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Renewable Energy Generation of Portable and Wearable Devices

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Abstract: *Motion is involved in our everyday life - walking, running, swinging arms… … It would be convenient if these movements can be converted into useful energy. There are other methods of energy generation such as piezoelectricity - produced through deformation, and triboelectricity - energy generation through contact-separation process of two different materials. "Renewable energy generation of portable and wearable devices" is an energy related engineering project that aims to find an efficient solution of converting motion energy into electric energy through consistent, portable sources. The source's oscillation motion requires large amplitudes in order to increase the efficiency of energy generation. Locations on human's body such as wrists or ankles are ideal sources of energy harvesting. Energy collection is done through the use of a pendulum that runs gear systems and generators in portable devices such as watches. The models are 3D designed and constructed to test their mechanism. Two models utilizing a brushed DC motor incorporate a single-bearing system and a ratchet gear system, used for single-direction conversion. The model utilizing a brushless motor doesn't require direction convertors, which only consist of gear systems that increase the rotational ratio. The electric potential of the three models are tested and conclusions are drawn on their efficiencies and consistency, which will be the basis of future works aiming to minize the models and apply them into portable devices.*

Keywords: *Renewable Energy, Portable, Wearable Devices*

1. Introduction

In recent years, there was a significant increase in discussions about generating energy from wearable devices, as well as an increase of products using such technologies. There are currently numerous approaches to generate electricity, such as through generating electricity through heat. In February 2023, a group of researchers in Korea created a portable thermoelectric generator capable of converting temperature differences into electric potentials [1]. The approach that's relatable to the project is generating electricity directly from mechanical systems.

SEIKO watches, a company that developed "Kinetic Perpetual", was a pioneer in motion-based energy generation. First developed in 2007, Kinetic technologies included a rotating pendulum within the watch, which is attached to a large gear that meshes with a very small pinion. As the arm swings, the pendulum rotates and spins the pinion at an extremely high speed. Combining with the self-winding rotor mechanism of watches, the microgenerator will be capable of charging the capacitors [2]. Other companies such as Swiss company ETA and Ventura developed watches with similar systems.

2. Ratchet Gear Model

2.1. Pendulum System

In a watch-like structure, a pendulum system is needed to convert motion energy into rotations. During movements such as walking, the pendulum would rotate due to horizontal or vertical accelerations, causing the related gears to rotate as well. In this model, the pendulum was designed with a radius of 65mm. The 3mm hole at the center was used to stable the pendulum on an axe. The 6 surrounding carved-out rectangles with slight filets at the corners have the dimensions of 19.2mm * 11.5mm. The empty spaces were designed to fill in 12 metal plates to increase the weight of the pendulum - 2 in each spot. A greater weight would increase the inertia of the system, thus makes it easier to rotate and more convenient for the testing processes.

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Below the pendulum, an area was extruded with a thickness of 4mm, in order to prevent the pendulum from contacting with the screws used as axes for the gear system. Below the upper board, a gear with a thickness of 9mm was extruded. The gears in the gear system used the same module of 0.5, which was found to be space-efficient and capable of having the gear system rotating properly without misconnections. The final version of the extruded gear has a teeth number of 30.

2.2. Ratchet Gear Mechanism

The ratchet gear system has multiple components: the base gear which connected with the pendulum, the connector which was attached to the extruded axe on the base gear two clips that attached onto the ratchet gear. Two carbon-fiber sticks were used to attach between the clips and the connector. Such material was selected for it's durability and elasticity, making sure that the sticks can withstand being slightly bent.

The ratchet gear in this model has a teeth number of 60. The relatively large teeth number was to minimize the size of each teeth so that the clips can be attached more smoothly as the gear rotates. A 9mm hole was extruded in the center of the gear, in order to fit in a gear if the gear ratio wasn't ideal and that additional gear systems need to be added.

The base gear has a module of 0.5, while it has a larger teeth number of 54, compared to the gear on the pendulum. Unlike the pendulum gear, the base gear was attached using a carbon-fiber stick instead of a conventional screw, same as the ratchet gear. The connector attached to the base gear would perform circular movements around the center, and the carbon-fiber sticks that extended to the ratchet gear would block any axes that goes through the center. Lengths of carbon-fiber sticks can be adjusted through cutting, which can be restricted to the top of the gear. It was measured that the diameter of the carbon-fiber stick has a diameter of 2.4mm. The center hole of the base gear was designed to be 2.8mm wide, in order to leave room for errors during the 3D printing process and to ensure smooth rotations around the axes.

At 3.9mm from the center of the base gear, a cylinder with a diameter of 4.5mm and a height of 5mm was extruded. The cylinder was used to attach the connector, which also has a thickness of 5mm, with a center hole in the middle that has a diameter of 4.8mm. When the base gear rotates, the connector's position changes along a circle with a radius of 3.9mm, but a 0.3mm gap in diameters ensured that the connector won't be stuck on the cylinder so that it won't rotate.

He connector has a diameter of 13.5mm, with two holes having the diameter of 2.8mm, separated by an angle of 35 degrees. After calculations, as well as considerations of whether the tips of the clips can successfully connect onto the ratchet gear, it was designed that the lengths of the sticks attached to the connector are 78mm, given the distance between the base gear and the ratchet gear was 84mm.The holes were used to attach one end of the carbon fibers using strong glue, with the other end was attached to the clips. The relatively small angle of 17.5 degrees between carbon fiber sticks and the central axis was designed, because a larger angle would likely result in the clips failing to attach onto the ratched gear. Smaller angle would ensure that while the base gear rotates, and the connector moves back the forth, the sticks would largely move in the vertical direction rather than in the horizontal direction.

In this model, the design of the clips changed multiple times. While the overall design with a 2.8mm hole extruded on the end of each clip remained the same, the shape of the tip used to attach the ratchet gear was a difficult part of the design. The tip of the clip was an isosceles triangle with a tip angle of approximately 40 degrees. After the clips were 3D printed, it was found that the clip was effective in staying attached to the ratchet gear the clip was being pushed forward. When it was being pushed backward, the clip remain attached, instead of traveling to the next teeth. It was most likely due to the triangular shape of the tip, therefore a new version was designed.

The tip angle was much more acute in this model. The curve was designed so that it can be easily hooked onto the ratchet gear, while the incline on the back of the tip was made for smooth transitions between the teeths. After testings, it was found that the clips were have difficulties to attach onto the ratchet gear, given the current angle between the sticks and the position of the connector, the tip of the clip wasn't connected to the teeths)

Another problem was that the direction of the teeths on the right side and the left side of the ratchet gear were opposite in direction. Therefore, the direction of the tips of the clips also need to be opposite in direction. The final version of the clips were designed, successfully solving the previous problems.

While the connector moves forward towards the ratchet gear, the clip on the left hooked onto the

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ratchet gear and moved it forward, causing it to rotate counterclockwise. The other clip was skipping the teeths due to its angle. While it moves backward, the right clip would hooked onto the gear, also causing the ratchet gear to rotate counterclockwise[3-4].

2.3. Mechanical Analyzation

One of the advantages of the ratchet-gear electric generation system is that it uses brushed DC motor, which generates significantly higher electric potential than brushless DC motor. The system converted movements from two directions into one direction, allowing the brushed DC motor to maximize its efficiency. The system was also very reliable - the chain of mechanical gear systems meant that it would be less prone to malfunctions.

Through testings, it was discovered that the rotation of the ratchet gear was inconsistent, as modeled by the equations above. When the base gear rotates to areas nearest or furthest away from the ratchet gear, the back-and-forth motion per degree of rotation decreases significantly. While the base gear rotates in areas in the middle, the back-and-forth motion per degree is significantly greater. This was because of the nature of circular motion which can be represented in a sin graph. The inconsistency in the system would decrease the efficiency of the system. Moreover, the system was relatively complex, with the additional ratchet gear, base gear, carbon-fiber sticks, etc. The high complexity would make the minimization effort more difficult - which is important for applications to wearable devices.

3. Single Bearing Model

His model was similar to the ratchet gear model. Both models use brushed DC motor, and the same pendulum for energy input. The single bearing model also used gear systems to adjust gear ratios to achieve higher efficiencies. The difference is that this model used single bearings as a replacement for the ratchet gear system in direction conversions. The second model aimed to resolve the drawbacks of the ratchet gear system, such as its complexity.

3.1. Materials

The single bearing is a set of two rings, attached together by a string of spheres between them. When the outer ring is fixed, and an axis is attached and fixed to the inner ring, the axis can only rotate in one direction. Using the pendulum as the axis, when it rotates clockwise, the axis was attached to the teeths on the inner ring, causing the ring to rotate. When it rotates counterclockwise, there were no resistance on the axis, meaning that the rotation of the axis won't drive the gear system.

The gear systems and the board was constructed in acrylic materials. It's an ideal material for lazer cutting where the process creates precise components designed in the 3D model. Using such material, the teeths of the gears would be attached to each other more accurately, which played a role in decreasing friction in the system.

3.2. Mechanical Design

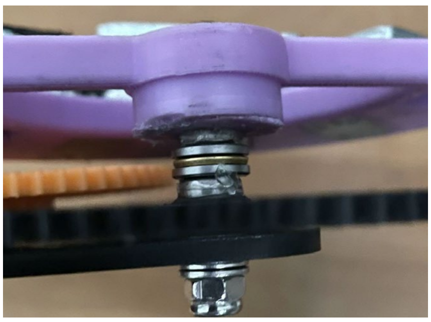

Figure 1: Sandwich-like triplets of plates

A 3mm screw was attached to the axis of the pendulum using strong glue. At the bottom of the pendulum, a sandwich-like triplets of plates were used to alleviate friction (as shown in fig. 1). The single bearing that fits the 3mm screw was attached to the black gear. In the initial model, a 1:4 ratio was designed to test whether the ratio was inefficient or it's difficult to rotate the motor. A set of 5 gears, with

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teeth numbers of 80, 30, 20, 20, and 20 respectively.

The gears cut from a 3mm acrylic board were attached onto the base board made of the same material. The 130 DC mini generator was attached to the board via strong glue. After testings, it was determined that the pendulum can rotate very easily with little resistance, meaning that there's a large room for the gear ratio to be increased.

In the updated model, the gear connected with the pendulum also has a teeth number of 80. The second gear was a merged gear, with the top gear and the bottom gear having a teeth number of 60 and 20 respectively. The pendulum gear was attached to the bottom gear, while the top gear was then connected to the gear attached to the motor, which has a teeth number of 20. The 1:12 ratio was tested and it has moderate resistance, which meant that there was a reasonable balance between friction and efficiency.

Through mechanical testings, it was found that the single bearing can be easily worn off. The singer bearing was replaced 3 times in a period of an hour. The teeths of the single bearing used to attach the screws are unreliable comparing to the ratchet gear systems and are poor candidates to long-term usage.

4. Brushless Motor Model

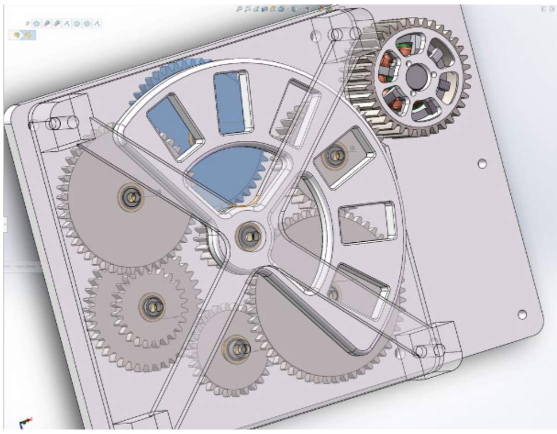

Figure 2: Brushless model 3D design

Taking into account of the complex system of the ratchet gear system, and the design utilizing the single bearing which was prone to worn-off by friction, the third model was created using brushless DC motor, which can rotate and generate energy from both directions. Brushless motors are easier to rotate comparing to brushed motors, which means that there can be a higher gear ratio in this design to increase the power generation. However, given a fixed rotation rate, brushless motors generate much less energy than motors in previous designs. As is shown in Fig.2.

The overall design is similar with the previous models, which also used the same pendulum as the rotation source, a set of gear systems, and attaching them to a board. A design change used bearings to attach the gears with the board, instead of gluing them to a carbon fiber, which can decrease frictio.

The gear attached onto the motor was also improved, with three 1.85 mm diameter circles on the top of the gear corresponding to the three axles on top of the motor, which increased its points of connection with the motor:

In addition, an X-shaped stablizer was designed to cover the area of the gear system. Its center connects with pendulum and its corresponding gear, which would significantly enhance its rotational stability compared to previous models. The set of 5 gears produces the a total gear ratio of 1 : 14.

5. Data collection process

5.1. ADS1115 Converter

After all three models were 3D printed and their mechanism tested from physical problems, the data collection process began with analog-to-digital conversion. In the diagram, the positive and negative ends of the generator connect with the 5V and Ground pins on the ADS1115 module (in the middle) and

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the arduino board (on the left). The SCl and SDA pins on the module reads analog signals from the motor as a value between 0 - 1023, and output digital voltage values between 0 - 5. This value is transmitted to the arduino via A4 & A5 pins. The arduino board is then connected to the computer via USB cable, where the graph of voltage as a function of time would be displayed in the Arduino App.

5.2. Rectifying Circuit

The ADS1115 module converted analog to digital signals, but the waveform of the output for both brushed and brushless motors remains a sinusoidal function. The rectifying circuit attached onto the motor converts signals from both terminals of Vac to a single terminal at V0. The signal from the upper terminal transmits through D1, passes through capacitor C1, transmits through D3 and D2, then to V0. While the lower terminal transmits through D3 and D2, passes through capacitor C1, transmits to D4 and D1, then to the same terminal V0. The circuit effectively converts the positive-and-negative sinusoidal waveform initially generated by the motors to an all-positive output waveform that can be used for data collection and analysis.

5.3. Mechanical Testing

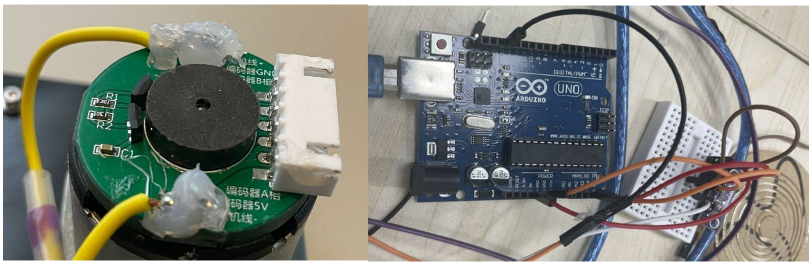

Figure 3: Connection on terminals and Circuits for data collection

In order to ensure the wire is consistently attached to the generator, wires were hot-glued onto the positive and negative ends of the motor, after numerous soldering attempts on the terminals failed during test trials where the model was being shakened. As is shown in Fig.3.

During the voltage output test, the models were held in hand while the testing person, which is me, walk at a naturally comfortable pace that simulates the real-life situations similar to a smart watch swinging back and forth on a person's wrist during exercises[5-6].

6. Data & Analysis

6.1. Electric Potential Output

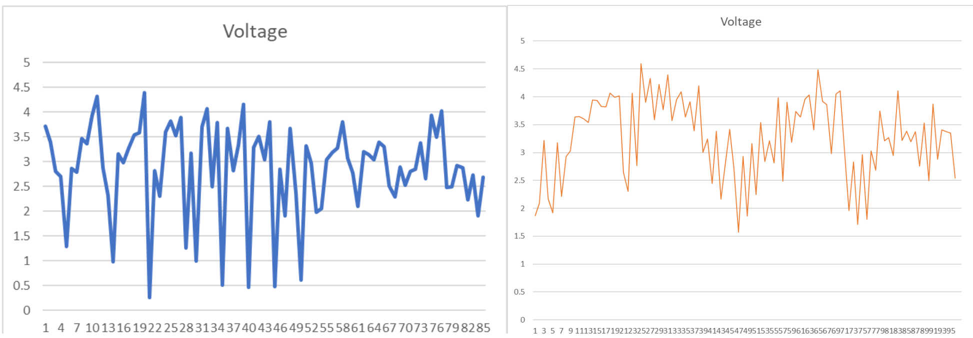

Figure 4: First trial data and Second trial data

In the first trial, the single-bearing model was shaked back-and-forth for 8.5 seconds. The peak voltage reached 4.38V, with the average value being 2.86V. It was important to note that the voltage output during the period reached a variance of 0.85V, which was a significant value given that the variance was 29.7% of the average value. The turbulence of power output was most likely due to the structural instability of the pendulum, which tended to tilt away from its supposed axis. Inconsistency of the shaking was considered the minor cause, since it wouldn't result in such significant output turbulence. With the structural issues fixed, the average power output has the potential reach closer to 4.38V, which

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is the peak output. As the result is shown in Fig.4.

After re-fastening the pendulum with the model, the second trial was conducted. In the 9.5 seconds period, peak voltage reached 4.60V and the average voltage increased to 3.27V. There was still significant inconsistency in the power generation, but the variance was decreased to 0.50V.

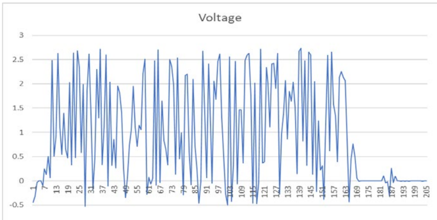

Figure 5: Brushless model data

During the power output test for the brushless motor model, it was found that in some occasions, the voltage dropped below 0(Figure 5). This was a result of parasitic inductances caused by switching transitions, when the direction of motion was briefly switched due to the inconsistencies of the shaking motion. For the positive section of the graph, the peak voltage reached 2.73V, lower than the average output of the single-bearing model, and the average was 1.39V during the time period.

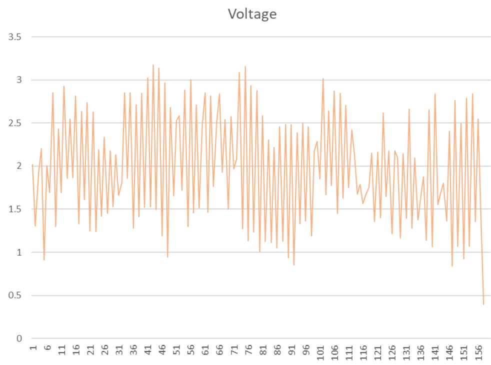

Figure 6: Ratchet gear model data

For the ratchet-gear model, the highest voltage generation reached 3.18V in the 15.6 seconds period, with the average output voltage at 1.98V(Figure 6). Despite its average voltage output being lower than that of the single-bearing model, graph of the ratchet gear model displayed higher consistency compare to the other two models due to the precision of the ratchet gear-clips mechanism and that the gear system didn't undergo component replacement at all during testing. Based on the data collected, the order of average voltage output is listed as the single-bearing model, ratchet gear model, and the brushless motor model from highest to lowest.

Using the data from the single bearing model, it's capable of powering many portable devices that use a 3V battery, not limited to watches. Portable devices such as calculators, digital compasses, and TV remotes can be powered by the model once it's minimized. The ratchet gear model can power devices with a 1.5V battery, where the common examples are flashlights, clocks, remote controls, household gadgets, etc.

6.2. Energy analysis

$$J = P \times \frac{L_{stepLength}}{V_{walkingSpeed}} \times N_{stepsPerDay}$$

Figure 7: Energy derivation

Taking future works into consideration where a battery storage system would be added to ensure a consistent flow of current to power the watch functions(Figure 7), it's necessary to calculate the total energy generated per day based on an average person's daily activities. The equation takes 3 mph as the average walking speed, 2.5 feet as the average step, and 4000 steps per day as the average daily walking. The equation yields $3.43 \cdot 10^{-2}$ J.

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7. Conclusion

The data from the power output tests indicated that the single-bearing model has the highest peak voltage output and average output, but with poor consistency since the single bearing model required many layers of metal rings on the pendulum axis to lessen the resistance, which result in the pendulum being deviated from the axis by some angle during testing. The single bearing itself was also worn off numerous times during the voltage testing, when the pendulum briefly switched to the other direction of rotation that deals material damage to the metal spheres in the single bearing. These disadvantages downgrades the model to a poor candidate for long-term usage, which means it would be very difficult for applicational use. Moreover, the single-bearing model restricts the pendulum to rotate in one-direction instead of converting the other into useful motion, which means that one direction of motion doesn't contribute to the output, which decreases its applicational power output by 50%.

Compare to the single-bearing model, the ratchet gear model has much higher consistency since there was no signs of any component damage to the ratchet gear mechanism during testing. The mechanism that involved a precise ratchet gear-clips system also contributed to a consistent flow of output, which is a key property to watch components that demands long-term consistency.

The project explored designs of energy generation systems of wearable devices on a macroscopic level. Moving on to future works, the motors and the ratchet gear mechanism would be minized for the model to be applicable to watch dimensions. A power storage system would be added to ensure a consistent flow of current that allows the model to independently generate energy from renewable sources in our everyday life.

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