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DESIGN AND STRUCTURAL ANALYSIS OF PELTON WHEEL TURBINE BLADE

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Abstract: - **A hydro-mechanical energy conversion system is a Pelton-wheel impulse turbine that transforms elevated water's gravitational energy into mechanical operation. Using an electrical generator, this mechanical work is transformed into electrical energy. In the high head and low water flows, the Pelton turbine was used to set up a micro-hydroelectric power plant due to its easy design and ease of development. The turbine parameters must be included in the design procedure in order to achieve a Pelton hydraulic turbine with optimum efficiency under different operating conditions. Using MATLAB SOFTWARE, all design parameters were measured at full efficiency here These parameters included turbine strength, turbine torque, runner diameter, runner length, runner velocity, and bucket dimensions, bucket number, nozzle dimension, and specific velocity of the turbine. Designing a Pelton Turbine bucket and testing its suitability for the Pelton turbine were the main focus. The literature on the design of Pelton turbines is scarce; this work exposes the theoretical and experimental aspects of the design and study of a Pelton wheel bucket, while using the standard rules to design a Pelton wheel bucket. The bucket is intended for optimum effectiveness. The modelling and study of the bucket was performed using SOLIDWORKS 2015. The material used in the development of Pelton wheel buckets is analysed in detail, and these characteristics are used for analysis. By considering the force and considering the pressure exerted on various points of the bucket, the bucket geometry is studied. For the static case, the bucket was evaluated and the Vonmises tension, static displacement, and safety factor results were obtained.**

Keywords: - *Hydro Power Plant, Pelton Wheel Turbine Blade*

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I INTRODUCTION

In order to drive turbines, hydro power plants use the potential energy of water stored in a reservoir. Turbines are attached to large generators and can run on various water volumes in order to adjust to changing electricity demands. There are primarily three parts of the power system, namely generation, transmission and distribution.

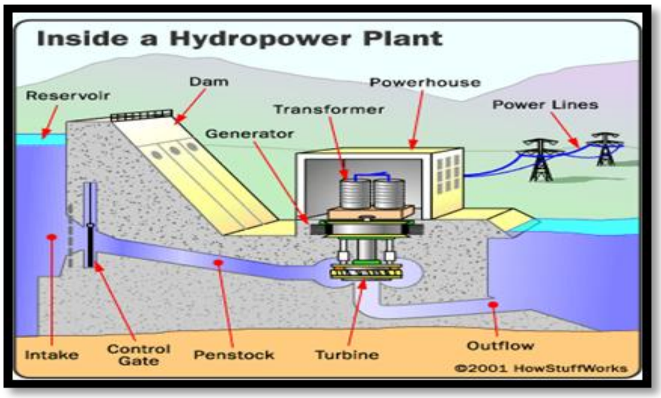


Fig. 1.1 Hydro Power Plant

As we know, the hydraulic turbine A transforms flowing water energy into mechanical energy. This mechanical energy is transformed into electricity by a hydroelectric generator. A generator's operation is based on the principles which Faraday discovered. He discovered that it allows electricity to flow as a magnet is transferred past a conductor. By circulating direct current through loops of wire wrapped around stacks of magnetic steel laminations, electromagnets are generated in a large generator. These are known as field poles and are located on the rotor's perimeter. The rotor is connected and rotates at a set speed to the turbine shaft. It makes the field poles (the electromagnets) shift past the conductors installed in the stator as the rotor turns. This in turn causes electricity to flow and a voltage to build at the output terminals of the generator. And there are various methods of generating electricity, but we concentrated only on generating electricity using hydro or water (hydropower plant) in this article. As we know, the power plant is known as the place where power is produced from a given source, so here the source is hydro that

1.2 Literature Survey

The author experimented with "Flow Analysis inside a Pelton Turbine Bucket" in this study and studied flow in the pelton turbine fixed bucket. In order to cover a broad range of turbine operating points, the head, jet incidence, and flow rate have varied. The experimental research offers both pressure and torque measurements and flow visualization. Using the two-phase flow volume of fluid system, the numerical analysis is performed with the FLUENT code. A thorough torque and thrust analysis helped determine the losses due to the edge and the bucket cut-out. They also streamlined the method of constructing Pelton turbines to achieve the best performance. [1]

The researcher examined in this research that Laser Doppler anemometer was being used for flow distribution information and empirical study on pelton turbine jet flow in 'Experimental studies of the jet of a pelton turbine'. The jet flow in pelton turbines has also been introduced to CFD. [2]

Multiphase flow analysis in Pelton turbine utilizing water and air as working fluid to calculate the performance, blade loading, velocity and water distribution over the bucket at various operating regimes of the turbine was performed in this study researcher conducts an assessment on' Numerical simulation of six jet Pelton turbine model' For transient multiphase flow simulation, the impact of mesh size, turbulence model and time stage is also being analyzed. [3]

In this review the author analysed the effects of 3D URANS simulations of the flow and entrainment processes in a jet-mixed tank on the 'CFD modelling of turbulent jet mixing in a storage tank.' Several jet velocity, nozzle diameter and nozzle angle variations were studied and two differentiating schemes of various levels of accuracy have been implemented to estimate the convective fluxes. A CFD code has been developed that can be used as a versatile modelling method for water storage tank design and optimization, such as the impact of varying water depths and density stratification. [4]

The researcher of this study presented an article on "Performance analysis of nozzles used in impulse hydraulic turbines utilizing CFD simulated water streamlines and pressure distribution at various openings in 3 distinct nozzle shapes.CFD was concluded to be a very effective method to predict the efficiency of different nozzle shapes at different mass flow rates and nozzle openings at least in time. [5]

"The FLUENT software is selected for the determination of flow pattern in this studies researcher survey on The Advancement of Bulb Turbine for Low Head Storage Using CFD Simulation. Considering the current civil structure of the dam, the flow control for irrigation and the constraint of the water level that can affect the efficiency of the hydropower plant in the upper dam, the hydro turbine for the Lower Mae Ping dam has been built. Optimizations for all objectives have been taken into account. [6]

II. DEFINITION OF TURBINE

It is possible to describe a hydraulic turbine as a rotary machine that uses the potential and kinetic energy of water and transforms it into mechanical energy that is useful. The machines that use water energy and transform it into mechanical energy are hydraulic or water turbines. In particular, a water turbine comprises of a wheel that has several specially built vanes or blades or buckets, called a runner rotor. When the runner strikes the water treatment, a significant amount of hydraulic energy acts on the runner and causes it to rotate. The generator connected to the runner, which then produces electrical energy, is supplied with the mechanical energy so generated. The best choice of turbine for any specific hydro project relies on the characteristics of the site, with the head and flow available being the dominant ones. Selection often depends on the intended running speed of the turbine loading generator or other unit.

2.1 Types of Turbine

Turbines are also divided by their principle of operation and can be either impulse turbines or reaction turbines.

1. Reaction Turbine: The reaction turbine's rotating part is completely immersed in water and is enclosed in a pressure casing. The runner and casing are deliberately crafted so that they reduce the clearance between them. The runner blades are profiled so that pressure differences across them impose lift forces that cause the runner to rotate, similar to those on aircraft wings.

2. Impulse Turbine: An impulse turbine runner works in the air in the contest, powered by a water jet (or jets). And before and after making contact with the runner wheels, the water stays at ambient pressure. In this case, the pressurised low-velocity water is converted into a high-speed jet by a nozzle. To maximise the change in momentum of water and thus maximise the force on the blades, the runner blades deflect the plane. As the interior is at atmospheric pressure, the casing of an impulse turbine is mainly intended to control splashing. Impulse turbines are typically cheaper than reaction turbines because a specialised pressure casing or carefully designed clearances are not needed. But they are only acceptable for moderately high heads as well. As follows, there are 3 types of impulse turbine.

The Pelton wheel is a water turbine of the Impulse form. It was developed in the 1870s by Lester Allan Pelton. In comparison to water's dead weight, like the conventional overshot water wheel, the Pelton wheel derives energy from the impulse of moving water. Prior to the design of Pelton, many types of impulse turbines existed, but they were less powerful than the design of Pelton. Usually, water leaving those wheels also had high velocity, taking away much of the dynamic energy carried to the wheels. Pelton's paddle geometry was designed such that the water left the wheel with very little speed as the rim ran at 1⁄2 the speed of the water jet; so his design removed almost all of the impulse energy of the water making for a very powerful turbine.

2.2 Runner and Buckets

The runner consists of a circular disc on the periphery of which a number of equally spaced buckets are fixed. The buckets are spaced in a double hemispherical cup or tub. By dividing the wall, known as the Splitter, each bucket is divided into two symmetrical sections. The Splitter separates the jet into two equal parts. The buckets are shaped in such a way that 160 ° or 170 ° are deflected by the plane. Depending on the head at the inlet of the turbine, the buckets are made of cast iron, cast bronze steel or stainless steel.

Fig. 2.1 Runner and Buckets

III. DESIGN OF PELTON TURBINE

A. Preparing the Site Data of Power Plant

This involves the calculations and measuring the net head and the water flow rate.

1) Calculation of the net head (H_n):

$$H_n = H_g - H_{t1}$$

For Micro hydro Power plant, assume Hg = 50 m

$$H_{t_1} = 0.06 * Hg = 3 \text{ m}$$
$$H_n = 47 \text{ m}$$

2) Calculation of the turbine input power (Pti)

The electrical input Power to the turbine in (Watt) can be calculated as:

$$P_{ti} = \rho * g * C_n^2 * H_n * Q_t \text{ (Watt)}$$
$$P_{ti} = 44.285 \text{ kw}$$

3) Calculation of the turbine speed (N)

The turbine Speed Can be Calculated as:

$$N = N_s * H_n^{5/4} / \sqrt{P_{ti}}$$

$$N = 620\, rpm$$

4) Calculation of the runner circle diameter (Dr)

The water jet through nozzle has a velocity (V_j) in ($m.s^{-1}$) can be calculated as:

$$V_j = C_n * \sqrt{2 * g * H_n} \quad (m.s^{-1})$$
$$V_j = 29.75\, {}^{m}/_{s}$$

The runner tangential Velocity (V_{tr}):

$$V_{tr} = w * R_r = \pi N D_r / 60 \quad (m.s^{-1})$$

Also the runner tangential Velocity can be given as:

$$D_r = 38.60 * \sqrt{\frac{H_n}{N}}$$
$$D_r = 0.426\, m$$

5) Calculation of nozzle dimensions

The water flow rate through each nozzle (Q_n) can be calculated as:

$$Q_n = V_j * A_j \quad (m^3.s^{-1})$$

Nozzle Area (A_j) can be calculated as:

$$A_j = \pi * Dj^2/4 = 3.36 * 10^{-3} \quad m^2$$
$$Q_n = 0.01 \frac{m3}{s}$$

The Nozzle Length can be calculated as:

$$L_n = D_{pn} - D_j / \tan(\beta)$$

$$L_n = 0.270\, m$$

The distance between the nozzle and runner should be 5% of the runner circle diameter plus an extra (3) mm clearance to account for emergency deflectors as:

$$X_{nr} = 0.05 * D_r + D_t$$
$$X_{nr} = 0.0243\, m$$

Clearance between the nozzle& buckets is:

$$X_{nb} = 0.625 * D_r$$
$$X_{nb} = 0.266\, m$$

6) Calculation of Bucket Dimensions

The bucket axial width can be calculated as:

$$B_w = 3.4 * D_j$$
$$B_w = 0.22 \text{ m}$$

The bucket radial length can be calculated as:

$$B_t = 3 * D_j$$
$$B_t = 0.195 \text{ m}$$

The bucket depth can be calculated as:

$$B_d = 1.2 * D_j$$
$$B_d = 0.078\, m$$

The number of buckets can be calculated as:

$$N_b = 15 + D_r / 2 * D_j$$

$$N_b = 19$$

The radius of bucket centre of mass to centre of runner was given:

$$R_{br} = 0.47 * D_r$$
$$R_{br} = 0.2\, m$$

The bucket Volume was given as:

$$V_b = 0.0063 * D_r^3 \quad (m^3)$$
$$V_b = 4.87 * 10^{-4} \quad m^3$$

7) Deflector Design

The force in each deflector can be calculated as:

$$F_d = \rho_w * Q_n * V_j$$
$$F_d = 2975\, N$$

The required force in each deflector was given as:

$$F_{dr} = F_d * S.F$$
$$F_{dr} = 7437.5\, N$$

8) Calculation of Maximum Turbine Efficiency

The input power to the turbine can be calculated as:

$$P_{ti} = \frac{\rho_w * Q_t * V_j^2}{2}$$

$$P_{ti} = 44.253\ KW$$

The power output developed by the turbine was given as:

$$P_{to} = \rho_w * Q_t * V_{tr} * [(V_j - V_{tr}) (1 + \Psi * \mathrm{Cos}\,(\Theta))]$$

$$P_{to} = 42.855\ \mathrm{kW}$$

The turbine hydraulic efficiency can be calculated as:

$$\eta_{th} = \frac{P_{to}}{P_{ti}}$$

$$\eta_{th} = 96.80\ \%$$

For Maximum hydraulic turbine efficiency:

$$\eta_{th(Max)} = \frac{[1 + \Psi * \mathrm{Cos}\,(\Theta)]}{2}$$

$$\eta_{th(Max)} = 97.33$$

3.1 With the Help of Matlab Programming We Have Achieved Two Tables for Two Different Conditions

Hg	P_{to} (Kw)	η (%)	T (N.m)	N (r.p.m)	N_s	n_b
50	43	96.9	660	620	33.5	19
60	51.5	96.9	722	680	32	19
70	60	96.9	779	735	31	19
80	68.5	96.9	832	787	30	19
90	77.2	96.9	882	835	29	19
100	85.8	96.9	930	881	28.3	19
110	94.3	96.9	974	925	27.7	19
120	103	96.9	1016	967	27	19
130	111.5	96.9	1057	1007	26.6	19
140	120	96.9	1097	1045	26	19

Table 1: The Pelton Turbine at Maximum Efficiency and Constant Flow Rate (Qt =0. 1 M3.S-1)

Hg	Qt $(m^3.s^{-1})$	P_{to} (Kw)	T_t (N.m)	η (%)	N (r.p.m)	N_s	n_b
(50)	0.1	43	660	96.9	620	33.	19
	0.2	85.8	1320	96.9	620	47.	19
	0.3	129	1980	96.9	620	58	19
	0.4	171.5	2640	96.9	620	67.	19
(60)	0.1	51.5	722	96.9	680	32	19
	0.2	103	1444	96.9	680	45.	19
	0.3	154.4	2167	96.9	680	55.	19
	0.4	206	2889	96.9	680	64.	19

Table 2: Design Parameters of the Pelton Turbine at Maximum Efficiency and Constant Gross Head

3.2 Generated Graphs

A. Graph for Constant Flow Rate (condition ‘1’):

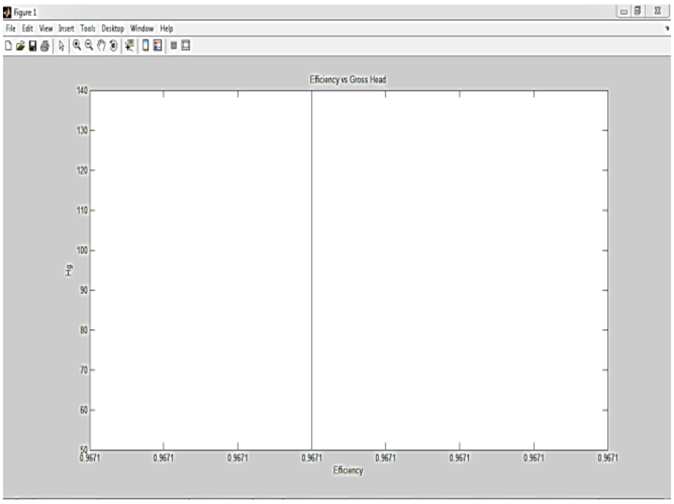


Fig. 3.1 Efficiency vs. Gross Head

B. Graph for Constant Head (condition ‘0’):

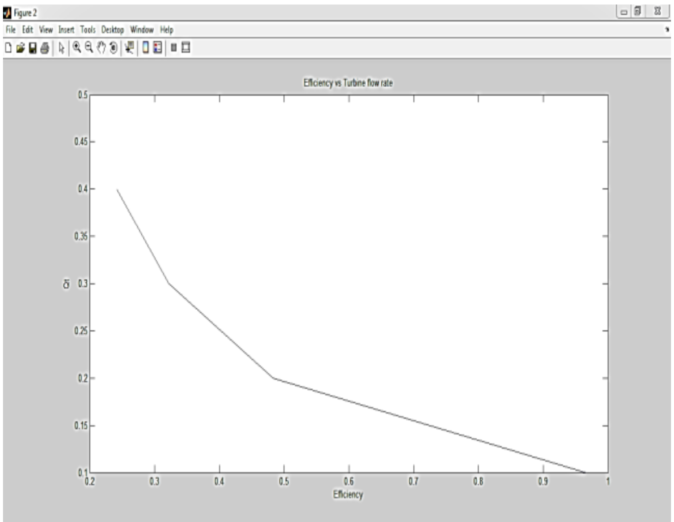


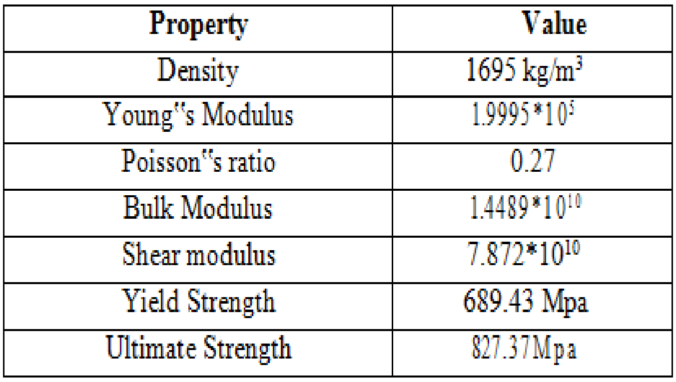
Fig. 3.2 Efficiency vs. Turbine Flow Rate

IV. MODELLING OF PELTON TURBINE BUCKET IN SOLIDWORKS

SOLIDWORKS (originally Solid Works) is a CAD (computer-aided design) solid modelling software running on Microsoft Windows manufactured by Dassault Systems SOLIDWORKS Corp., a subsidiary of Dassault Systems, S. A. (France, Velizy) since 1997. Over 2 million engineers and designers in more than 165,000 enterprises around the world currently use SOLIDWORKS. 3D CAD software from Solid Works enables parts to be built and assembled in a better way.

A. Material Properties

The material primarily used in the industrial manufacture of pelton wheel turbines is CA6NM. This is a mixture which is hardened by heat treatment of iron, chromium, nickel, and molybdenum. The tensile strength and impact strength of this material are very high. This is not corrosive, and is thus primarily used in the construction of water-formed structures. For power generation, a significant application of the alloy has been in large hydraulic turbine runners.



Property	Value
Density	1695 kg/m^3
Young"s Modulus	$1.9995*10^5$
Poisson"s ratio	0.27
Bulk Modulus	$1.4489*10^{10}$
Shear modulus	$7.872*10^{10}$
Yield Strength	689.43 Mpa
Ultimate Strength	827.37Mpa

Table 3: Major Material Properties

B. Solid works Model of Pelton Turbine Bucket

From all the above calculated parameters and some standard parameters the modeling of the bucket is done using Solidworks 2015.

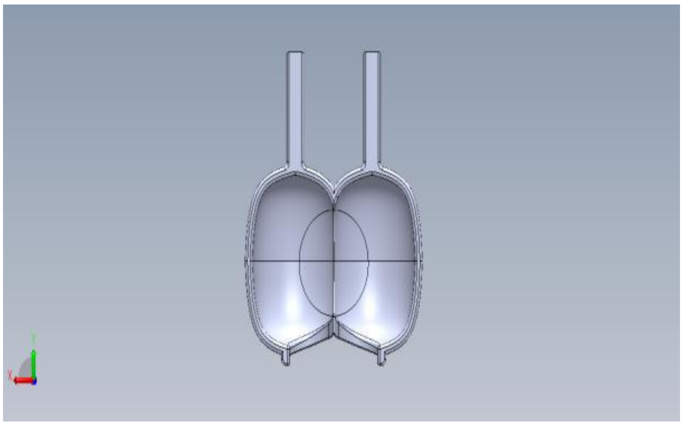


Fig. 4.1 Bucket 3D Models

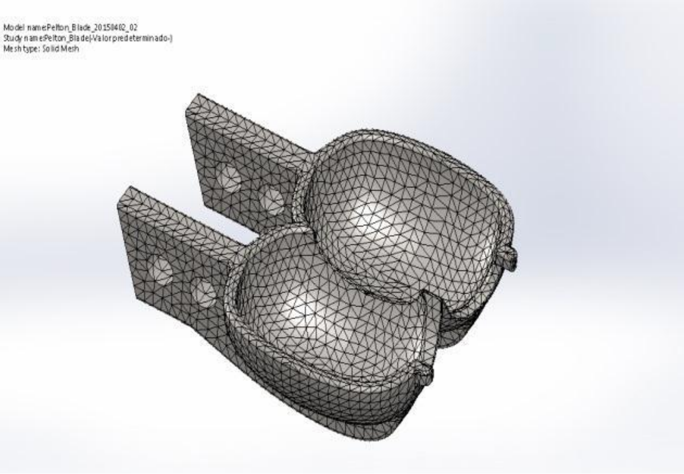


Fig. 4.2 Bucket Solid Mesh Model

4.1 Analysis of Pelton Turbine Bucket

In engineering field the analysis of component can be done in various ways like static, dynamic, fluid interactions etc. depending up on application. Here the analysis can be done based on linear static analysis. During the analysis various assumption were taken. The following is the assumptions:

1) Linearity Assumption
2) Input for Linear Static Analysis
3) The bucket is stationary
4) The bucket profile is uniform
5) Effects of external forces are negligible
6) The fixed at its arm acts similar to a cantilever beam

4.2 Analysis Result

In the analysis of bucket various plot is being generated which shown in below The bucket is operated at a head of 50 m and the mass flow rate is 0.1 m3/s , the first impact force on the splitter is given by F= 153.864 KN.

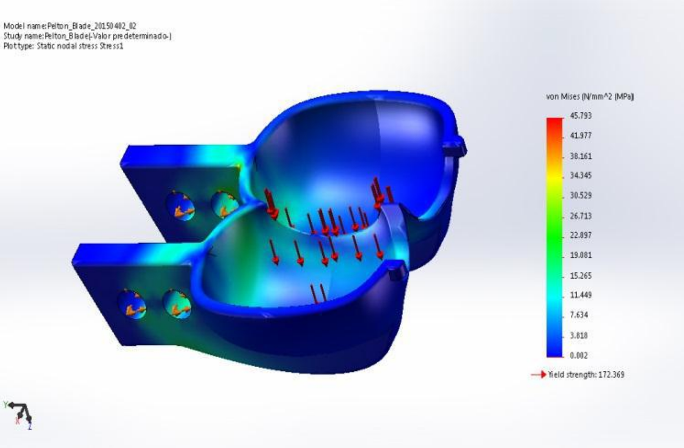


Fig. 4.3 Vonmises Stress

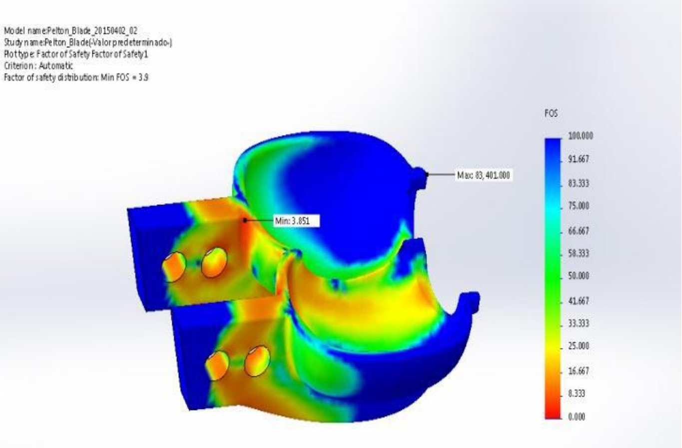


Fig. 4.4 Factor of safety

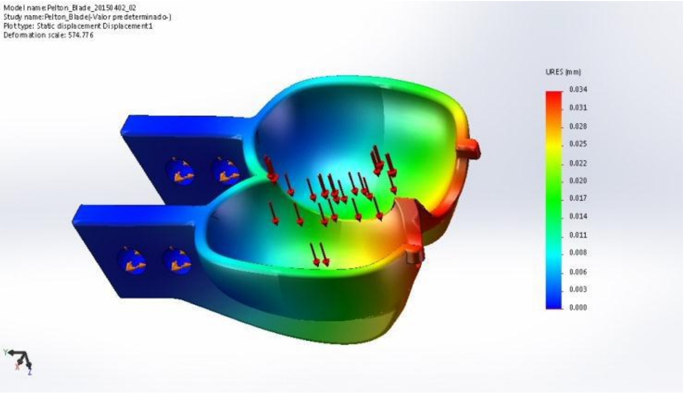


Fig. 4.5 Displacement analysis

V. RESULT & DISCUSSION

A. Result of MATLAB Programming

The design calculations of the Pelton turbine were implemented by a Matlab Simulink computer program. Table (1) shows the design parameters of the Pelton turbine with constant flow rate (Q = 0.1 m3.s-1) and variable gross head of the plant site (Hg= 50 to 140 m), while table (2) shows the same turbine parameters at constant head (Hg = 50 to 60 m) with variable water flow rate (Q = 0.1 to 0.4 m3.s-1) of the site. Figure (3.1) shows the variation of runner to nozzle diameter ratio with specific speed at different values of water flow rate, while in figure (3.2) shows the variation of the same ratio with the nozzle length.

From these results, the turbine maximum efficiency was found to be 97% constant. In case of variable head, all the design parameters were varied with head except of number of runner buckets and runner diameter, while in a variable flow rate all the design parameters were constant except of turbine power, specific speed and nozzle length.

B. Result of Modeling and Analysis

After modelling and analysis of the pelton turbine bucket, the calculated load is 153.684 KN, and impact due to this load on the bucket is described here.

Factor	Maximum	Minimum
Von mises Stresses(N/mm^2)	45.793	0.002
Factor of safety	83401.000	3.851
Displacement	0.034	0.000

Table 4: Analysis Result

VI. CONCLUSIONS

In the case of a high head and a low water flow rate, the Pelton turbine is ideal for building small hydroelectric power plants. Based on theoretical analysis and some empirical relations, a complete design of such turbines has been presented in this paper. For various head and water flow rate values, the maximum turbine efficiency was found to be 97 percent constant. Using the MATLAB programme, complete design parameters such as turbine strength, turbine torque, turbine speed, runner dimensions and nozzle dimensions are calculated for maximum turbine efficiency.

The bucket model is constructed according to the parameters determined and in SOLIDWORKS the analysis is performed for different parameters. The FOS achieved from the analysis result is 3.5, so the design model is safe. The maximum stress produced by the water jet is about 45 N/mm2 that the bucket material can easily withstand (SS316 THE MAXIMUM STRESS CAPACITY = 172.36 N/mm2)

ABBREVIATION (NOMENCLATURE)

Ab	Peripheral area of penstock (m^2)
Aj	Jet or nozzle cross-sectional area (m^2)
Ap	penstock cross-sectional area (m^2)
Ar	River or steam cross-sectional area (m^2)
Bd	Bucket depth (m)
Bl	Bucket radial length (m)
Bw	Bucket axial width (m)
Cn	Nozzle (jet) discharge coefficient (≅ 0.98)
Dj	Jet or nozzle diameter (m)
Dpn	Diameter of penstock connected to the nozzle
Dpt	Diameter of penstock connected to the turbine
Dr	Runner (wheel) circle diameter (m)
Dt	Deflector thickness (m)
Fc	Friction factor acted upon by bearings (≅1.2)
Fd	Deflector force (N)
Fdr	Required deflector force (N)
g	Gravity acceleration constant (9.81 m.s-2)
Hg	Gross head (m)
Hn	Net head (m)
Hs	Surge head (m)
Ht	Total head (m)
Htl	Total head loss (m)
Kd	Drag coefficient
Kwm	Bulk water modulus ($2.1*10^9$ $N.m^{-2}$)
Lab	Length of bucket moment arm (m)
Ln	Nozzle length (m)
Lpt	Length of penstock between intake and turbine
Mb	Mass of bucket (Kg)
Mp	Modulus of penstock material
nb	Number of buckets
nj	Number of turbine nozzles
np	Manning factor of penstock
N	Turbine (runner) speed (r.p.m)
Nr	Turbine run-away speed (r.p.m)
Ns	Turbine specific speed
Pti	Turbine input power (watt)
Pto	Turbine output power (watt)
Qn	Nozzle flow rate (m3.s-1)
Qt	turbine flow rate (m3.s-1)
Rbr	Radius of bucket center of mass to runner center
Rd	Radius of deflector arm (m)
Rr	Radius of runner (m)
S.F	Safety factor to prevent water hummer effect (>
tp	Thickness of penstock (m)
tpe	Effective thickness of penstock (m)
tsp	Tensile strength of penstock material (N.m-2)
Td	Deflector torque (N.m)

GREEK SYMBOLS

β	Nozzle tapper angle (degrees)
ψ	Bucket roughness coefficient (0.98)
Θ	Deflection angle between bucket and jet (160° to 170°)
ρ_a	Air density (1.23 Kg.m^{-3})
ρ_m	Density of bucket material (Kg.m^{-3})
ρ_w	Water density (1000 Kg.m^{-3})
	Runner velocity (radian.sec^{-1})
ω_r	Runner run-away velocity (radian.sec^{1})
η_t	Total turbine efficiency
ηth	Turbine hydraulic efficiency
ηtm	Turbine mechanical efficiency
ηtw	Turbine windage efficiency

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