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Pelton Wheel Driven Micro-Hydro Plant

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ABSTRACT

The most important problem faced by a country like India is that of rural electrification. This paper proposes a micro hydro power generation. The prime mover of the system is the hydraulic turbine, essentially a pelton wheel turbine in this proposed scheme. The water will run straight through the turbine and back into the reservoir to use it for the other purposes. In this paper we are considering a constant output power from the turbine system which drives the alternator.

Index Terms—**Alternator, Hydraulic Turbine, Micro-Hydro Power Generation, Pelton Wheel..**

I. INTRODUCTION

The purpose of this project is to gain familiarity with combined Electrical and Mechanical applications sometimes known as Mechatronics. The project will consist of the design of a theoretical micro-hydroelectric plant used in off grid applications to generate "Green" power for isolated cottages or farms. Then a working model of the system will be constructed in order to test the design. Finally the maximum load of the system will be measured through experimentation.

To provide power to the water turbine, our calculations will be based on residential water pressure to act as the prime mover. Residential pressure can vary depending on several factors, including: distance and elevation difference from the water reservoir, age of the pipes, leakage in the municipal water network, level of impurities present, etc. For a North East India, the average water pressure will be between 45 to 80 psi, with some extreme cases reaching from 30 to 115 psi. For calculation purposes, we will assume the low end of acceptable pressure and use 45 psi.

The flow rate will be determined experimentally, but based on the Indian residential standard, a ½ inch copper pipe.

Hydraulic Head : In hydroelectric projects, calculations are based on the available hydraulic head. This is a measurement of the difference in elevation between the water source and the turbine. For this project, we will calculate the theoretical hydraulic head based on the available water pressure.

Residential Water Pressure 45 psi
1 psi = 6894.757 Pascal

Therefore 45 psi = 3.1×10^5 N/m^2

In order to calculate the hydraulic head, we use the simplified Bernoulli's equation of incompressible fluids and assume that the pressure at the surface of the water supply is negligible.

Head (m) = [Final Pressure (N/m^2) – Initial Pressure (N/m^2)] / Specific Weight of Water

Specific Weight of Water = (10000 kg/m^3)(9.81 m/s^2)

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$= 9810\ N/m^3$

Therefore Net Head = $[(3.1 \times 10^5\ N/m^2) – (0)] / 9810\ N/m^3$

$H_n = 31.62m$

Flow Rate (q): The second fundamental value to be derived is the amount of water available through the pipe, known as the flow rate. To measure the flow rate, the water supply was opened, and the amount that flowed out in 10 seconds was collected in a large bucket. Once the experimental time had elapsed, the contents of the bucket were measured by pouring it into a measuring cup. The following is a summery of the calculations

3.75 L in 10 seconds

0.375 L/s

$q = 3.75 \times 10^{-4}\ m^3 s^{-1}$

Basic Calculation of Available Power : Once the hydraulic head and flow rate have been established for our theoretical micro-hydro project, a ballpark value of power is calculated in order to derive the requirements of the generator. The following formula was used

Power (kW) = [Flow Rate ($m^3 s^{-1}$)]x[Hydraulic Head (m)]x[Gravity(ms^{-2})]x[Density of Water (kgm^{-3})]x[Efficiency (%)]x[1/1000]

Or

$P(kW) = q(m^3 s^{-1}) \times H_n(m) \times g(ms^{-2}) \times \rho(kgm^{-3}) \times \eta(\%) \times [1/1000]$

As this calculation is just designed to give us our upper limit, we will assume an efficiency of 100%

$P(kW) = 3.75 \times 10^{-4} (m^3 s^{-1}) \times 31.62(m) \times 9.81(ms^{-2}) \times 1000(kgm^{-3}) \times [1/1000]$

= 0.116 kW

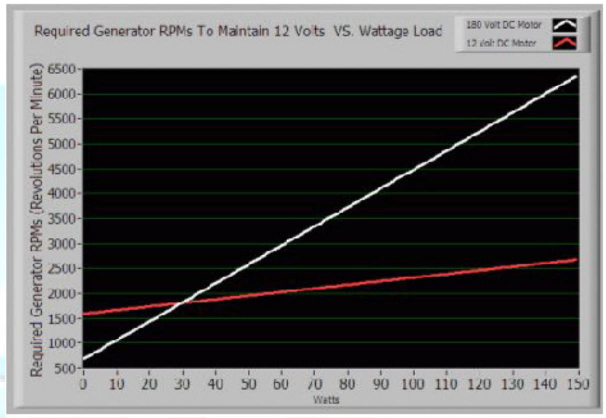
Or 116 Watts

Choice of Generator

Three main factors where used in choosing a generator for the project: cost, rate of rotation, and available power. The maximum available power was calculated above to be 116 watts. This means that for safety reasons, the generator should be rated for at least a minimum load of 116 watts, or we run the risk of overheating. With the minimum power set as a limiting factor, the following choices were considered:-

- Dedicated Electric Generator
- AC Motor repurposed to work as a generator Automotive Alternator
- DC Motor repurposed to work as a generator
- High Voltage VS Low Voltage permanent magnet DC Motors

Graph 1.1: RPMs required to Maintain 12v VS Load Power for a 12v and 180v Motors



As can be seen from the graph, though the high voltage generator (white line) requires less RPMs at a very low Load, at any reasonable power output it requires many times more RPMs than the low voltage generator (red line).

A limited rate of rotation is only a problem for wind turbines, because the rotational rate of a water turbine is a product of the water velocity and the diameter of the wheel. The result is that a relatively low voltage permanent magnet DC motor rated at least 116 watts is required.

Chosen Motor: The motor chosen was a second hand 12v Automotive Blower Motor ($10). No other information was available but a survey of similar brand motors reveals that the motors are rated at 120 watts, and between 2000 to 3000 RPMs.

Designing the Water Turbine : In a very basic sense, water turbines can be separated into two broad categories: reaction turbines that act on a change in pressure in the flow of a fluid, and impulse turbines that are put in motion by the impact of a water jet against a paddle or runner. The precise nature of the application is used to judge which of the many turbine designs is ultimately used. In general, reaction turbines require a very high level of precision between the impeller and its housing, as any gap between the two will result in a much lower efficiency. This requirement for a high precision housing makes the construction of a reaction turbine impractical for this project. The result is that an impulse turbine, specifically a Pelton Wheel was chosen for the turbine design.

The Pelton Wheel : A Pelton wheel is constructed of double cup runners that receive the impact from a high pressure water jet and convert it into rotational movement. The runners are contoured to split the water flow into two halves and reflect both halves backwards, thus maximizing the efficiency of the transfer of energy. Unlike other turbine designs once common in pre-industrial applications, the runners are not meant to hold fluid, rather to expel it, as gravity plays no real part in the collision and subsequent transfer of energy.
The design and dimensions of an ideal Pelton wheel can be calculated from the basic specifications already calculated above. The following is a summery of the pertinent information.
Hydraulic Head: $H_n = 31.62$m
Flow Rate: $q = 3.75 \times 10^{-4}\ m^3 s^{-1}$
Rotation: 2000 to 3000 RPMs

II. DESIGN OF THE PELTON WHEEL

The design of the ideal Pelton Wheel can be separated into three categories: calculating the ideal water jet width, calculating the ideal diameter of the wheel, and calculating the dimensions of the runners. In the first two cases, the calculations will be based on the initial characteristics summarized above, while the shape and dimensions of the runners will be determined primarily by the calculated width of the water jet.

The calculations used to generate the shape and dimensions of our Pelton Wheel were all based on those found in: MHPG Series, Harnessing Water Power on a Small Scale, Volume 9 Micro Pelton Turbines; published by SKAT, Swiss Centre for Appropriate Technology, 1991.

The Ideal Width of the Water Jet : The width of the water jet used is an important factor that will help to establish the physical shape of the Pelton Wheel runners. The width of the water jet determines the flow speed of the fluid impacting the runners and is based on the available Hydraulic Head. The following calculations are used to design the water jet width.

Absolute Velocity of the Water Jet c_1 : (ms^{-1})

Absolute Velocity of the Water Jet c_1 : (ms^{-1})
Nozzle Coefficient; k_c (0.96 to 0.98) assume worst case 0.96
Gravitational Constant: g (9.81 ms^{-2})
Hydraulic Head: H_n (m)

$c_1 = k_c (2\ g\ H_n)^{½}$
$= 0.96\ (2 \times 9.81 \times 31.62)^{½}$
$= 23.67$ m/s

Optimal Peripheral Velocity: u_1 (ms^{-1})

Optimal Peripheral Velocity: u_1 (ms^{-1})
Coefficient after Impact: k_u (0.45 to 0.49) assume worst case 0.45
Hydraulic Head: H_n (m)
Gravitational Constant: g (9.81 ms^{-2})

$u_1 = k_u (2\ g\ H_n)^{½}$
$= 0.45\ (2 \times 9.81 \times 31.62)^{½}$
$= 11.097$ m/s

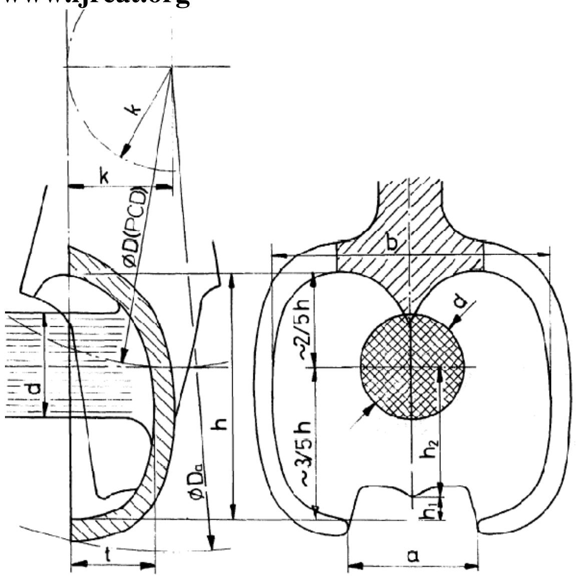
Pitch Circle Diameter: D (m)

Pitch Circle Diameter: D (m)
Rotational Speed: n_0 (2500 RPM; see above)
Transmission Ratio: i (Assume 1:1 ratio of turbine to generator turns)
Optimal Peripheral Velocity: u_1 (ms^{-1})

$D = (60\ u_1\ i) / (\pi\ n_0)$
$= (60 \times 11.097 \times 1) / (\pi \times 2500)$
$= 0.0847$ m
Or 8.5 cm

The Physical Dimensions of the Runners
The dimensions of the runners are calculated based off of the width of the water jet. The following formulas were used based on established standards. The meaning behind these measurements can be obtained from the following diagram.

Figure 1.1 Ideal Dimensions of a Pelton Wheel Runner



Bucket Width: b (mm)
b = (3.2)d
= (3.2)(4.5)
= 14.4 mm

Bucket Height: h (mm)
h = (2.7)d
= (2.7)(4.5)
= 12.15 mm

Cavity Length: h_1 (mm)
h_1 = (0.35)d
= (0.35)(4.5)
= 1.6 mm

Length to Impact Point: h2 (mm)
h_2 = (1.5)d
= (1.5)(4.5)
= 6.75 mm

Bucket Depth: t (mm)
t = (0.9)d
= (0.9)(4.5)
= 4.05 mm

Cavity Width: a (mm)
a = (1.2)d
= (1.2)(4.5)
= 5.4 mm

Offset of Bucket: k (mm)
k = (0.17)d
= (0.17)(4.5)
= 3.4 mm

Working Values for the Pelton Wheel

Once the ideal values had been calculated, a times two safety factor was used to produce the working values. The following table summaries the working values.

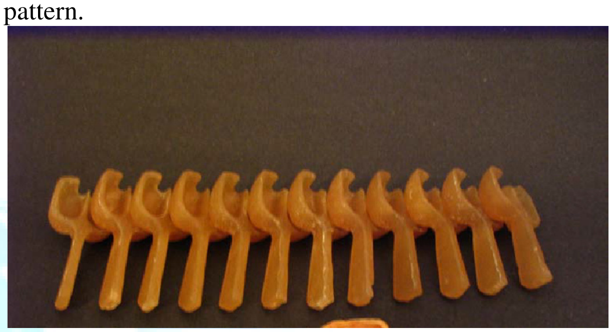
b = 28.8 mm
h = 24.3 mm
h1 = 3.2 mm
h2 = 13.5 mm
t = 8.1 mm
a = 10.8 mm
k = 6.8 mm
D = 85 mm
d = 4.5 mm

Construction of the Prototype Pelton Wheel Runners :

- The prototype runner was carved out of balsawood. This model was then used as the master pattern for the mass-produced runners.
- The balsawood runner was then water sealed using urethane lacquer to prevent it sticking to the mold material. To allow the balsawood runner to be removed easily from the mold, it was covered in a thin layer of wax.
- Thin pieces of wax were kneaded until they were soft, then they were stuck to the bottom of the master pattern adhering it to the working surface. More wax was used to plug up any holes that existed around the perimeter of the pattern. Excess wax was removed with an X-Acto knife.
- The front opening where the cavity is located (a x h_1 on the plans) was plugged with a large contoured wedge. This wedge both plugged up the hole, as well as acted as an alignment mark for the top half of the mold. In addition to the wedge, two half hemisphere balls of wax were added on either side of the flange to act as alignment groves.
- A thin piece of wax was added to the bottom of the formwork box that adhered it to the working surface. With the formwork stuck in place, a wax cone was added between the ends of the flange up to the edge of the box. This acted as an opening to pour the epoxy resin into the mold.
- Use a paintbrush, a thin layer of petroleum jelly was added to all surfaces within the box, including the wax paper that lined the sides. This layer acted as a parting agent preventing the plaster from sticking to either the mold or the balsawood pattern.
- A pre-measured portion of one part water to two parts Plaster of Paris was mixed in a small bowl using a spatula. When mixed, it was poured into the mold.
- In order to remove air bubbles trapped within the mixture, the side of the mold was agitated

by hitting it lightly with a small hammer. Once most of the air was out, it was left to dry for 45 minutes.

- When it was dried, a drywall spatula was used to peal off the mold from the working surface. The master pattern was then removed from the mold with an X-Acto knife. With the balsawood runner out of the mold, the mold was left to finish drying for one day. The whole process was repeated for three molds just in case one mold was to fail later on in the production.
- Air channels were added to the lower mold by cutting thin lines with an X-Acto knife. These lines extended from the end of the scoops to just below the alignment marks. As before, all surfaces were coated with a thin layer of petroleum jelly to prevent the epoxy from sticking to the plaster mold.
- The two halves of the mold were connected, and tied closed with masking tape. A measured amount of epoxy resin was then mixed with the hardener in a plastic up. Once mixed, the mixed compound was slowly poured into the three molds through the opening holes at their tops.
- When the hole was filled, it was left to stand for two hours. At this point, the epoxy was dry, but not completely hard. The masking tape was removed, and the two halves of the mold were cracked open. The partially solid epoxy pattern was removed from the mold, and left to harden on a sheet of wax paper.
- Once the epoxy pattern was removed, all remaining smudges of epoxy resin were removed with an X-Acto knife. Any damages made during the opening of the mold were repaired with wax, and a layer of petroleum jelly was reapplied to the surface of the mold. The two halves of the mold were held in place with a new layer of masking tape.
- When the epoxy patterns were removed from the molds, they were attached to extra material that either formed in errors in the mold that developed as the molds degraded with use, or were from necessary features like the air holes. In either case, these errors were removed through several steps.
- The first step was to use an X-Acto Knife to remove the unwanted imperfections, including the area at the end of the flange where it joins the opening hole, and the air holes.
- The second step was to sand the surface of the epoxy pattern with fine sand paper. This removed any small bumps caused by air holes left in the plaster mold. The third stage was to polish the epoxy pattern with a Dremel tool.
- Each runner was polished with the Dremel tool, and then washed in soap and water to remove any petroleum jelly still attached to the pattern.



Mounting the Runners on the Wheel

After the runners were cut, it was clear that with the smaller diameter wheel and its resulting high speed of rotation, any unbalance in the wheel would cause vibrations that might result in damage. As a result, extra care was taken to ensure that the wheel was as balanced as possible. This meant that the original plan of using the acrylics discs to sandwich the runners was considered too inaccurate and a new procedure that could place each runner accurately was conceived.

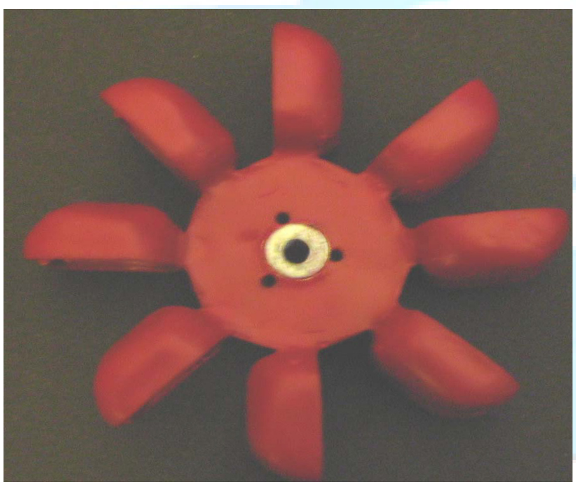
Precision Mounting of the Runners in the Radial Plain:

Though the acrylic disc would not be used for structure, it was used to act as a mount for the runners. The hole in the disc would act as a marker for the centre of rotation, while the machine screw attached through the hole would mark the axis perpendicular to the plane of rotation. Before each of the runners was cut, a line was drawn on their flanges to indicate the radial centre line.

Each of the runners was then stuck onto the wax. The first step was to line up the runner's centre line with the radial lines on the acrylic disc. Because the disc is transparent, this was accomplished by looking through the disc and sliding the runner until its center line completely matched the radial line scratch on the opposite side of the disc. This ensured that each runner was exactly spaced in the radial plane.

The second step was to make sure that the ends of each runner was pushed tightly against the washers. This ensured that each runner was exactly the same distance from the shaft.

Gluing the Runners into the Wheel:
Once each of the runners was properly positioned in the horizontal, vertical, and radial directions, they were held in place with a layer of epoxy resin. This was accomplished by simply applying a thin layer while the wheel was still held in the drill-press.
After the runners were held in place, wax formwork was added to the sides of the acrylic disc, and a structural layer of epoxy resin was pored on the top surface. The wheel was then painted to provide a protective layer to the finished wheel.



Construction of the Generator Mount : The basic idea for the generator mount was to design it in such a way as to allow for maximum access to the wheel. As such, the structural part of the machine consists of a single piece of plywood, with the remaining parts: wheel housing, generator, and the legs, simply being bolted to it. The generator mount was constructed from one piece of plywood, with a hole cut in the centre for the generator. Holes were drilled along the perimeter in order to attach the wheel housing. In addition, four small holes were drilled at the corners to be used as pilot holes to attach the legs that would eventually support the completed machine.

Mounting the Generator: To make sure that the shaft of the generator is mounted at the exact center of the hole, paper was wrapped around the shaft to a thickness just smaller than the hole.

Waterproofing the Generator: The electric motor used to create the generator is open at the bottom to help cool the motor during operation. Unfortunately this puts the generator in danger of becoming wet. In order to waterproof the shaft hole, a ring of wax was placed around the hole. On top of the wax ring was placed a shaft collar with a small sponge ring cut from a dishtowel. The shaft collar will prevent any water from directly hitting the hole. By soaking the sponge in oil, any droplets of water that find there way to the wax-ring/collar interface will hopefully be repelled by the thin layer of oil.

Adding the Water Pipes
One of the benefits to mounting the Pelton Wheel in a horizontal plane is that multiple water jets may be used at the same time. Adding more jets reduces the force of any one jet only if the flow rate is limited. For a practical application this would not be the case as it would be realistic to assume an endless water supply, but as we are using a residential water pip, it would be reduced. The result is that multiple water jets were added for demonstration purposes, but only one jet would be used for testing. This means that a method for opening and closing water lines was necessary.
The pipes were constructed out of prefab CPVC pipe because of its low cost and ease of gluing. Two flow control valves were added to allow a choice of water jets, and they were attached by threaded CPVC fixtures instead of glue.

The pipes were then attached to the top surface of the generator mount by CPVC latches.

Aligning the Water Jets
One of the most important parts of the assembly was the water jet alignment. The nozzle should be aligned so that the water jet hits the center ridge of the runners, and at a point 3/5 of the way from the front. This positioning is designed to produce the most efficient transfer of energy to a Pelton Wheel. But in order to

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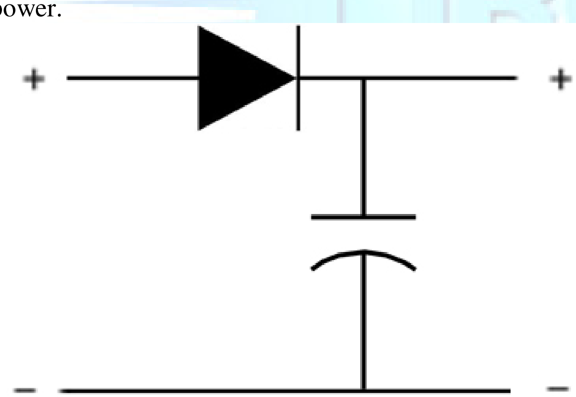
generate the larges amount of available torque, an impact at 90 degrees at the outermost point of the runners is needed. Because we had two water jets available, and flow control to be able to pick between them, we decided to design one jet with an ideal Pelton Wheel impact, and the second one with maximum torque.

The water nozzles were aligned by opening the back of the "T" joint and using a laser pointer to fire a beam out the front of the nozzle, in effect mimicking a water jet. This technique was used to know exactly where the water jet would hit the runners. By knowing this, the alignment of the jet was established.

Building the Rectifier Circuit

The power produced by a DC motor working as a generator is categorized as direct-current, but the voltage still oscillates between its maximum voltage and zero depending on the position of the windings with respect to the magnets. In order to provide a more steady DC power, a basic rectifier was constructed. The following simple circuit was used to smooth out the DC power.



The rectifier circuit was constructed from leftover bits of acrylic. Holes were drilled for the components on the top plate, with the diode resting on the bottom plate. The individual electrical components were soldered together with bits of house wire.

III. FINAL ASSEMBY

WITH ALL THE IND ASSEMBLY IVIDUAL PARTS COMPLETE, THE COMPLETED MACHINE WAS ASSEMBLED BY ATTACHING THE LEGS WITH WOOD GLUE AND FOUR SCREWS, THEN BY ATTACHING THE WHEEL HOUSING ALONG ITS PERIMETER WITH MACHINE SCREWS AND WING-NUTS.

Note: After testing, a PVC pipe was added to the hole at the bottom of the wheel housing to help direct the water to a drain.

IV. TESTING AND RESULTS

The machine was tested in the fluids lab using cold water from an available hose. The open terminal voltages were measured for the three possible water jet combinations, and the following data was collected.

• Open Terminal Voltage for 90 Degree Water Jet: 11V

• Open Terminal Voltage for Correctly Positioned Pelton Wheel Jet: 11.6V

• Open Terminal Voltage for Both Water Jets at the same time: 8V

It was clear that the correctly positioned Peltoln Wheel water jet was the most successful.

During a separate testing day, the rectifier was tested, and a 12v 60W portable television was used as a test load. Though the TV did not get any reception in the basement lab, it did turn on, demonstrating that the machine does function with a load.

V. CONCLUSION

The Green Micro-Hydro plant was successfully constructed and tested with a real load. Though there was insufficient time to produce a full Voltage/Current graph, the generator system was tested with both an open and short-circuit load. In the second case, the turbine continued to turn, though labored.

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