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Fatigue Analysis of Simple and Advanced Hoop Pelton Turbine Buckets

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Abstract

The Pelton impulse turbine, which is the most effective turbine that was invented by Lester Pelton, has good operation performance in high hydraulic head and low flow rates. The water from the jet strikes the bucket splitter ridge and induce the forces to propel the runner for producing mechanical energy from velocity head. This jet forces produce the main fatigue load that repeats the load cycles during the operation to occur the stresses on the bucket to become fatigue. This paper focus on the fatigue analysis of the Pelton turbine bucket by numerical approach that shows the results of life cycles, damage, Von Mises stress, and mean biaxiality ratio to estimate the better design and operating performance of the Pelton turbine bucket with minimum corrosion and failures. Solid Works 3D Cad software is used for modelling two different shapes of Pelton buckets that are simple, and advanced hoop buckets and ANSYS 16.2 nCode design life simulation software is used for analyzing fatigue with the finite element method. Stainless steel, aluminum alloy, and cast iron are considered for bucket materials to compare better results for turbine.

Keywords: Pelton turbine; fatigue analysis; simple bucket; advanced hoop bucket; Solid Works; ANSYS 16.2 nCode design life; stainless steel; aluminum alloy; cast iron.

1. Introduction

Water turbine is a primary essential tool for harnessing hydropower to produce electricity. Although there are many types of hydro turbines, the choice of suitable water turbine for the specified hydro power station considered on the geographical sites, altitude and water flow.

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Pelton impulse turbine is suitable for elevated regions between 50 to 1000 meters (165 to 3300 feet). From this water head, the jet is transformed into a high velocity to hit the inner splitter edge between two hemispherical buckets and the outward flow departs back an outlet angle of about 180 degrees of the bucket. This produces the centrifugal force on the bucket when striking it and exerts pressure on it. For the simple Pelton turbine, the change in momentum occurs when the outgoing velocity is lesser than the incoming velocity and generates torque to rotate the turbine shaft. Whereas in the hoop Pelton bucket, the torque is generated from the two hoops by producing the diverging force acting on the buckets. Although reducing the ratio between the bucket width and the jet diameter leads to increase in turbine efficiency and performance in the simple Pelton turbine, stresses occur greater due to load increases leading fatigue. However, the hoop Pelton runner can reduce stresses due to its construction in supplying the bucket as simply supported embedded beams. In recent years, Pelton turbines have already been written by many scholars with different aspects of view by various methods of modelling and analysis on numerical, analytical and experimental analyses. Varun Sharma in [1] researched about stress variations on the Pelton turbine bucket by using ANSYS software and found that the maximum stress occurred at 0° angle of jet when inducing the blade and the minimum stress found at the outermost periphery of the blade. N. Nava Indrasena Reddy [2] has discussed the efficiency and high stress handling factors of the Pelton wheel simulating with 3D modelling CATIA V5 software using coupled field analysis by changing three materials and number of buckets. It was observed that fiber glass reinforced plastic give better results in which deformation, stress and strain factors are lower than cast iron and steel is the second best allowable material. B. Vinod [3] has discussed about the stress between the simple Pelton turbine bucket and the hoop bucket with the materials of 1020 steel and 1060 alloy and simulated with Solidworks 2014 software. Among both materials, the best material is 1020 steel due to the higher material yield strength even though von misses' stresses values are nearly same. Based on the above literatures, the main contribution in this paper is to estimate the fatigue life cycles between the simple Pelton bucket and the hoop Pelton bucket with different materials for the safety and performance of good efficiency of the bucket by comparing the results between them.

2. Selection of Turbine Types

Turbine was invented by French engineer Claude Burdin in 1822 and was used as water mill in ancient times. Nowadays, many types of turbines were fabricated for different purposes based on different operating conditions in performance such as steam turbine, gas turbine, water turbine, and wind turbine. Water turbine is distinguished into three types- reaction turbine, impulse turbine and gravity turbine. The reaction turbine is driven depend on the pressure variation and altitude to obtain mechanical energy, and it is operated by high velocity and impulse turbine is operated depend only on the hydraulic head. The gravity turbine is operated by the water weight incoming from the upper head of the turbine and leaving the water to the tailrace. Francis reaction turbine, also known as a radial flow turbine, is commonly used for getting higher efficiency. Pelton impulse turbine is mainly used for the purpose of generating electricity and also utilized in producing mechanical power for the irrigation, machinery process in grain mills. The advantages for using Pelton turbine is that it works best at high head and low flow conditions and produce higher power from a small turbine, and it is not necessary to be considered for specific flow conditions like other turbines. Propeller turbine operates in low elevation and high flow conditions. Cross-flow impulse turbine is utilized for medium altitude and medium flow conditions. The turbine used in this analysis is Pelton turbine and the main specifications for modelling of the

Pelton turbine bucket are obtained from Baluchaung No.2 Hydropower Station located in the Baluchaung River, Myanmar. There are six turbines each with 20 buckets for producing the output power of 168MW to transmission lines and the type form of the turbine is HP-2R4ND.

2.1. Material Properties of Pelton Turbine

Selection of materials is important in operating of turbine performance because the poor material mainly induce on stress, strain, displacement values, and easily to be fragile. Therefore, the material that has properties of strong, abrasion resistant, and corrosion resistant should be chosen for longer life of turbine buckets. Stainless steel is used in most commercial runners because of high corrosion resistant and good ductility. Gray cast iron, structural steel, copper based alloys, and fiber glass reinforced plastic are also used for turbine buckets. Aluminum alloy is widely applied in producing small, low-head runners. The greatest benefit of it is that it can be cast easily and cheap in price. In this analysis, stainless steel, aluminum alloy and cast iron were chosen for materials and table 1 shows the properties of these three materials.

Table 1: Parameters of materials

Property	Density (kg/m^3)	Young's Modulus (MPa)	Poisson's ratio	Yield Strength (MPa)	Ultimate Strength (MPa)
Stainless Steel	7850	$1.9x10^5$	0.3	622	991
Gray Cast Iron	7300	$1.25 x10^5$	0.3	210	277
Aluminum Alloy	2821	$7.1x10^4$	0.33	-	544

2.2. Force Calculation of Pelton Turbine

In this paper, the calculation for force was just only considered for one velocity flow that acts upon the splitter ridge of the bucket. Table 2 presents the main specifications for calculating force in Pelton turbine. Table 3 shows the alphabetical symbol that was used for calculation of force for applying load in analysis.

Table 2: Specifications of Pelton runner

Maximum Output (kW)	Effective Head (m)	Discharge (m^3/s)	Speed (min^{-1})	Jet Diameter (mm)	Jet Pitch Circle Diameter (mm)	Width of Bucket (mm)	Number of Buckets	Bucket Length (mm)
29840	423.66	8.10	428.5	172	1820	521	20	640

Jet Velocity, $V_a = C_v \sqrt{2gH}$

Tangential Velocity, $V_t = \pi DN/60$

Rotational Velocity, $\omega = V_t/r$

Speed Ratio, x = (Tangential Velocity)/(Jet Velocity)

Jet Flow Rate, $Q_{jet} = A_{noz}\sqrt{2gH}$

Jet Force acting on Bucket, $F_{jet} = \boldsymbol{\rho_w Q_{jet} C_v \sqrt{2gH}\,(1-x)^2}\,(1+\zeta\,\boldsymbol{\cos}\,\gamma)$

Table 3: Nomenclature

Nozzle Coefficient of Velocity	Acceleration due to gravity (m/s^2)	Net Head (m)	Pitch Circle Diameter (m)	Efficiency factor for Bucket Flow	Exit Angle at inside Bucket	Rotational Speed (min-1)	Water Density (kg/m^3)	Flow Rate (m^3/s)
C_v	g	H	D	ζ	γ	N	ρ_w	Q_{jet}

3. Introduction of ANSYS Software

ANSYS is a Computer-aided simulation software that was established by John A. Swanson in 1970 to simulate structural analysis, finite element analysis, and computational analysis. There are many branches in utilizing ANSYS product software. ANSYS Mechanical software is used for structural, thermal, and modal analysis. ANSYS nCode design life is one of the branches of ANSYS mechanical for analyzing fatigue life of the specimen by calculating stresses and strains due to the effects of inducing repetitive loads on it. The expected design life can evaluate with different materials together with the results from the finite element static structural analysis. Three main solvers for nCode design life are Dang Van, stress-life, and strain-life. Dang Van Solver is mainly used for severe loading cycles and emphasizes only in endurance limit of complicated loadings. It can only give the results of safety factor calculation. Stress-Life Solver software solves the high-cycle fatigue life ($>10^5$ cycles) problem by applying stress life (SN) approach method and is concerned with estimating total fatigue life. Strain-Life Solver applies in low-cycle fatigue life ($<10^5$ cycles) for the local elastic–plastic strain approach and is focus on crack initiation and growth.

4. Fatigue Stress Analysis of Simple and Advanced Hoop Pelton Turbine Buckets

Fatigue occurs at the material that is induced by high effect repetitive loads in the certain periods. Fatigue phenomena starts from crack initiation and spreads through the material and fracture occurs due to inconstant growth of crack. Three different kinds of method for analyzing fatigue strength are (1) stress life, (2) strain life, and (3) fracture mechanics. In this paper, stress life (SN) constant design life analysis was used for predicting fatigue lifetime. Firstly, the input Pelton turbine buckets geometry were developed with SolidWorks software and further analyzed fatigue with ANSYS software. The force of 172000N was induced at the bucket splitter ridge and four anchor bolts at bucket handle were constrained.

The value of rotational velocity was 45 rad/s. Loading type used in this analysis was constant amplitude, fully reversed proportional loading. After getting total deformation and absolute maxium stress from ANSYS workbench, added to nCode fatigue stress analysis. “Figure 1” shows the meshed models of Pelton turbine buckets that had 8561 nodes, 4180 elements for simple bucket and 20929 nodes, 10029 elements for hoop bucket.

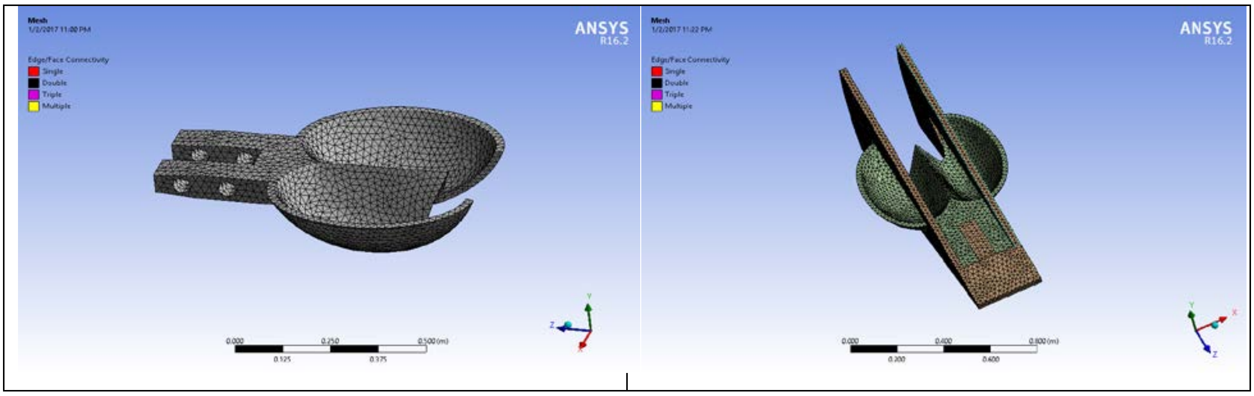
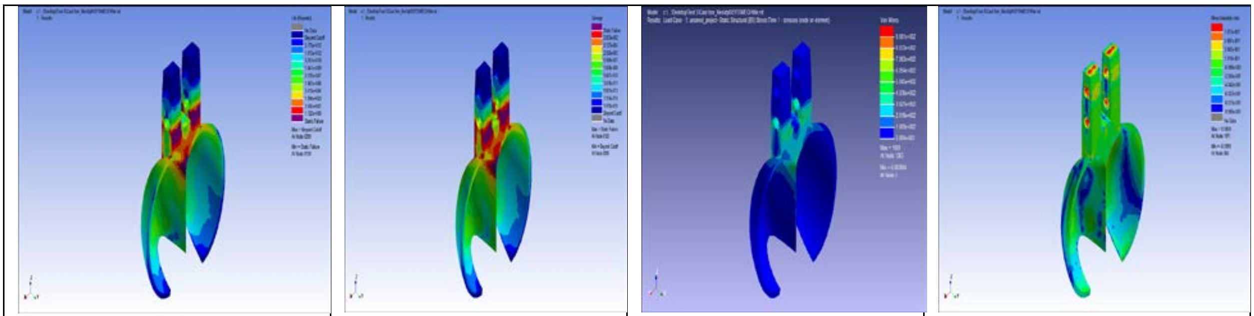


Figure 1: meshed model of simple and advanced hoop Pelton bucket



(a) Fatigue Life	(b) Damage	(c) Von Mises Stress	(d) Mean Biaxiality Ratio

Figure 2: fatigue simulation results of simple Pelton bucket using gray cast iron

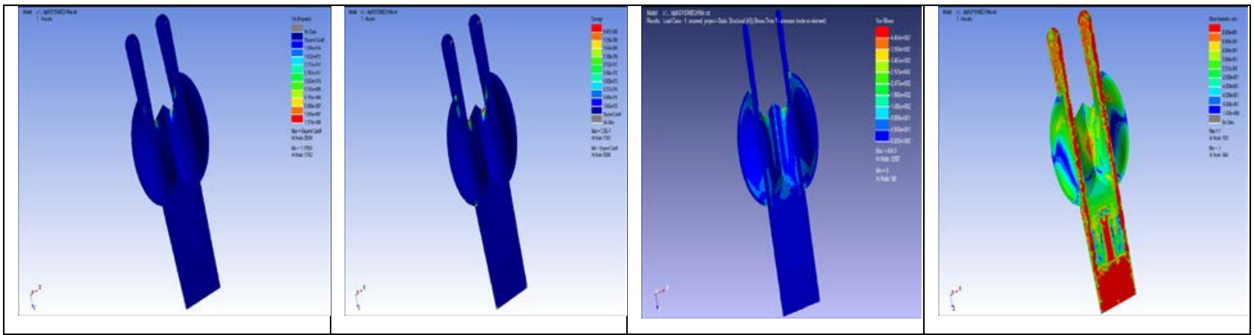
In this analysis, the the fatigue stress in simple Pelton bucket mainly occured at the bucket stem because the maximum bending moment and maximum bending stress mostly had in that area whereas the fatigue stress occured at the notch area of the bucket in advanced hoop Pelton turbine.

Figure 2 and 3 show the results of fatigue life, damage, Von Misses stress and mean biaxiality ratio of simple Pelton bucket by using gray cast iron and advanced hoop Pelton bucket by using stainless steel.

From the results of Table 4, the total deformation and maximum principal stress developed in advanced hoop Pelton bucket were lesser than simple Pelton bucket. Therefore, the construction and design of advanced hoop bucket can withstand the stress more than simple Pelton bucket at the same load.

Table 4: Comparison results of static structural analysis

Material	Total Deformation (mm)		Maximum Principal Stress (MPa)	
	Simple Pelton Bucket	Hoop Pelton Bucket	Simple Pelton Bucket	Hoop Pelton Bucket
Stainless Steel	6.4606	0.4526	498.4	424.26
Gray Cast Iron	9.7419	0.6868	495.09	424.56
Aluminum Alloy	16.445	1.2207	480.03	433.2



(a) Fatigue Life	(b) Damage	(c) Von Mises	(d) Mean Biaxiality Ratio

Figure3: fatigue simulation results of advanced hoop Pelton bucket using stainless steel

Table 5: Fatigue analysis comparison results of simple and advanced hoop buckets by design life

Material	Fatigue Life in Cycles		Damage		Mean Biaxiality Ratio		Von Mises Stress	
	Simple	Hoop	Simple	Hoop	Simple	Hoop	Simple	Hoop
Stainless Steel	6.211E2	3.179E6	9.72E-5	9.467E-8	7.903E-1	8E-1	9.125E2	4.454E2
Gray Cast Iron	1.122	2.777	2.85E-2	1.265E-2	7.873E-1	8E-1	9.081E2	4.438E2
Aluminum Alloy	1.438E3	3.265E3	4.55E-5	2.176E-5	7.877E-1	8E-1	8.427E2	4.309E2

As for fatigue life, as table 5 shows, the life cycles that exceed 10^5 cycles leads the infinite life. In hoop Pelton bucket, the fatigue life cycles obtained 3.179×10^6 cycles minimum at stainless steel indicating infinite life. Damage is the ratio of design life to available life and the maximum damage occured in bucket handle in simple Pelton bucket. Biaxiality indication shows the stress state and the value of "0"shows the uniaxial stress, the value of "-1" shows pure shear, and the value of "1" shows pure biaxial state. In both buckets, the results got nearly "0.8" that tends to pure biaxial state.

The maximum equivalent alternating stress for simple Pelton bucket is 2.0327e9 Pa and 4.4567e8 Pa for advanced hoop bucket. The maximum available life cycle for advanced hoop bucket is 13944 and there is no loading cycle for simple pelton bucket.

5. Conclusion

In this paper, simple and advanced hoop Pelton bucket models were generated with Solid Works software and simulated with ANSYS 16.2 nCode design life software to predict fatigue life cycles of both buckets. Total deformation and maximum principal stress values were calculated with static analysis solver and the SN constant design life solvers estimated the fatigue life, damage, mean biaxiality ratio, and Von Mises results. Stainless steel, aluminum alloy and cast iron materials were used in simulation. The minimum life cycles of stainless steel were infinite at high cycle fatigue analysis that indicate design life safe compared with other two materials. The values of stress in advanced hoop bucket was less half of the simple bucket that occurs stresses mainly at the bucket stem whereas these occurs at the notch area of the advanced hoop Pelton bucket. Moreover, only the load acting on the bucket was evaluated with hand calculation for Pelton turbine in this paper. In future, scholar can do the fatigue analysis with analytical method by calculating the stress occuring on each part of the bucket. In addition, this paper simulated with static analysis solver and SN constant design life solver. Therefore, maybe, the author will simulate the design life with transient structural analysis and SN timeseries design life solver. In conclusion, due to the comparison of the results, the construction and design of advanced hoop Pelton bucket is better than simple Pelton bucket. Among the most suitable materials – structural steel, cast iron and stainless steel for designing turbine, stainless steel is recommended to the designer for better operating performance.

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References

[1] Varun Sharma and Sanjeev Kumar Dhama (2014, July), “Analysis of Stress on Pelton Turbine Blade Due to Jet Impingement”, International Journal of Current Engineering and Technology. [On- line]. 4(4), pp. 2414-2417. Available: http://inpressco.com/wp-content/uploads/2014/07/Paper212414-2417.pdf [Aug. 1, 2014].

[2] N. Nava Indrasena Reddy, T. Siva Prasad (2015, August), “Design and Static Analysis of Pelton Turbine Bucket”, International Journal of Science Technology and Management. [On- line] 4(08), pp. 19-25. Available: http://www.ijstm.com/images/short_pdf/1438944780_P19-25.pdf [Aug, 2015].

[3] B.Vinod, B. Biksham, Veeranjaneyulu (2014, December), “Design and Analysis of Pelton Wheel”, International Journal & Magazine of Engineering. [On-line] 1(12), pp. 549-558. Available: http://docplayer.net/28350894-Design-and-analysis-of-pelton-wheel.html [Dec, 2014].

[4] Hans-Jorg Huth (2005), “Fatigue Design of Hydraulic Turbine Runner”, Norwegian University of Science and Technology, Norway

[5] Gaurangkumar C. Chaudhari, Dr.S.A.Channiwala, Samip P.Shah, “Comparative Assessment of the

Developed Stress in both Traditional and Hooped Pelton Runners", Tenth International Congress of Fluid Dynamics, Ain Soukhna, Red Sea, Egypt, 2010.

[6] Jeremy Thake,"The micro-hydro Pelton turbine manual, design, manufacture and installation for small-scale hydro power" (2000), ITDG Publishing, UK, P.136-146

[7] Gaurangkumar C. Chaudhari, Dr.S.A.Channiwala, Samip P.Shah (2011, June), "A Hooped Pelton Runner: FE Analysis and Experimentation", American Society of Mechanical Engineers Turbo Expo, Vancouver British Columbia, Canada.

[8] http://engr.bd.psu.edu/ansysug/2007-11-20/WBEFatigue.pdf

[9] http://www.mallett.com/wp-content/uploads/ANSYS-nCode-DesignLife-13.0.pdf

[10] https://support.ansys.com/staticassets/ANSYS/Conference/Confidence/Houston/Downloads/fatigue-analysis-using-ansys-fatigue-module-and-ansys-ncode.pdf