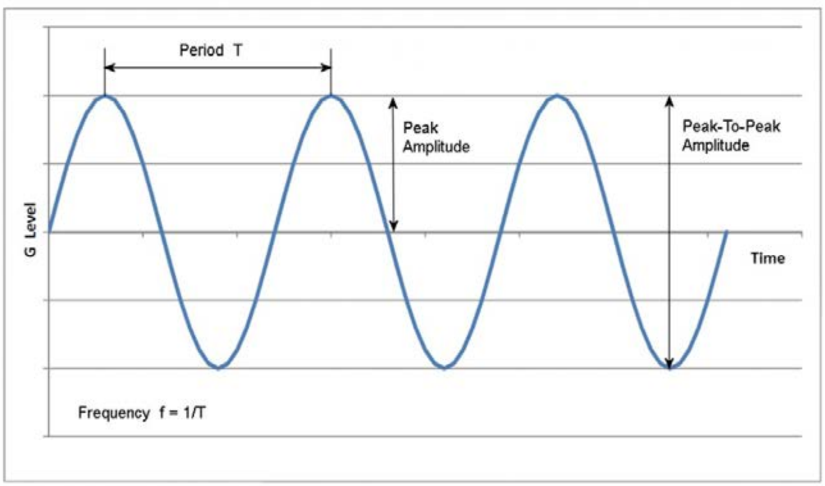


Figure1. Simplified waves mode

The vertex point and nadir point of curve is viewed as waves crest and waves trough respectively; the horizontal distance between two adjacent waves crests or waves troughs is regarded as waves length; the time of two adjacent waves crests or waves troughs passing one fixed point is called period, then the waves propagation speed is waves length/period; the vertical distance between waves crest and waves trough is called waves height and half of waves height is amplitude which is the maximum displacement of particle away from horizontal level.

Sinusoidal function is expressed as below:

$$\zeta = a\sin(kx - \sigma t) \tag{1}$$

a: waves amplitude; ζ: vertical distance between waves plane and horizontal plane. Obviously, it is the function of displacement, time, waves number and frequency. k and σ defined as waves number and frequency are expressed as:

$$k = \frac{2\pi}{\lambda} \tag{2}$$

$$\sigma = \frac{2\pi}{T} \tag{3}$$

k and σ are waves number and frequency respectively.

The amount of power of ocean waves can be calculated based on the amplitude of waves, A, the density of waves, p, the gravitational acceleration, g, and the period of waves, T[2].

$$P = \frac{\rho_w \cdot g^2 \cdot A^2 \cdot T}{8\pi} \tag{4}$$

With this equation, the waves energy can estimated under a specific waves condition. The greater waves amplitude and waves period is, the more power can generate as waves move.

The feature of waves propagation is that waves height becomes decreased; waves length and period increase and waves propagation accelerates gradually during the process because of the energy lost.

Necessity of Exploiting Wave Energy

With the development of human society, the growth rate of worldwide demand for energy continues increasing including petroleum, natural gas and coal, which is fossil fuel and non-renewable resource. It is estimated that petroleum will run out in 40 years; natural gas will run out in 60 years and coal will run out in 220 years[3]. Not only this issue should be considered, but also consuming fossil fuel can release large amount of carbon dioxide, sulfur dioxide and inhalable particles worsening greenhouse effect, increasing atmospheric temperature and abnormal climate. Considering these severe environmental conditions, a lot of conferences regarding climate and environment have been hold over the world making agreement on greenhouse gases release control, reduction of consuming fossil fuel and promotion of exploiting renewable resource. By now, several types of new-energy technology like nuclear energy power generation, hydraulic power generation have been developed, however, these technologies are faced with some safety and environment issues.

Nuclear energy power generation can decrease the demand for fossil fuel as well as exhaust and smoke emission, however, there is potential danger that severe nuclear radiation happens posing threat to lives and property, besides, it is hard to store and deal with nuclear waste. Hydraulic power generation can be also viewed as utilizing renewable resource but building a reservoir needs to move residents out of living area and make change to underground water level, even brings out earthquake. Ocean waves energy generation is free of fuel and neither discharge waste nor cause environmental problems as severely as other power generation methods. As a result, it is necessary to develop ocean waves energy converter not only for reduction of exploiting fossil fuel but also for environmental protection.

The worldwide resource of waves energy has been estimated more than 2 TW, and locations with the most potential for waves power include the western seaboard of Europe, the northern coast of the UK, and the Pacific coastlines of North and South America, Southern Africa, Australia, and New Zealand depicted as Figure 2.

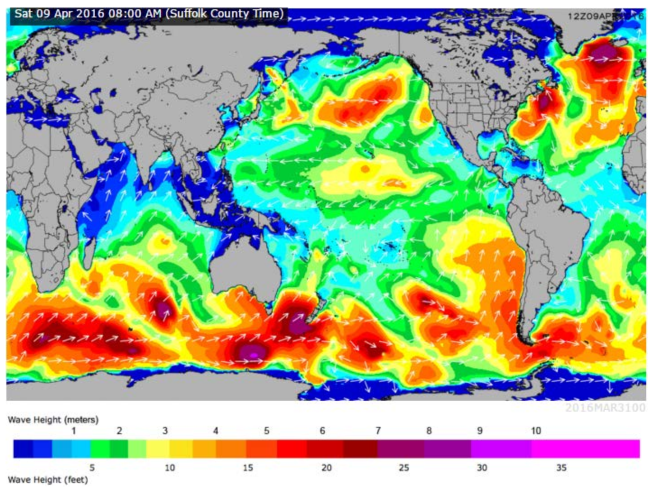


Figure 2. Wave Energy Distribution over the World

Waves energy potential is given in terawatts-hours/year and Electric Power Research Institute estimates the total waves energy along the outer continental shelf at 2640TWh/yr, which is tremendous considering just 1TWh/yr can supply about 93850 homes in US annually and recoverable waves energy is around 1170TWh/yr. Waves energy is huge near shoreline which areas are densely populated and industrial developed causing plenty of energy consumed. Traditional energy resource can release amount of effluent and exhaust leading to water contamination and air pollution, however, waves energy is clean power which leaves less influence on environment. Although ocean waves energy performs advantages stated above, it is still limited today compared with wind energy, solar energy and other renewable energy resource . In fact, the Renewable 2010 Global Status Report [4] states that ocean wave power conversion is the least mature technology compared with other renewable energy technologies. By the end of 2008, ocean power only accounted for about 300 megawatts produced worldwide, as opposed to photovoltaic systems with 13 gigawatts and wind power with 121 gigawatts[5]. The difficulty in exploiting wave energy mainly for three reasons:

First, ocean waves energy is tremendous in total, however, the energy is distributed over the world resulting in energy stored in unit volume is far less than expected and hard to utilize. Waves energy near shoreline has potential to develop compared with energy in deep ocean, which is far away from shore, terrible current condition and hard to exploit, besides, waves condition is variable in different areas and time, presenting sever challenges to develop waves energy.

Second, ocean waves converters installed in ocean have to endure extreme situations such as choppy waves condition and high pressure of waves as well as the damage to the converter structure caused by corrosion of waves and organism, a process known as biofouling[6]. It is unavoidable to conduct frequent maintenance, thus increasing the development cost of ocean waves converters. For instance, the three first generation Pelamis was located off the northwest coast of Portugal and generated as much as 2.25MW as the world's first multiple machine waves power project, however, it was taken offline in November 2008 due to the financial difficulties[7].

Third, developing ocean waves energy also can leave influence on environment like influencing environmental condition and changing current level. These issues must be taken into consideration.

Classification of ocean wave converters

The working theory and structure of ocean waves converters is not as complicated as other power generation methods. Often two systems including in a ocean waves converter: energy capture system for capture waves energy like Oscillating Water Column, Buoy, Pendulum, Salter Duck, Raft, Tapchan and Clam; power take-off system like air impeller, hydraulic system, mechanical system and generator.

Idea of waves energy take-off is from the observation of waves in the daily life. Waves motion is a kind of reciprocating movement that can make converters do work and convert to electrical energy. There are many kinds of designs based on this idea and their general working theory is similar: one object moves along with waves and another one is relative still compared with it, then a power take-off system will convert the mechanical energy to electrical energy. Ocean wave energy converters vary in structures and working theory. Designers should build converter dependent on waves condition in different areas. Classification of ocean wave converters in mounting types and power take-off systems has a certain reference value for the designers.

Classification in mounting types:

Ocean wave converters are classified as floating and fixed form. The main structure is fixed under waves and waves power take-off system directly generator energy from waves. Fixed ocean wave converters are classified in on-shore and off-shore according to location. On-shore wave converter installed near shore is more convenient for management, maintenance and power transmission and in most cases efficiency becomes high when located appropriately, however, the waves energy density near shore is relatively lower compared with off shore. Off-shore wave converter fixed on the seabed may absorb more energy because wave energy density is higher but amount of waves pass by converters leading to low efficiency of energy conversion as well as difficulty for maintenance and high power transmission cost. On-shore fixed wave converter and off-shore wave converter are described as Figure 3 and Figure 4 respectively.

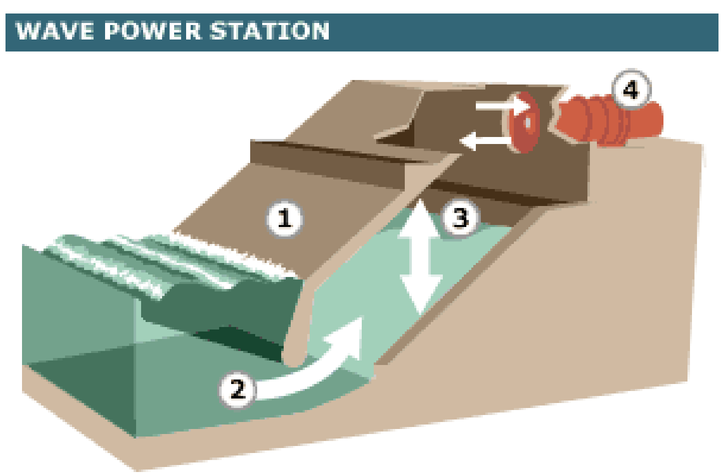


Figure 3. On-shore fixed wave converter

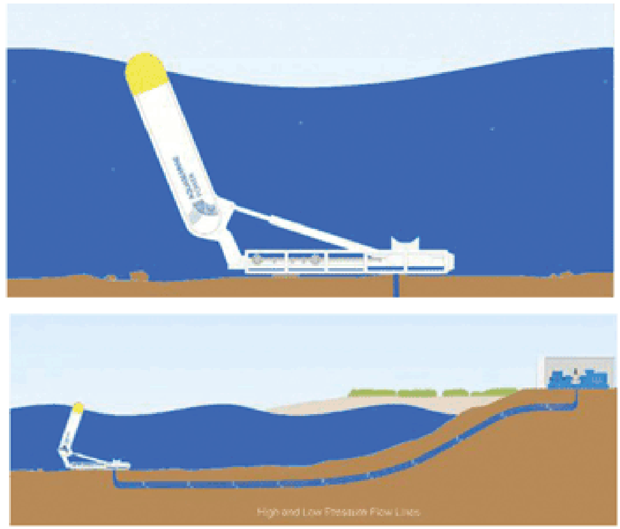


Figure 4. Off-shore wave converter

Wave capture chamber is made of reinforced concrete set into rock face and tide power forces water into chamber which results in air alternately compressed and decompressed. Well turbine driven by rushes of air always rotates in same direction regardless of the air direction and system continuously generates power.

Oyster wave device attached to the seabed at depth of between 10 and 15 meter pitches back and forth under the influence of waves and flap drives hydro-electric turbine via two hydraulic pistons.

For floating ocean wave converters, main structures floating on waves with a cable connected to the seabed absorb wave energy and convert to mechanical energy, finally, electricity outputs via power take-off system. The disadvantages of floating wave converter lies in low efficiency and more probability of structure and power transmission system damage under the situation where the waves come roughly. Two typical floating wave converters are depicted as Figure 5:

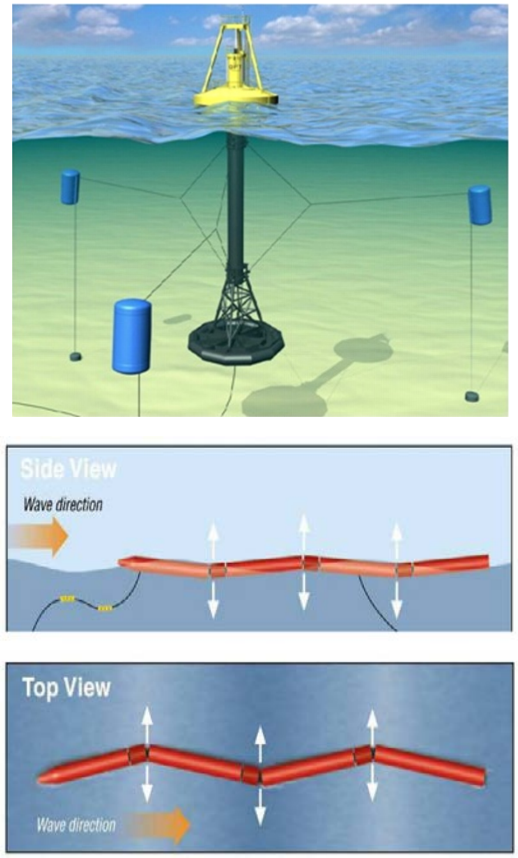


Figure 5. Floating wave converters

Buoys utilize the reciprocating motion of swells caused by rising and falling of waves to drive hydraulic pump and generate electricity. Pelamis wave converter [8] is made up of four sections which flex and bend as waves pass. Hydraulic system in the sectional chambers works while waves pass by and drive hydraulic generator to output electricity.

Classification in energy conversion type:

Power take-off systems classify in pneumatic, hydraulic and mechanical systems.

Pneumatic power take-off system converts the wave energy to air as waves go forth and back and air drives turbine rotates to generate power depicted as Figure 6. When waves come, the air is pushed upward to drive turbine rotate and when waves leave, the pressure in chamber decreases and air will be pushed up when the next waves come. In most cases, the pneumatic power take -off system is utilized in on-shore wave energy converters.

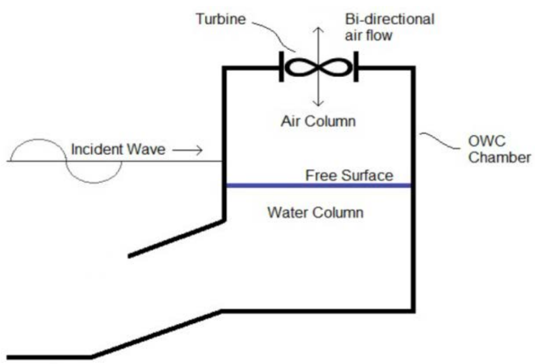


Figure 6. Pneumatic power take-off system

Hydraulic power take-off system converts the wave energy to hydraulic energy as waves pass. Mechanical movement of body drives hydraulic piston and hydraulic oil is pressured to make turbine rotating output electricity described as Figure 7:

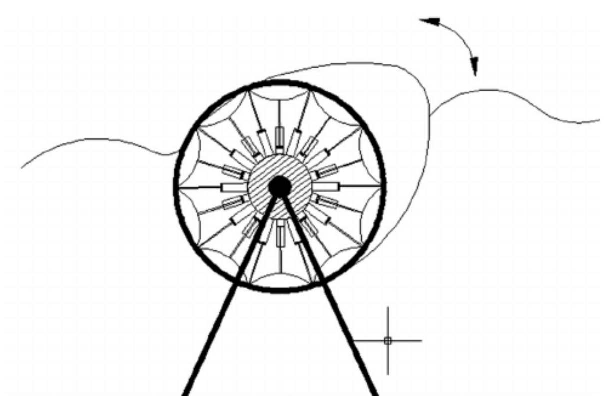


Figure 7. Hydraulic power take-off system

Mechanical power take-off system converts the wave energy to mechanical energy that drives generator via gearbox described as Figure 8. The mechanical power take-off system connected to the ocean wave converter can convert mechanical energy to electricity energy. The rotating speed of input shaft is relatively low and in most cases, there is a gearbox including in the power take-off system used as acceleration to improve the power output. The input energy is intermittent and usually there is flywheel installed in the system functioned as energy storage to smooth the power output.

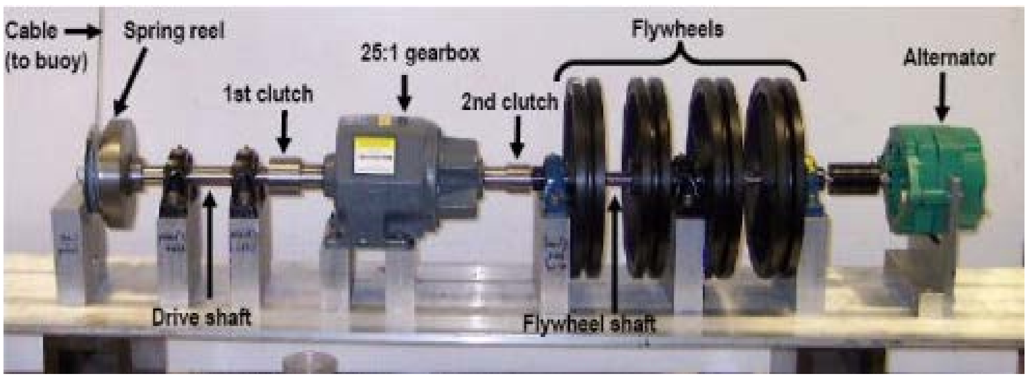


Figure 8. Mechanical power take-off system

Energy storage system

Buoy moves in a swinging way while receiving waves, and converts the kinetic energy of ocean waves to electrical energy as waves move forward. A buoy utilizes this kind of energy conversion is called Salter Duck. A conceptual illustration of Salter Duck is depicted as Figure 9.

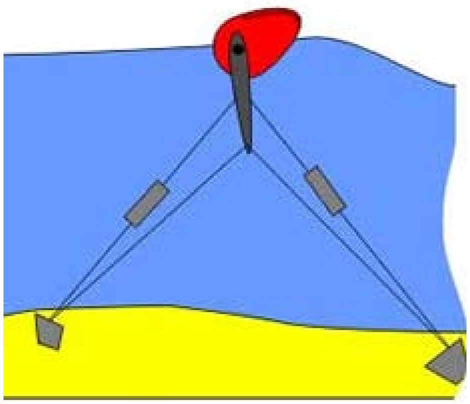


Figure 9. Conceptual design of Salter's Duck

The buoy depicted in Figure 9 is the motivation of the Salter Duck in the research. It is a buoy that floats on the waves and moors to the seabed with long cable. Inside there is a shaft mounted on the Salter Duck body, and shaft rotates clockwise and anticlockwise with the motion of buoy. The shaft connects to generator via a gearbox, then the system will output electricity.

Renewable energy system is faced with more challenges than the conventional power system and the most serious challenge is that the input to the system is unpredictable and intermittent. Conventional energy system generate power utilize gas or steam, which can be controlled considering the condition of output energy and undesirable factors. For instance, solar energy is unavailable if the day is cloudy or in the evening, which prevents the solar collectors absorb sunlight, then the solar system fails to generate power. Also for wind energy, wind condition is variable in one period and intensity of wind can change which results in the unpredictable input to system, even damages the wind power system. For waves energy converter, challenges are more serious in two aspects, first, the corrosion of waves and organism can damage the ocean waves converter gradually leading to frequent maintenance of device, second, the waves is more unstable than other resource that results in unpredictable and intermittent input.

Moment of inertia of flywheel

Considering the intermittent energy input, energy should be stored and release when the input process ends. Battery can be used in this case, however, it cannot react very fast while charging and discharging and lifespan will reduce due to frequent working of battery. Instead flywheel is installed in system that functions as energy storage. The input energy will partially convert to rotating kinetic energy stored in flywheel[9] and flywheel delivers energy to generator constantly.

Equations indicate that energy stored in flywheel depends on the rotating speed and moment of inertia. Moment of inertia referred to rotating inertia must be calculated with a specific rotating axis. For a point mass, the moment of inertia is the mass times the square of the perpendicular distance to the rotating axis. Given as:

$$I=m*r^2 \tag{5}$$

Continuous mass distributions require an infinite sum of all the point mass moments which make up the whole[10]. Given as:

$$I=\int_0^M r^2 dm \tag{6}$$

Three properties of an object will influence its moment of inertia: shape; density distribution of object and the position of axis.

Moment of inertia for a hollow cylinder as Figure 10 can be calculated according to the length L; mass M; volume V. Given as:

$$\rho = \frac{M}{\pi(R2^2 - R1^2)L} \tag{7}$$

$$I = 2\pi\rho L \int_{R1}^{R2} r^3 dr = 2\pi\rho L \left[\frac{R2^4}{4} - \frac{R1^4}{4}\right] \tag{8}$$

$$I=\frac{\pi}{2}\left[\frac{M}{\pi(R2^2 - R1^2)L}\right] L[(R2^2 - R1^2)(R2 + R1^2)] \tag{9}$$

$$I = \frac{1}{2}M(R2^2 + R1^2) \tag{10}$$

Moment of inertia of hollow cylinder dependents on mass M, internal diameter R1 and external diameter R2. Under the same mass condition, the larger the internal and external diameter are, the more moment of inertia can gain. That is why the mass of flywheel should concentrate on the outer part.

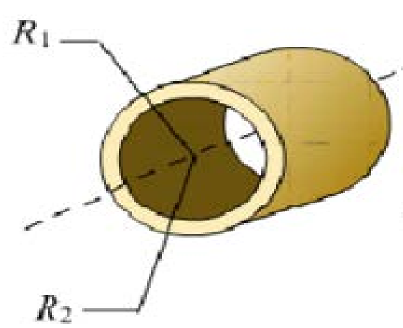


Figure 10. Hollow cylinder

Moment of inertia of a solid cylinder as Figure 11 can be calculated from the integration of equation:

Length L; Radius R; Mass M; Volume V; Density: M/V

$$dm=\rho dV=\rho L2\pi rdr \quad (11)$$

$$I=2\pi\rho L\int_0^R r^3dr = 2\pi\rho L\frac{R^4}{4} \quad (12)$$

$$I=2\pi\left[\frac{M}{\pi R^2 L}\right]L\frac{R^4}{4} = \frac{1}{2}MR^2 \quad (13)$$

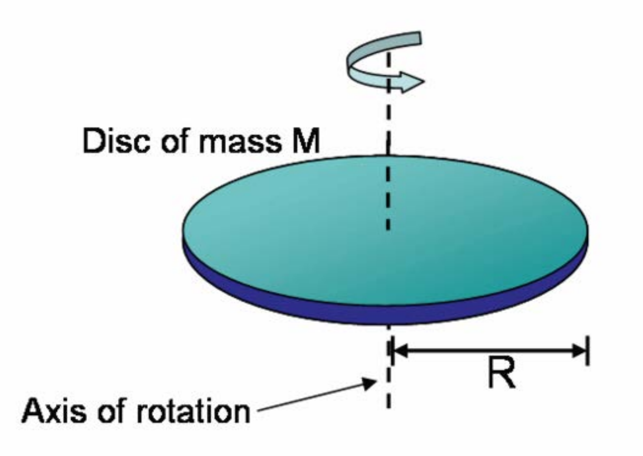


Figure 11. Solid cylinder

Moment of inertia of solid cylinder depends on the mass and radius of cylinder. The larger the mass and radius are, the more moment of inertia can gain. Under this case, density is distributed uniformly which means radius has to be large enough to gain more moment of inertia.

According to equation 10 and equation 13, under the given mass case, moment of inertia of a hollow cylinder is proportional to $(R1^2 + R2^2)$ and moment of inertia of solid cylinder is proportional to R^2, which means the size of hollow cylinder is smaller than solid cylinder to obtain the same moment of inertia. Under the given external diameter condition, $(R1^2 + R2^2)$

of hollow cylinder must be larger than R^2 of solid cylinder which means the hollow cylinder mass can be smaller than solid cylinder mass to achieve the same moment of inertia. This is the reason that in most cases, the mass of flywheel concentrates more on the outer part and the shape is not just a solid cylinder for saving space and decreasing weight.

Equation 14 shows the energy stored in flywheel depends on the rotating speed and moment of inertia of flywheel.

$$E = \frac{1}{2} I\omega^2 \qquad (14)$$

According to the equation 14, the energy stored in flywheel can be larger as the rotating speed of flywheel increases. That is why in most cases, the flywheel in installed exactly before generator for higher energy storage. The most of energy stored in flywheel must be transferred to generator before next wave front comes so that the energy of next wave can be stored in flywheel[11]. According to the equation 14, more and more rotating speed of flywheel is desirable, however, the maximum rotating speed of flywheel is limited to the its bearings.

A flywheel energy storage system operates by storing the input energy as rotating kinetic energy during the period when flywheel rotating accelerates. Later rotating kinetic energy of flywheel is transmitted to generator and the rotating speed decreases. Without a flywheel system, the energy output can experience a peak and lull process which is like sine pulse wave as Figure 12.

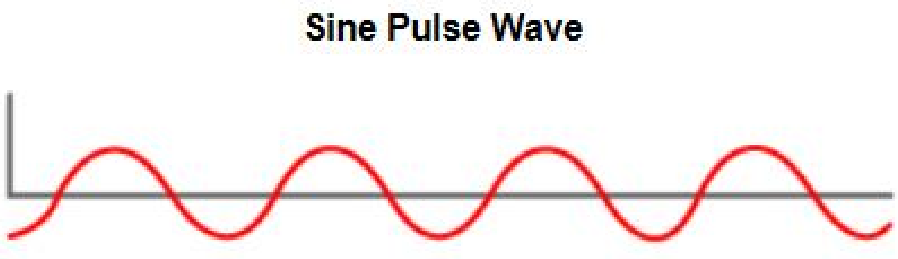


Figure 12. Impulse energy output

As waves arrive, Salter Duck body starts to rotate and decelerates finally becomes still at the moment when Salter Duck body reaches the vertex point. In this period, the shaft connected to generator also experience from acceleration to deceleration resulting in power output fluctuation, and the same condition as waves leave. The output power should be continuous and smooth for utilization by facilities. Considering about this issue, a kind of energy storage system should be included in power take-off system and flywheel is an ideal option compared with battery and other energy storage types. Flywheel begins to store energy as rotating accelerates which can smooth power output at peak and later transfers the energy stored in the flywheel to generator as waves movement becomes weak to maintain the power output stability.

Furthermore, energy stored in flywheel can prevent the generator from sometimes coming to a complete stop at the moment when Salter Duck body reaches the vertex point and nadir point. The start-up torque is known as the torque that requires to make generator work and opposes to the shaft rotating direction, which means extra torque is needed as long as generator stops working. Such issue will cause a lot of energy lost in the power take-off system leading to low efficiency.

As a result, flywheel energy storage system can not only smooth the output power but also is able to decrease the possibility of energy lost improving energy conversion efficiency. The flywheel installed in power take-off system is depicted as Figure 13.

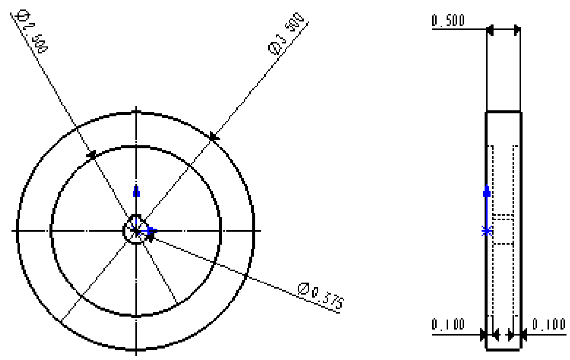


Figure 13. Flywheel in power take-off system

The flywheel designed in project can be viewed as the combination of solid cylinder and hollow cylinder. The mass concentrates on the outer part to achieve higher moment of inertia. According to the property of moment of inertia, the moment of inertia of flywheel can be calculated by the plus of moment of inertia of hollow cylinder and moment of inertia of solid cylinder. The moment of inertia of solid cylinder can be calculated according to the equation 13 and moment of inertia of hollow cylinder can be calculated according to the equation 10, then the moment of inertia of flywheel designed in this project can be calculated according to the equation 15.

$$I = \frac{1}{2} M_2 (R2^2 + R1^2) + \frac{1}{2} M_1 R1^2 \tag{15}$$

Of which the M_2 is the mass of outer part on the flywheel and M_1 is the mass of inner part of flywheel . From the equation, it can explain that why in most cases, the flywheel is made with most of mass concentrating on the outer part to gain high moment of inertia.

Chapter 3: Laboratory Prototype

Conceptual Design of Salter's Duck Body

Although this thesis concentrates on the design of power take-off system, it is also necessary to point out the basic ideas of designing Salter's Duck Body. The ocean wave energy converter power take-off system can work according to the reciprocating motion of Salter's Duck body. For the design of Salter's Duck body, three issues should be taken into consideration of which the first is the conversion efficiency and second is the returning of Salter's Duck body after waves pass and last is the mounting method. The efficiency of Salter's Duck body converting wave energy to mechanical energy can be up to 90% according to the test conducted by other group. The reason why Salter's Duck body can achieve such high efficiency is that as waves pass, the Salter's Duck body can rotate in two directions along with waves, under this case, the shape of Salter's Duck body is very important which can determine whether the Salter's Duck body is perfectly fit with wave length and absorbs the maximum wave energy. A simulation of Salter's Duck body moving along with waves should be carried out to determine which shape designed is the best for absorbing wave energy. In this paper, the design concentrates on the power take-off system and simulation is not conducted here. After simulation, the model should be put into water tank for test and utilize measuring meters to determine the how much wave energy is converted to mechanical energy after waves pass through Salter's Duck body. The second issue is about the returning back of Salter's Duck body after waves crest pass by. Now there are mainly three methods of which the first is to utilize hydraulic system to force the Salter's Duck body back after waves pass; the second is to utilize spring system to force body back and last is to utilize the gravity of Salter's Duck body to force body back. Among three methods, the strict calculation should be conducted because if the force supplied by hydraulic system, spring system and the gravity is too large, it is hard for Salter's Duck move along with waves causing the energy lost, and if the back force is too small, the Salter's Duck body may rotate more than 90 degree under the strong waves condition leading to the failure of returning back, then the whole system fails to convert energy. In this paper, the design of Salter's Duck body is not carried out and such calculation is not included in. The last issue should be taken into consideration is that the mounting method. In the current waves energy converters there are main two ways to fix the equipment. The first one is totally to fix the waves energy converters on the shore or seabed and the second one is to utilize a cable connect converters to seabed. For the Salter's Duck, often utilize a cable to fix equipment because Salter's Duck has to float on waves and it is hard to design a structure that can totally fix Salter's Duck because there is certain distance between Salter's Duck and seabed and the cost will be high. If the Salter's Duck can be totally fixed compared with waves, the conversion efficiency is higher as when waves pass the Salter's Duck will not move horizontally. The Salter's Duck can move horizontally as waves pass if it is fixed by cable connecting to seabed which means partial wave energy will be consumed for horizontal movement that should be avoided. There is an optimum distance value between Salter's Duck and seabed that can make Salter's Duck absorb maximum energy from waves in a given sea area and cable length can be calculated. For Salter's Duck, it is unavoidable that some wave energy will be lost in the horizontal movement and the cable should be selected under serious consideration to minimize the energy lost.

This paper emphasizes on the design of power take-off system. The wave energy is converted to mechanical energy through the rotating of Salter's Duck body and power take-off system utilizes the mechanical energy extracted from Salter's Duck body to convert into electric energy. To accomplish the function, a system should possess two features of which the first is a kind of system can convert dual directional rotating of Salter's Duck body to one-directional rotating and acceleration of shaft rotating connected to generator.

Ocean wave converter absorbers wave energy through the movement of Salter Duck body. As discussed above, Salter Duck body floating on waves will rotate clockwise and anticlockwise when crest and trough of waves pass through Salter Duck body, however, the shaft connected to flywheel and generator should rotate in one direction at all times to guarantee the polarity of output electricity same. A kind of transmission system should be designed to accomplish the function of converting dual-directional rotating to unidirectional rotating of shaft. Considering about these issues, three generation designs are carried out of which the first generation and second generation designs are conceptual designs and the third generation design has been built as prototype to test to demonstrate the practicability of dual-directional power took off and the function of flywheels that can be used to store the energy, then transfer energy to generator to make power output smooth under the situation where the waves become weak.

First generation design of power take-off system

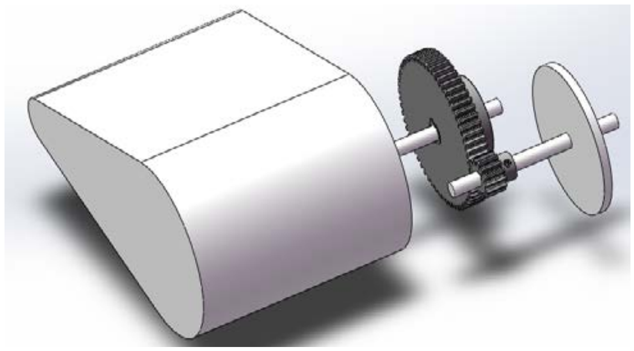


Figure 13. Firsr generation conceptual design

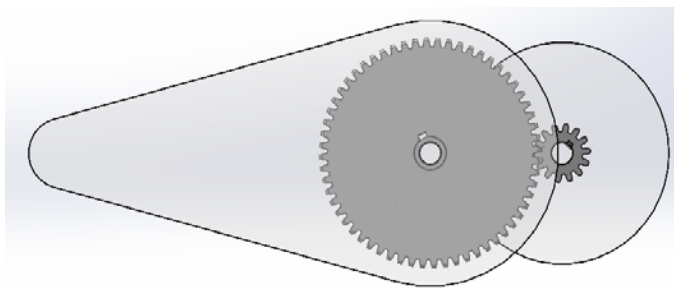


Figure 14. Mechanical structure

In the first generation design as Figure 13 and Figure 14, the function can be achieved by utilizing two one-way clutches and two spur gears. 60-teeth spur gear press fit on one-way needle clutch is set on the shaft connected to Salter Duck body and another 16-teeth spur gear is set on the shaft connected to generator. When Salter Duck body rotates clockwise, one-way needle clutch locks to transmit torque that drives 60-teeth spur gear rotate along with shaft and the shaft with 16-teeth spur gear will rotate anticlockwise to drive generator for electricity output. When Salter Duck body rotates anticlockwise, one-way clutch rolls freely and 60-teeth spur gear continues rotating clockwise although the shaft rotates anticlockwise resulting in the continuous power output of generator. A flywheel is included in power take-off system before generator used for energy storage.

This first generation power take-off system design is able to converter dual-directional rotating of Salter Duck body to unidirectional rotating of shaft utilizing clutch and gears to accomplish the basic function, however, the power take-off system can only work in one direction when Salter Duck body passes through waves crest as waves come. In another direction, Salter Duck body continues absorbing wave energy but the power take-off system fails to convert wave energy to electrical energy as one-way clutch rolls freely in this direction leading to the failure for 60-teeth spur gear transmitting torque to 16-teeth spur gear. As a result, the efficiency of converting wave energy to electrical energy nearly decreases 50% as spur gears become idle when Salter Duck body returns to the original position. As a result, a kind of power take-off system able to convert wave energy to electrical energy in dual directions should be taken into consideration.

Second generation design of power take-off system

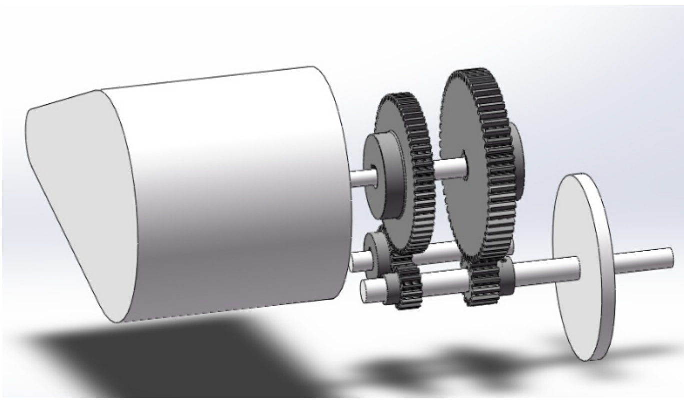
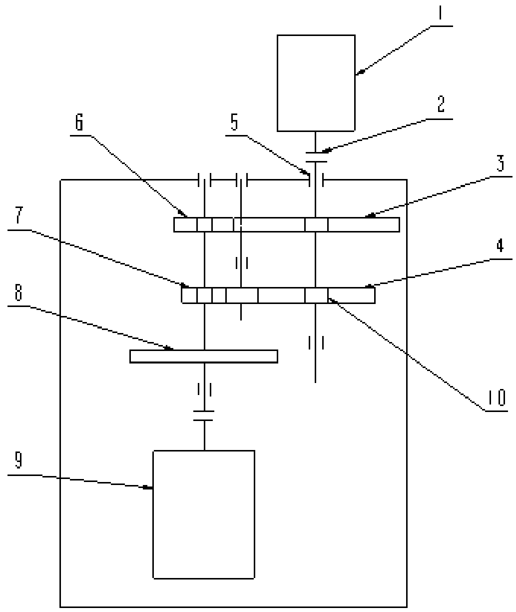


Figure 15. Second generarion conceptual design



1-electical generator 2-shaft coupler 3-10 pitch 60 teeth spur gear 4-12 pitch 60 teeth spur gear 5-mounted bearing 6-10 pitch 15 teeth spur gear 7-12 pitch 15 teeth spur gear 8-flywheel 9-generator 10-one-way needle overrunning clutch

Figure 16. Demonstration of parts

Compared with first generation design, the second generation design as Figure 15 and Figure 16 utilizing four one-way needle clutches, five spur gears including one idle gear is able to convert the wave energy to electrical energy no matter in which direction Salter Duck body rotates. Two one-way needle clutches are set on the shaft connected with Salter Duck body and each can lock to transmit torque in clockwise and anticlockwise rotating respectively and another two one-way needle overrunning clutches are set on the shaft connected to generator which function is explained later. The first gear system includes 12 pitch 60 teeth, 12 pitch 15 teeth and 12 pitch 24 teeth gears and the 24 teeth gear functions as idle gear. Besides, there is another gear system including 10 pitch 60 spur gear and 10 pitch 15 spur gear. When shaft across the Salter Duck body rotates clockwise, one of clutch will lock to transmit torque to drive 12 pitch 60 teeth gear rotate clockwise and the shaft with 12 pitch 15 teeth spur gear also rotates clockwise via idle gear while another needle clutch can roll freely in anticlockwise direction which drives 10 pitch 60 teeth spur gear rotate anticlockwise to guarantee the continuous clockwise rotating of shaft connected to generator for power output. When Salter Duck body shaft rotates anticlockwise, the one-way needle clutch rolled freely before turns to lock to transmit to drive the 10 pitch 60 teeth spur gear rotate anticlockwise and shaft connected to generator continues rotating clockwise through the fit of 15 teeth spur gear with 60 teeth sour gear while the one-way needle clutch locked before turns to roll freely in clockwise direction driving 12 pitch 60 teeth spur gear rotate clockwise and 15 teeth spur gear continues rotating clockwise via idle spur gear to accomplish the dual-directional rotating of Salter Duck shaft converting to unidirectional rotating of shaft connected to generator. When waves become weak but the shaft connected to motor still rotates in one direction, the power input become less, however, the system will keep rotating for a while then the system will decelerate gradually. Under this case, the five spur gears, shafts and "flywheels" can be all viewed as flywheel and flywheel here is not just a physical flywheel, however, the efficiency of system will decrease as more gears are involved in. As a result, two more one-way needle overrunning clutches are add into system which are fit into the two spur gears on the flywheel shaft. Now when the shaft connected to Salter's Duck rotating slows down, the spur gears on the flywheel shaft rotating also decreases but the flywheel shaft can continues rotating fast for a while with the help of overrunning which reduces the energy lost caused by contact of spur gears. Compared with first generation design, the second generation design basically accomplish the function of dual-directional power take-off resulting in more waves energy conversion with higher efficiency as waves pass through Salter Duck body. For prototype, the gear box here is just designed to demonstrate the basic function of dual-directional power take-off system that means the simplest design obtaining the highest gear ratio is preferable. In this design, there are two problems existing in the gear ratio and dimension issue. First, in both directions, the gear system functions only as first stage transmission leading to the lower ratio which is 4:1 in the design. Second, arrangement of gears is needed to be seriously considered as the same gear ratio is desirable no matter the shaft rotates clockwise or anticlockwise which means the gear system including idle gear has to be larger than another gear system causing the larger size of gearbox.

Considering about these issues, a third generation design which can separate the function of converting dual-direction rotating to unidirectional rotating and rotating acceleration should be taken into consideration for higher gear ratio and smaller gearbox size.

Third generation design of power take-off system

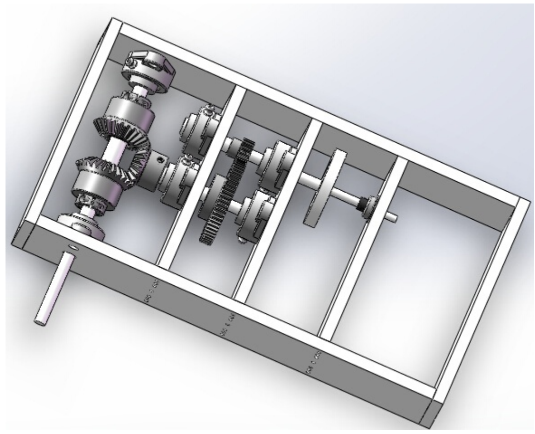


Figure 17. Third generation conceptual design

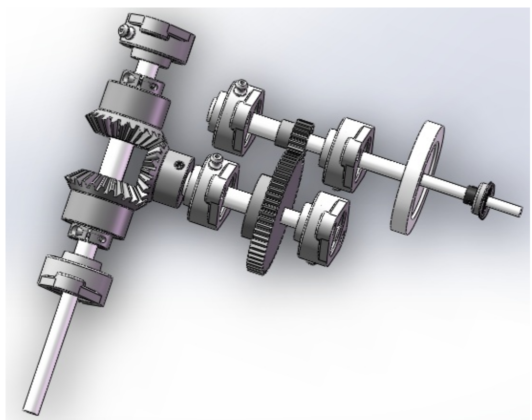


Figure 18. Demonstration of detailed structure

The third generation conceptual power take-off system designed as Figure 17 and Figure 18 accomplishes the dual directional power take-off utilizing bevel gears as Figure 19, spur gears as Figure 21 and one-way needle clutches as Figure 10. The shaft outside gearbox is connected with the shaft across Salter Duck body and rotates clockwise and anticlockwise along with Salter Duck body, and inside the shaft is mounted by two-bolt flange mount self-aligning ball bearings. Two 25-teeth, 10-pitch bevel gears with two one-way clutches inside are set on the input shaft two one-way clutches set on shaft roll in reverse directions. When input shaft rotates clockwise, one of the clutches locked to transmit torque will roll along with shaft which drives one of bevel gears rotate while another clutch rolls freely and another bevel gear pressed fit on the clutch rotates freely in reverse direction. When input shaft rotates anticlockwise, the one-way clutches locks to transmit torque before will roll freely and drive the bevel gear fit on also rotate freely while another one-way clutch and bevel gear start to rotate along with shaft. One of bevel gears set on shaft will always rotate along with shaft no matter which direction the shaft rotates in. The third 20-teeth bevel gear fit with two bevel gears on the input shaft will be driven depicted as Figure 18.

Figure 19. Bevel gears

Figure 20. One-way needle overrunning clutch

When input shaft rotates clockwise, the left 25 teeth bevel gear will be driven to rotate clockwise along with shaft which drives the third 20-teeth bevel gear rotate, then this 20 teeth bevel gear will drive the right 25 teeth bevel gear fit on the shaft rotate in reverse direction compared with the left one, and with the help of one-way clutch inside, the right 25 teeth bevel gear can rotate freely without influence on the input shaft rotating. When input shaft rotates anticlockwise, the right 25 teeth bevel gear will be driven to rotate anticlockwise along with shaft which continuously drive the 20 teeth bevel gear rotate in one direction while the left 25 teeth bevel gear rotates freely without influence on shaft. As a result, with three bevel gears and two one-way clutches, the shaft with 20 teeth bevel gear can continuously rotate in one direction no matter which direction the input shaft rotates in to accomplish the basic function of dual power-take off system. Now the basic direction conversion has been achieved, however, under this situation, the flywheel system cannot function well because the flywheel fails to decouple with the former part which means if bevel gear system stops rotating, although the flywheel shaft can also rotate with the help of one-way clutch in the bevel gear, energy stored in flywheel is lost caused by the friction of gears especially bevel gears. As a result, a solution should be came up to reduce the flywheel energy lost. In this prototype, there are four ways to reduce the energy lost of flywheel caused by friction. First, design a structure utilizing one-way ball overrunning clutch and sleeves which means a sleeve is set on the outer part of one-way ball bearing and the flywheel shaft is fixed into this sleeve while the shaft connected with 15-teeth spur gear is across the inner part of one-way ball bearing. Under this situation, when the gear system decelerates, this structure designed with one-way ball bearing and sleeve can decouple the flywheel shaft and spur gear shaft making flywheel continue rotating and energy stored in flywheel is mainly converted to generator. This is an ideal design to reduce the energy lost of flywheel, however, high precision is required to for machining parts, otherwise, slipping may occur between shaft and sleeve, shaft and inner part of one-way ball bearing or sleeve and outer part of one-way ball bearing. In this prototype, it is hard to reach such high precision and this structure is not decided to use here. Second, an one-way needle overrunning clutch can be added into the 15-teeth spur gear which means the 15-teeth spur gear drives shaft rotate and flywheel starts to store energy and when energy input to the system reduces, the 15-teeth spur gear rotating speed decreases, the shaft is able to rotate freely and flywheel can release energy to generator. Compared with the first design, the second design is a preferable choice for minimum energy lost caused by three mounted bearings, however, the 15-teeth spur gear is relatively small and it is hard to install one-way needle clutch inside. Under this situation, the second design fails to be practical. Third, a one-way needle overrunning clutch can be installed into the 60-teeth spur gear and once the gear shaft rotating decelerates, the flywheel system can continue rotating. In this design, the 15-teeth spur gear can be also viewed as "flywheel" because it can also generate moment of inertia which contributes to the flywheel system. The biggest problem is that the 15-teeth spur gear with small size and mass is unable to generate enough moment of inertia, meanwhile, there is energy lost caused not only by friction between shafts and mounted bearings but also by the friction between 60-teeth spur gear and 15-teeth spur gear. Considering above issues, the last design is came up. Add another one-way needle bearing into the 20-teeth bevel gear and now there are overrunning clutches in all bevel gears. As the input energy decreases, the 20-teeth bevel gear rotating speed may decrease but the one-way needle overrunning clutch can decouple the flywheel system and bevel gear system which means that although the 20-teeth bevel gear rotating slows down, the system after it can continue rotating with the help of overrunning clutch. In this condition, the 60-teeth spur gear can be regarded as "flywheel" and 60-teeth spur gear is much higher than 15-teeth spur gear discussed in the third design. Despite there is still energy lost caused by transmission of spur gears and friction of mounted bearings, the 60-teeth spur gear can function as flywheel that can offset the energy lost to some degree. The fourth design is taken into consideration and built at last. In addition, the 25 teeth bevel gears with 20 teeth bevel gear generates gear ratio of 1.25:1 which can also accelerate the rotating speed of shaft.

For ocean wave energy power take-off system, high rotating speed of shaft connected to generator should be gained in order to maximize power output. Considering the issue, a pair of gears used for acceleration is needed to include in the power take-off system functioned as accelerating and for this prototype, the design as Figure 21 is relatively simple compared with real model. In the commercial gearbox, the transmission ratio is much higher. In reality, the gearbox can be divided into main three types: the first is worm gearbox that consists of worm gears but can only function as speed reducer and is hard to build because of the high precision; the second is planetary gearbox that can function both as speed reducer and speed accelerator, however, for a prototype, it is too expensive and also becomes hard to build it; the third is spur gearbox that is the easiest to build but still needs high precision. In the prototype, just build a simple spur gearbox to accelerate. The commercial gearbox will be used in the real ocean wave converter model.

Figure 21. Spur gears

The teeth of two spur gears are 60 teeth and 16 teeth respectively. The 60 teeth spur gear is mounted on the same shaft as 20 teeth bevel gear while the 16 teeth gear is mounted on another parallel shaft connected to flywheel and generator. The three bevel gears system described before accomplishes the continuous rotating of shaft with 60 teeth spur gear whichever direction the Salter Duck body rotates in, then the shaft with 16 teeth spur gear connected to generator will rotate resulting in power output. This pair of spur gears can generate gear ratio of 3.75:1, along with the gear ratio of bevel gears, the gear ratio of whole power take -off system is 4.7:1.

Compared with first generation design, the third generation design achieves the function of converting dual-directional shaft rotating to unidirectional shaft rotating obtaining more power output and higher efficiency. Compared with second generation design, as bevel gears system mainly functions as converting rotating direction and spur gears system mainly functions as rotating acceleration, the gearbox size becomes smaller, besides, the gear ratio of bevel gears system is 1.25:1 which also contributes to increasing the gear ratio of whole system which is higher than the second generation design.

The design of gearbox in this thesis is ineffective if applied to the real commercial model as in reality, the gear ratio should be much larger to accomplish high rotating speed of shaft to maximize the power output, however, for prototype discussed above, the design of gearbox is just used to verify the practicability of dual power take-off system.

For this prototype, I decide to use a worm gear reducer motor to simulate the movement of Salter Body by waves ahead of gearbox for three reasons:

First, in this thesis, the project more concentrates on the design of dual-directional power take-off system instead of Salter Duck body. The key point is to demonstrate the function and practicability of system and for power take-off system, the rotating of motor shaft and movement of Salter Duck body can achieve the same effect and using motor is more convenient compared with building a Salter Duck body.

Second, for prototype, it should be tested in a lab tank at the first design stage to verify its practicability then moved into ocean waves for further test, however, such test for ocean wave converter is not available in the department and two problems have to be faced if directly test the prototype in waves: the sealing issue of gearbox which means the leakage of gearbox will lead to generator breaking down and lubrication failure; although Salter Duck is widely used near shore, there is still certain distance away from the shore. The equipment is relatively limited in the lab and it is difficult to fix the system in the waves.

Considering about the reasons listed above, a worm gear reducer motor as Figure 22 is decided to install ahead of gearbox to verify the function of gearbox. The worm motor is connected with

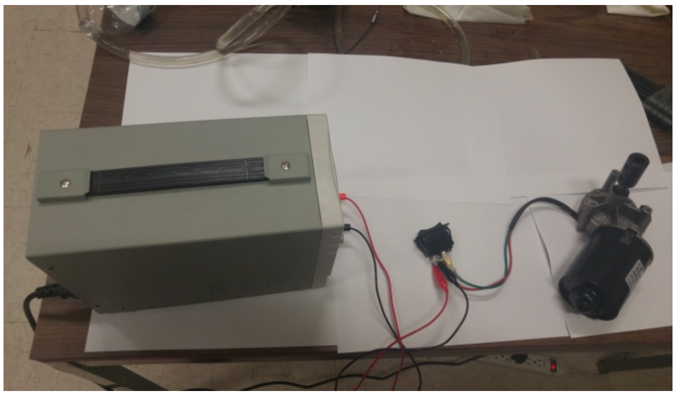


Figure 22. Ocean waves motion simulation

Figure 23. Regulated DC power supply

A DC regulated power supply as Figure 23 is connected to worm gear reducer motor via a Switch Polarity Reverse DC Motor Control. The input power transmitted to motor is supplied by DC regulated power supply which can be calculated by the voltage and current displayed on the screen. The Switch Polarity Reverse DC Motor Control can accomplish the function of changing the motor shaft rotating by reversing the power output polarity pressing the button on switch, then the motor shaft rotating can be controlled to rotate clockwise or anticlockwise which can be viewed as movement of Salter Duck body.

Chapter 4: Guideline for Designing Gearbox

In this prototype, the design of shafts and selection of bevel gears and spur gears mainly based on achieving function because the torque is relatively low in this condition and strength check and relative calculation is not carried out in this paper, however, for the real model, such calculation must be conducted as the torque is much higher in reality which can lead to parts working failure if the diameter of shafts, size of gears and some other parameters are not appropriately determined. As a result, it is necessary to carry out strength check of shafts and gears. Although calculation is not included in this design, it is necessary to introduce basic principles for designing gearbox.

Power Input Estimation

When design a ocean wave energy converter utilizing mechanical system, it is important to estimate how much the energy can be converted and what kind of generator should be selected. A generator can be selected based on the design of ocean wave capture device which refers to Salter Duck body in this paper or the capture device can be designed based on generator. To design Salter's Duck body based on selected generator is preferable because in most cases, the amount of electricity desired to generate is set before designing the ocean wave converter that means the kind of generator is decided at the beginning. Under this case, the design of Salter's Duck body is based on the calculation depending on the parameters of generator.

For generator, the rated voltage and rated current output under rated rotating speed is know. For Salter's Duck body, the oscillating rotating speed and rotating period is determined by the wave length and wave period of ocean waves. The oscillating rotating of shaft connected to Salter's Duck body finally is converted to unidirectional rotating of shaft connected to generator and rotating speed of Salter's Duck shaft and generator shaft can be viewed as known conditions which determine the transmission ratio and structure of gear system. The transmission efficiency of gear system mainly dependents on the efficiency of gears transmission, bearings and shaft couplers. Plus the efficiency of each part and total transmission efficiency can be obtained as η. According to the transmission efficiency and generator power output Poutput, the desirable input power Pinput can be calculated as equation 14.

$$Pinput=Poutput/\eta \qquad (14)$$

To obtain the desirable input power of system, the design of Salter's Duck shape and size is important because more wave energy can be converted if the Salter's Duck body shape and size are determined appropriately. At the first design stage, it is much convenient to conduct a simulation of Salter's Duck movement on the waves to decide the size and shape of Salter's Duck body to obtain the desirable power input to the gear system, then test the Salter's Duck in a water tank and collect data for analysis and optimization for further design. Finally, the design of Salter's Duck body can be finished.

Transmission Ratio Distribution in Power Take-off System

Transmission ratio of power take-off system can be calculated by the rotating speed of shaft connected to generator and rotating speed of shaft connected to gearbox as equation 15.

$$i=n_{motor}/n \qquad (15)$$

The transmission ratios of different pairs of gears can be determined by total transmission ratio and gears property which are depicted as i_{1}, i_{2}, i_{3}, ...i_{n}.

Calculation of Dynamic Parameters on Shafts

Until now, rotating speed of shaft connected to generator and transmission ratio of each pair of gears are known, the rotating speed of each shaft can be calculated according to known conditions. The relationship of rotating speed between two shafts can be determined as equation 16.

$$n_1=n_2/i \qquad (16)$$

The rotating speed of each shaft can be calculated as n_{1}, n_2, n_3,......,n_n.

The power transferred on each shaft can be decided by power input to power take-off system which refers to the power converted by Salter's Duck body and corresponding efficiency accumulated to each shaft as equation 17. The power transferred on shafts can be calculated as P_1, P_2, P_3,.....,P_n.

$$P_1=P_{input}*\eta_{1}; P_2=P_1*\eta_2=P_{input}*\eta_1*\eta_2=;......;P_n=P_{input}*\eta_1*\eta_2*.....*\eta_n \qquad (17)$$

The torque exerted on each shaft can be calculated based on the corresponding transferred power and rotating speed. The power transferred on shaft is expressed by torsion exerted on shaft and shaft linear rotating speed as equation 18.

$$P=F*V \qquad (18)$$

P is expressed as power transferred on shaft (W) ; F is expressed as torsion exerted on shaft (N) ; V is expressed as shaft linear rotating speed (m/s).

The torque exerted on the shaft can be calculated by torsion and its corresponding radius according to equation 19 and equation 20.

$$T=F*R \tag{19}$$

$$F=T/R \tag{20}$$

T is expressed as torque toque exerted on shaft (N*m); F-Torsion exerted on shaft (N) ; R is expressed as Shaft radius (m)

The linear velocity of shaft can be calculated by rotating speed and radius of shaft according to equation 21.

$$V=2*\Pi*R*n/60=\Pi*R*n/30 \tag{21}$$

V is expressed as linear velocity of shaft (m/min); n is expressed as shaft rotating speed (rad/s); R is expressed as shaft radius (m)

Insert equation 20 and equation 21 into equation 18 and the power can be expressed by torque and rotating speed as equation 22.

$$P=F*V=T/R*\Pi*R*n/30=T*\Pi*n/30 \tag{22}$$

The unit of power output is watt and convert unit into kilowatt, then get equation 23, 24 and 25:

$$1000*P= T*\Pi*n/30 \tag{23}$$

$$P= T*\Pi*n/(30*1000) \tag{24}$$

$$P= T*3.1415926*n/(30*1000)=T*n/9549.297 \tag{25}$$

From the equation 21, the power transferred on shaft is related to the torque as well as rotating speed of shaft, then the torque exerted on each shaft can be expressed as equation 26.

$$T=9550*P/n \tag{26}$$

Now the power transferred on shaft and rotating speed of each shaft can be calculated according equations 16 and equation 17 and torque can be calculated according to equation 26. Torque on each shaft can be calculated as: T_1, T_2, T_3,......, T_n.

Calculation of Gears Transmission

In most cases, it is necessary to check the stress of the smaller gear in a pair of transmitted gears and the calculation introduced below are all in metric unit. According to the power take-off system working property, determine the gears precision and gear material through checking charts related to gear property and assume tooth number of gears. Calculate the diameter of pitch circle of gears according to equation 27.

$$d \geq 2.32 * \sqrt[3]{\frac{KaT_1}{\phi_d} * \frac{u+1}{u} * (\frac{Z_E}{[\sigma_H]})^2} \tag{27}$$

T_1 is the torque transferred on the gear which can be calculated according to the corresponding shaft rotating speed and transferred power that are discussed before. K_a referred to load coefficient which is assumed to a value at first and ϕ_d referred to face width coefficient and Z_E referred to elastic coefficient can be determined from chart. $[\sigma_H]$ referred to permissible stress can be calculated as equation 28.

$$[\sigma_H] = Z_{N1} * \sigma_{lim} /s \tag{28}$$

Z_{N1} referred to contact fatigue life coefficient and S referred to safety coefficient and σ_{lim} referred to contact fatigue strength limit can be obtained from chart. Based on these values, the pitch circle diameter range can be calculated. Determine the minimum pitch circle diameter as the temporary diameter of the gear, then the face width of smaller gear can be calculated as equation 29.

$$b=\phi_d*d \tag{29}$$

The module of smaller gear and addendum are calculated from equation 30 and 31.

$$m=d/z \tag{30}$$

$$h=2.25*m \tag{31}$$

The ratio of face width to addendum can be calculated as equation 32.

$$b/h \tag{32}$$

Load coefficient can be calculated from equation 33.

$$K=K_A*K_V*K_{Ha}*K_{Hb} \tag{33}$$

K_A, K_V, K_{Ha} and K_{Hb} can be checked from table according to the ratio of face width to addendum. This load coefficient is the accurate coefficient for smaller gear compared with K_a which is an assumed load coefficient and calculate pitch circle diameter of gear with K this time as equation (34).

$$d_1=d*(K/K_a) \tag{34}$$

Now calculate the module of smaller gear as equation 35.

$$m=d_1/z \tag{35}$$

According to the assumption and verify calculation of smaller gear, its module is decided, then the pitch circle diameter of small gear and large gear can be determined as well as the normal center distance. In addition, shafts are also important and necessary to be checked because the shaft working life may be reduced or even broke down if the stress is larger than the stress limit of shaft. As a result, a introduction to strength check of shaft is also included in this paper.

Calculation of Shaft Design

There are bending moment and torque exerting on the shaft and shaft design must be taken into consideration for long life and durability. The minimum diameter of shaft can be determined by equation 36.

$$d \geq C\sqrt[3]{\frac{P}{n}} \quad (36)$$

P is the corresponding power transferred on shafts and n is the rotating speed of shafts. C can be checked from table according to the material of shaft. The diameter of shaft should be considerable larger if there is keyway on the shaft.

The force exerted on the gears is divided into circumferential force and radial force which can be calculated according to equation 37 and equation 38.

$$F_t = \frac{2000T}{d} \quad (37)$$

$$F_r = F_t \tan a \quad (38)$$

T is the torque exerted on the corresponding gear and d is the pitch circle diameter and a is the pressure angle of gear. Bending moment can be calculated by the force decomposed by circumferential force and radial force. Torque transferred on shaft can be calculated by the circumferential force generated by gears. According to the bending moment and torque exerted on the shaft, the shaft section with highest bending moment and torque can be determined and in most cases, the strength check is only conducted on this shaft section according to the equation 39.

$$\sigma_{ca} = \sqrt{(\frac{M}{W})^2 + 4(\frac{aT}{2W})^2} = \frac{\sqrt{M^2+(aT)^2}}{W} \leq [\sigma_{-1}] \tag{39}$$

M and T represent bending moment and torque respectively; W represents section factor which can be calculated. If the calculated stress is smaller than the permissible stress, the design of shaft can be viewed qualified.

In addition, bearings, keys and shaft couplers check should also be taken into consideration and calculation of these parts are not introduced here. The check calculation of gears and shafts depicted above are the basic design process which should be carried out in real model design.

Chapter 5: Experiment for Power Take-off System

Experiment Devices

A prototype is built after conceptual design of power take-off system is conducted which depicted as Figure 24 and Figure 25.

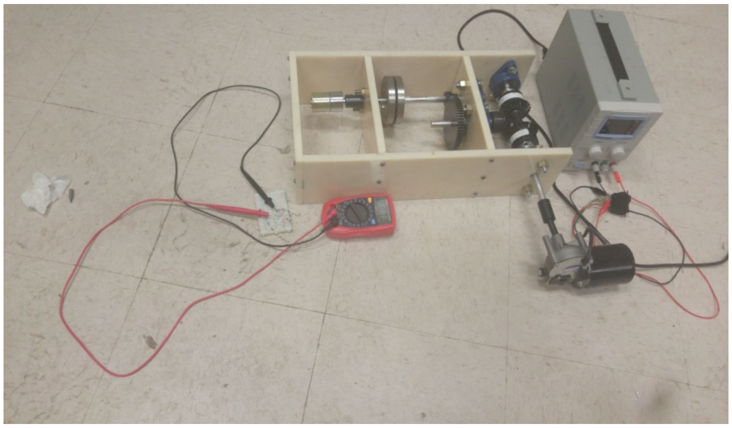


Figure 24. Power take-off system test

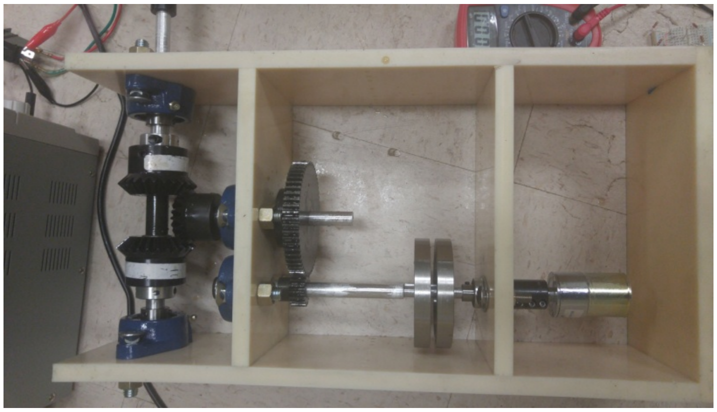


Figure 25. Power take-off system

For this prototype, it is hard to test it under the water considering about sealing and fixation issues. Instead a worm gear reducer motor is used in the test to simulate the movement of Salter Duck body which rotates clockwise and anticlockwise when waves come and leave. A DC regulated power supply shown in Figure 23 supplies power to drive motor. In reality, the Salter's

Duck body rotates 60 degree every 2 second, however, for this system if the motor shaft rotates in two direction as Salter's Duck, the system will fail to work as the start torque of generator is high[12] while the torque provided by motor is relatively low at this rotating speed. As a result, rotating speed of motor shaft is set to be higher. Build this power take-off system is just to demonstrate the function of dual-directional power take-off, although the input property is not practical, it can verify the conceptual design. In the future, a large Salter's Duck body can be built to overcome the high start torque of generator and a gearbox with higher transmission ratio can be included to provide flywheel with more energy storage in case of rotating stopping. Totally ten groups of tests are carried out to make comparison to verify the practicability of dual power take-off and function of flywheel.

The first three tests are carried out under the condition that DC regulated power supply provides 6 volts power to motor and motor shaft rotating speed is 20 RPM is one direction. In the test, motor is set to change rotating direction every 1 second by switch that means the motor shaft rotates 120 degrees in one direction, then rotates 120 degrees in another direction and the power take-off system with two bevel gears on input shaft is installed with none, one and two flywheels. Although in reality, the Salter's Duck can only rotate about 60 degrees every time, here is just to test to verify that the system can convert energy in both directions and flywheels can function as energy storage and smooth the power output.

The second three tests are carried out under the condition that DC regulated power supply provides 8 volts power to motor and motor shaft rotating speed is 30 RPM. In the test, motor is set to change rotating direction every 1 second by switch that means the motor shaft rotates 180 degrees in one direction, then rotates 180 degrees in another direction and the power take-off system with two bevel gears on the input shaft is installed with none, one and two flywheels. Although in reality, the Salter's Duck can only rotate about 60 degrees every time, here is just to test to verify that the system can convert energy in both directions and flywheels can function as energy storage and smooth the power output.

The third three tests are carried out under the condition that DC regulated power supply provides 12 volts power to motor and motor shaft rotating speed is 40 RPM. In the test, motor is set to change rotating direction every 1 second by switch that means the motor shaft rotates 240 degrees in one direction, then rotates 240 degrees in another direction and the power take-off system with two bevel gears on the input shaft is installed with none, one and two flywheels. Although in reality, the Salter's Duck can only rotate about 60 degrees every time, here is just to test to verify that the system can convert energy in both directions and flywheels can function as energy storage and smooth the power output.

The last test is carried out under the condition that DC regulated power supply provides 12 volts power to motor and motor shaft is set to change rotating direction every 1 second by switch that means the motor shaft rotates 240 degrees in one direction, then rotates 240 degrees in another direction and the power take-off system with only one bevel gear on the input shaft is installed with two flywheels. Although in reality, the Salter's Duck can only rotate about 60 degrees every time, here is just to test to verify that the system with two bevel gears on the input shaft can convert more power compared with the system with only one bevel gear that can just capture energy in one direction.

In each groups of tests except the last test, the power take-off system is tested when the system is installed with none, one and two flywheels. The comparison in each group demonstrates that the flywheel can function as energy storage and smooth power output and the comparison between different groups demonstrates that flywheel energy storage system can work better when the rotating speed of flywheel shaft is higher.

Data Collection

The voltage generated by DC generator is collected by the multimeter which utilizes a multimeter directly connected with generator to measure the output voltage. When multimeter is set to measure current and connected to generator, the torque of generator becomes so high as now the multimeter is viewed as a wire which leads to the very hard rotating. As a result, only voltage values are collected to demonstrate that flywheel system can smooth the power output. In each test, the voltage value is collected every 0.5 second because the multimeter can only measure voltage value every 0.5 second.

For 6 voltage power supply, the voltage output property under the condition that system is installed with two bevel gears and none flywheel is depicted in line chart as Figure 26 below.

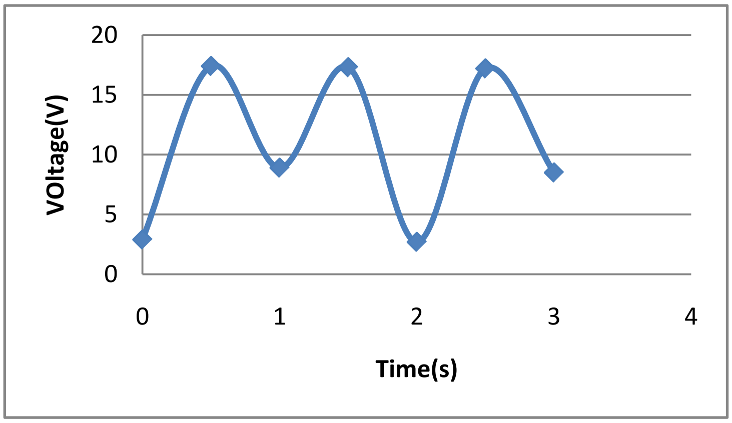


Figure 26. Voltage output

The voltage output property under the condition of 6 voltage supply and system with two bevel gears and one flywheel is depicted in line chart as Figure 27 below.

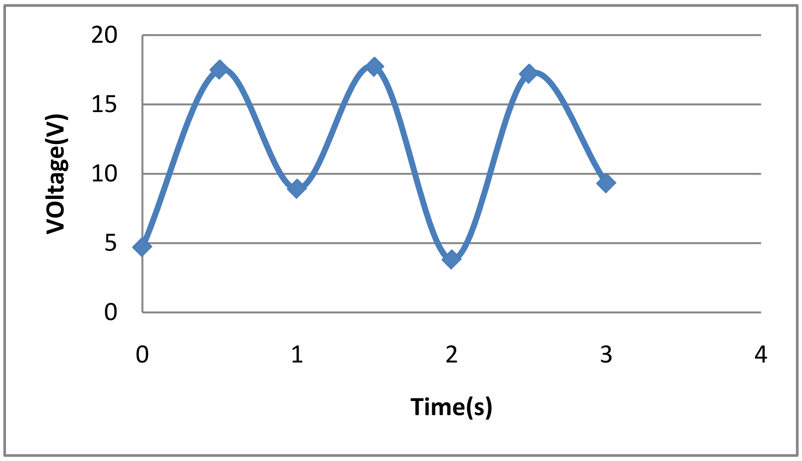


Figure 27. Voltage output

The voltage output property under the condition of 6 voltage supply and system with two bevel gears and two flywheels is depicted in line chart as Figure 28 below.

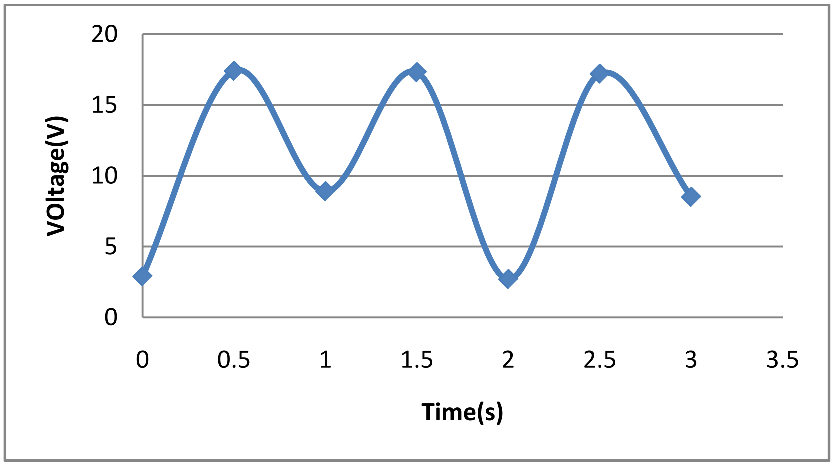


Figure 28. Voltage output

For 8 voltage power supply, the voltage output property under the condition that system is installed with two bevel gears and none flywheel is depicted in line chart as Figure 29 below:

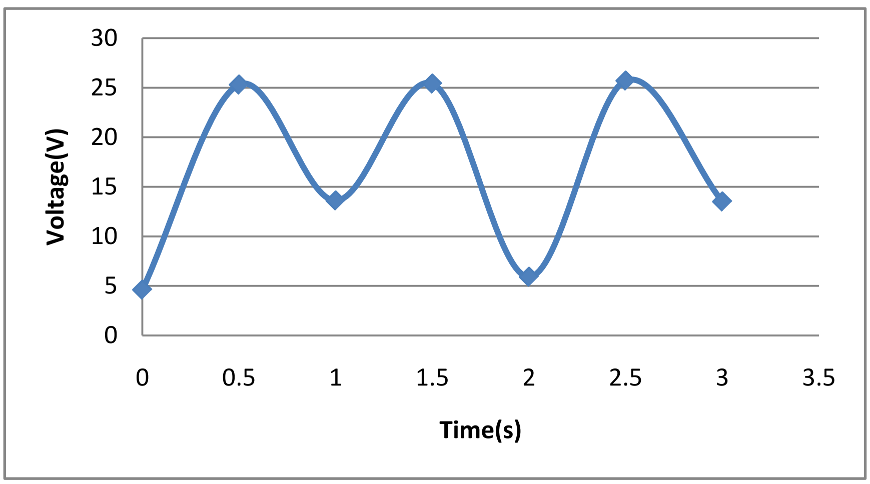


Figure 29. Voltage output

The voltage output property under the condition of 8 voltage supply and system with two bevel gears and one flywheel is depicted in line chart as Figure 30 below.

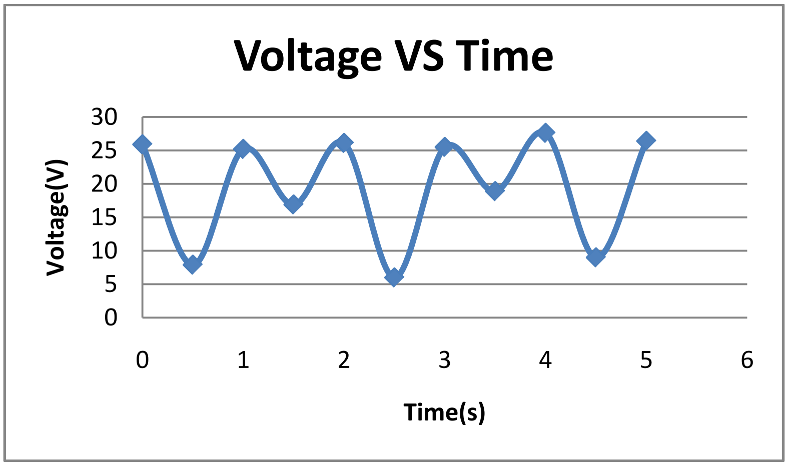


Figure 30. Voltage output

The voltage output property under the condition of 8 voltage supply and system with two bevel gears and two flywheels is depicted in line chart as Figure 31 below.

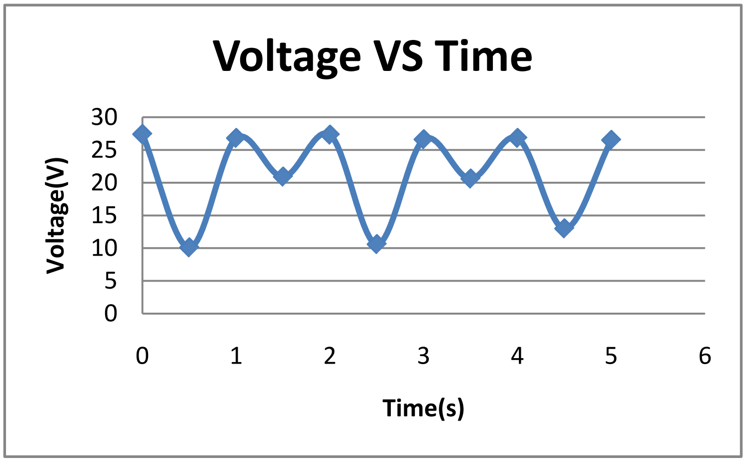


Figure 31. Voltage output

For 12 voltage power supply, the voltage output property under the condition that system is installed with two bevel gears and none flywheel is depicted in line chart as Figure 32 below.

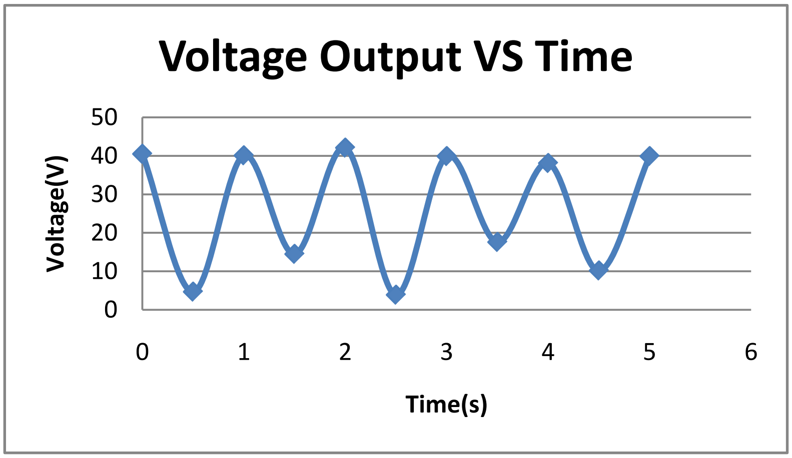


Figure 32. Voltage output

The voltage output property under the condition of 12 voltage supply and system with two bevel gears and one flywheels is depicted in line chart as Figure 33 below.

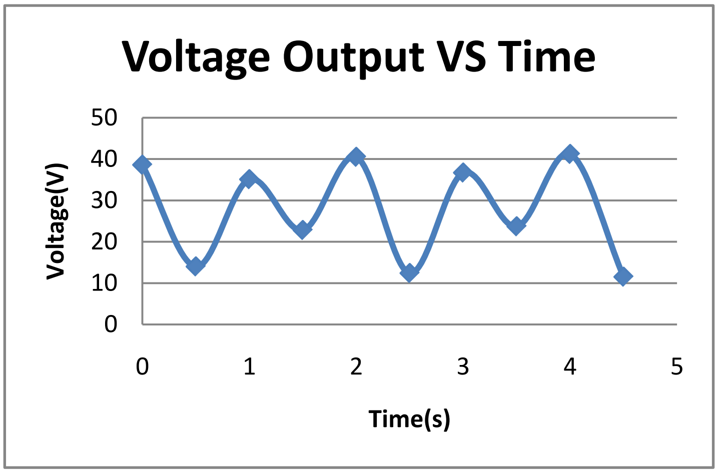


Figure 33. Voltage output

The voltage output property under the condition of 12 voltage supply and system with two bevel gears and two flywheels is depicted in line chart as Figure 34 below.

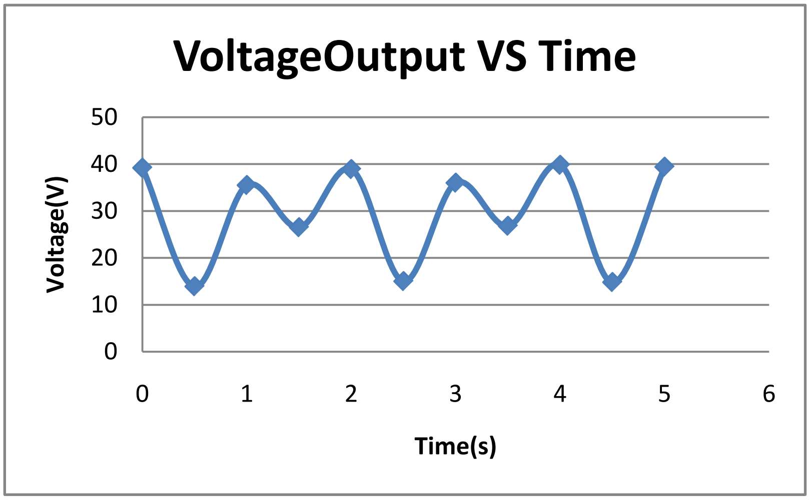


Figure 34. Voltage output

Data Analysis

The tests include four groups of which the first group is under the condition of 6 V power supply with none, one and two flywheels as well as two bevel gears on the input shaft; the second group is under the condition of 8 V power supply with none, one and two flywheels as well as two bevel gears on the input shaft; the third group is under the condition of 12 V power supply with none, one and two flywheels as well as two bevel gears on the input shaft; the last group is under the condition of 12 V power supply with two flywheels and one bevel gear on the shaft. The purpose of these tests is to verify the idea that flywheel can function as energy storage and power output smooth. The Salter's Duck reciprocating movement on waves can be viewed as 5 RPM in one direction , however, in the tests the rotating speed of motor shaft is 20 RPM, 30 RPM and 40 RPM and this is because that the flywheel can only function in high rotating speed and the effect of flywheel energy smooth is not obvious under 5 RPM condition. The tests mainly demonstrate the function of flywheel energy storage. In reality, transmission ratio of gear system can be much higher to make flywheel work better.

In each group, 11 values are selected from tests that can better represent the voltage output property. First, make a comparison between tests in each group to demonstrate that flywheel functions as energy storage and can smooth the output power. Second, make a comparison between tests in different groups to demonstrate that the flywheel can work better when the rotating speed is higher. Last, compare the voltage output of system with two bevel gears and system with one bevel gear on the input shaft under the same power supply and number of flywheels to demonstrate that the dual-directional power take-off system can capture more energy than the unidirectional power take-off system.

For the first group, the value collected from test under the condition that there is none flywheel installing in system is listed as table 1 below.

Time(s)	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
Voltage(V)	15.9	3.5	16.9	10.8	16.7	2.9	18	10.8	16.2	2.7	17.4

Table 1. Voltage output

Although the data is not precisely collected due to the limit of multimeter, the line chart depicted as Figure 25 can show the trend of voltage output. From 0.5 second to 1.5 second, the voltage output increases from 3.5 V to 16.1 V, then decreases to 10.8 V and period is 1 s that can match with the condition that motor is set to rotate reversely in every 1 second. For the whole process, it seems that voltage output begins to increase at about 3 V and reaches the highest voltage about 16 V, then begins to decrease to about 10 V and again starts to increase to 16 V and finally, decreases to 3V. This trend indicates that the motor changes rotating direction at 0.5 second and shaft rotating begins to accelerate resulting in the voltage output increase and motor begins to rotate in reverse direction at 1.5 second which leads to the low voltage output at the moment reaching to the lowest voltage output. Again voltage increases during the period when motor rotating accelerates reaching to highest voltage output at 2 second, then the motor changes its rotating direction at 2.5 second leading to the decrease of voltage output. Actually, the voltage output at 0.5 second should be nearly same as the voltage at 1.5 second because the motor changes its rotating direction at these two moments, however, the voltage output at 1.5 second is much higher than voltage output at 0.5 second. From figures listed above, this law is nearly same and in my opinion, it is because that the prototype is not precisely machined and the torque exerted on the shafts in one direction is higher than the torque exerted in another direction that leads to the rotating in another direction is more likely to decelerate at the moment of changing motor rotating direction. In one direction the energy lost from flywheel caused by friction is higher than another direction that leads to the lower voltage output. In this test, although there is no flywheel installing in the system, the 60-teeth spur gear functions as flywheel and this is the reason why there is still voltage output at the moment when motor changes its rotating direction. The average voltage output is 11.98 V and the average voltage output is 11.98 V in this case and average of voltage output crest is 16.85 V and average of voltage output trough is 6.14 V. The fluctuation degree is 40% and -48.7% respectively.

The value collected from test under the condition that there is one flywheel installing in the system is listed as table 2 below.

Time(s)	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
Voltage(V)	18.7	3.9	17.9	13.6	18.1	3.9	18.1	14.6	17.4	5.7	18

Table 2. Voltage output

The trend of voltage output in this test is still like the first test, however, the difference is that voltage output becomes more smooth than the first test, especially at the moment that motor changes rotating direction that indicates the energy stored in flywheel contributes to the system. The average voltage output is 13.63 V and the average of voltage output crest is 18.03V and the average of voltage output trough is 8.34V. The fluctuation is 32.28% and -38.81% respectively.

The values collected from test under the condition that there are two flywheels installing in the system is listed as Table 3 below.

Time(s)	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
Voltage(V)	18.7	3.9	17.9	13.6	18.1	3.9	18.1	14.6	17.4	5.7	18

Table 3. Voltage output

The trend of voltage output is same as former tests. The average voltage output is 13.63V and the average of voltage output crest is 18.033 and average of voltage output trough is 8.34V. The fluctuation is 32.27% and -38.81% respectively. The fluctuation degree of three tests in the first groups is listed as Table 4 below.

Flywheels	0	1	2
Up fluctuation	40%	32.28%	32.27%
Down fluctuation	-48.7%	-38.81%	-38.81

Table 4. Voltage output

According to the Table 4, it indicates that the fluctuation degree is higher under the condition of none flywheels installed in the system than another two cases. It demonstrates that flywheels have the function of energy storage and power output smooth as discussed before, however, it seems that the fluctuation degree is nearly same on matter one flywheel or two flywheels are installed in the system. This is because the flywheel shaft rotating speed is about 80 RPM which is relatively low and under this case, the effect of adding one or two flywheel into system is not obvious as the amount of energy stored in flywheel is related to flywheel mass and rotating speed. The energy stored in flywheel is not high enough to continue transferring energy to generator if the rotating speed is low. That is why the fluctuation degree of voltage is nearly same no matter one flywheel or two flywheels are installed into system. To demonstrate the flywheel energy storage function, another group of tests are carried out. In this group of three tests, the voltage supplied by DC power supply increases from 6V to 8V which means that flywheel shaft rotating speed also increases. Under this case, compare the voltage output again to see if the more flywheels added in system can make a contribution to smooth power output.

For the first group, the value collected from test under the condition that there is none flywheel installing in system is listed as table 5 below.

Time(s)	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
Voltage(V)	25.7	4.6	25.3	13.9	24.4	4.1	25.7	14.6	26.6	4.6	26.4

Table 5. Voltage output

The voltage output trend is still like the former tests. The average voltage output is 17.81V and the average of voltage output crest is 25.68 and average of voltage output trough is 8.36. The fluctuation degree is 44.19% and -53.06%.

The values collected from test under the condition that there is one flywheel installing in the system is listed as Table 6 below.

Time(s)	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
Voltage(V)	25.9	7.9	25.2	16.9	26.1	6	25.5	18.9	27.6	9	26.4

Table 6. Voltage output

The average voltage output is 19.58V and average of voltage output crest is 26.12V and average of voltage output trough is 11.74V. The fluctuation is 33.40% and -40.04% respectively.

The values collected from test under the condition that there are two flywheels installing in the system is listed as Table 7 below.

Time(s)	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
Voltage(V)	27.4	10.1	26.8	20.9	27.3	10.6	26.6	20.6	26.8	13	26.5

Table 7. Voltage output

The average voltage output is 21.51V and average of voltage output crest is 26.9V and average of voltage output trough is 15.4V. The fluctuation is 25% and -28.4% respectively. The fluctuation degree of three tests in the second group is listed as Table 8 below.

Flywheels	0	1	2
Up fluctuation	44.19%	33.40%	25%
Down fluctuation	-53.06%	-40.04%	-28.4%

Table 8. Voltage output

From the Table 8, it is obvious that the power output is more and more smooth as the number of flywheels increases. In this test, the input shaft rotating speed is 30 RPM in one direction compared with 20 RPM in the first group and it verifies that flywheel can store more energy if the rotating speed increases which will better smooth the power output. In this test, the power output of system is better smoothen when there are two flywheels installing in the system. For the prototype, the flywheels are relatively undersize and moment of inertia is still not high enough, but in the test it has demonstrated that as the rotating speed increases, the more moment of inertia the flywheels obtain, the more smooth power can output. Compared with first group test, the fluctuation of voltage output under the condition that none flywheel is installed in system is higher. In my opinion, the reason is that the system can output more power in the second group because the input power increases, however, the degree of fluctuation is related to the amount of moment of inertia and how much the energy can be stored in flywheels. When there is on flywheels installing in the system, only 60-teeth spur gear functions as flywheel but its moment inertia is not high enough to store energy for power smooth. The voltage output in the second group is higher than the first group, under this case, the fluctuation becomes more obvious when there is no flywheels installing in the system. After adding flywheels into system, the power output is better smoothen compared with first group and it verifies that flywheel needs high rotating speed. In real model, a gearbox with higher transmission ratio should be included to make flywheel work better.

According to the first group test and second group test, the function of flywheel system including energy storage and power output smooth has been verified, and the third group of tests are carried out to further verifies that the higher the rotating speed is, the more energy can be stored in flywheels and more smooth the power output. In the third group, the voltage supplied by DC regulated power supply is 12V and input shaft rotating speed in one direction is 40RPM.

For the third group, the value collected from test under the condition that there is none flywheel installing in system is listed as table 9 below.

Time(s)	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
Voltage(V)	40.5	4.7	40.1	14.5	42.1	3.9	39.9	17.6	38.1	10.2	39.9

Table 9. Voltage output

The average voltage output is 26.5V and average of voltage output crest is 40.1V and average of voltage output trough is 10.18V. The fluctuation is 51.32% and 61.58% respectively.

The values collected from test under the condition that there is one flywheel installing in the system is listed as Table 10 below.

Time(s)	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
Voltage(V)	38.6	14	35.1	22.8	40.5	12.4	36.7	23.7	41.2	11.5	38.1

Table 10. Voltage output

The average voltage output is 28.6V and average voltage output crest is 38.37V and average voltage output trough is 16.88V. The fluctuation is 34.2% and 40.98%.

The values collected from test under the condition that there is two flywheels installing in the system is listed as Table 11 below.

Time(s)	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
Voltage(V)	39.2	13.9	35.5	26.5	38.9	15	36	26.8	39.8	14.8	39.4

Table 11. Voltage output

The average voltage output is 29.62V and average voltage output crest is 38.13V and average voltage output trough is 19.4V. The fluctuation is 28.73% and 34.5% respectively. The fluctuation degree of three tests in the third group is listed as Table 12 below.

Flywheels	0	1	2
Up fluctuation	51.32%	32.4%	28.73%
Down fluctuation	-61.58%	-40.98%	-34.5%

Table 12. Voltage output

According to the table 12, the fluctuation of voltage output under the situation where there is no flywheels installing in system is more obvious than the former two group tests. The reason is that in this test, the rotating speed of shaft is higher compared with former tests and more voltage outputs, as a result, the fluctuation is more obvious. From the table 12, the voltage output is smoothen as more flywheels are added into system and the function of flywheel system is again proved in this test. Compared with the second group tests, the fluctuation in the third group under the condition that two flywheels are installed into system is also more obvious than second group. In my opinion, the reason is that the initial fluctuation of voltage output for third group is more violent than the second group and the flywheels with higher moment of inertia should be installed which can make power output more smooth.

These three group tests are conducted under different rotating speed and under each rotating speed, no flywheel/ one flywheel/ two flywheels are added into system respectively. Totally nine tests are carried out to demonstrate that flywheel can smooth the power output and the effect is more obvious under the situation where the rotating speed is higher. The assumption is verified by prototype and can be referred to in the future for building real model. The flywheel should be larger in the energy storage system so that more energy can be stored and transferred to generator when the input power becomes weak for continuous smooth power output.

Chapter 6: Conclusion

The tests of dual-directional power take-off system demonstrate that the power take-off system can convert mechanical energy to electrical energy in both input rotating directions and flywheel system can function as energy storage and smooth the power output. Totally three groups of tests are carried out and in each group, three tests are conducted for comparison. The voltage supplied to each group is 6V, 8V and 12V respectively that can be viewed as different rotating speed of input shaft. In each group, three tests are conducted under the condition that none/one/two flywheels are installed into system respectively. The results show that the flywheel energy storage system can reduce voltage output fluctuation degree which means that flywheels store partial energy and transfer energy to generator when the waves become weak so that the output power is smoothen. With more flywheels added into system, the power output is better smoothen. Compare between the tests in different groups that the tests are conducted under the situation where the input shaft rotating speed is 20 RPM, 30 RPM and 40 RPM respectively and it shows that effect of flywheel energy storage system is more obvious when the rotating speed of flywheel shaft is higher. The energy stored in flywheels is related to the moment of inertia and rotating speed. As the number of flywheels added into system increases, the fluctuation degree of output voltage becomes less violent which indicates that under the same rotating speed, the increase in moment of inertia of flywheels resulting in the increase of energy stored in flywheels. As rotating speed increases, the output power can be better smoothen which indicates that the energy stored in flywheels is also related to flywheel rotating speed. With higher rotating speed, more energy can be stored in flywheel system.

The tests are conducted in the prototype and results are able to verify that the increase in moment of inertia and rotating speed of flywheel can result in more energy storing in flywheel. The tests outcome can be referred to for building real model in the future. A gearbox with high transmission ratio should be included in power take-off system that can make flywheel shaft rotate fast and a full-size flywheel should be selected compared with undersize flywheel installed in this prototype. With higher rotating speed and moment of inertia of flywheel system, the power output of power take-off system can be better smoothen.

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