DYNAMIC BALANCING OF PELTON WHEEL TURBINE RUNNER TO MINIMISE VIBRATIONS USING STATISTICAL QUALITY CONTROL AND PELWHELPRO1 SOFTWARE

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ABSTRACT

This study investigated the effect of Pelton bucket masses designed for Pico hydro system on balancing and speed of computation of result to facilitate decision making process. Statistical quality control method was used in the analysis of the Pelton bucket masses and PELWHELPRO1 was used in decision making. A Pelton turbine runner was developed for a Pico hydro system, with 60 cast buckets, 24 buckets were selected because their masses were in the control limit region while 16 buckets were required by system as designed with masses ranging from 95.10 and 117.80 g. The mean of the mean masses for 16 buckets was 96.56 g and the mean of range is 2.30 g. PELWHELPRO1 revealed that buckets with masses close to the mean of the mean is a condition for selection; as they give positive balancing angle and reasonable masses. Bucket with large discrepancies reveals a negative balancing angle and large balancing masses are required. Hence Pelton bucket masses have significant effect on dynamic balancing and vibration.

Keywords: Balancing, Vibration, Pico, hydro, Pelton turbine runner, PELWHELPRO1, Graphical User Interface (GUI).

INTRODUCTION

Balancing is a process of correcting or eliminating, either partially or completely, the effects due to inertia forces and couples acting on the machine parts or components. The purpose of balancing is to avoid the vibration of the machine by balancing the resultant inertia forces and couples, (Randall, (n.d); Desmidt and Jung, 2011). Balancing is of two types namely: Static and Dynamic (complete) balancing. Balancing is a procedure in which the mass distribution (mass eccentricity) of buckets is assessed and where necessary, adjusted via addition or subtraction of weight to ensure that the vibration of the journals and /or forces on the bearings are within the specified limits. Dynamic (complete) balancing principle still cannot avoid a substantial increase in mass and inertia. Resulting balancing will always be required. (Volkert and Just, 2009). Balancing is a technique for determining the magnitude and the location of this heavy spot so that an equal amount of weight can be removed at this location, or an equal amount of weight can be added directly opposite. This allows the mass centre line to move closer to the true axis. Determination of this amount of mass and inertia is tasking and time consuming, (Volkert, *et al.* 2009; Amit and Mubarish, 2013). Vibration is a mechanical movement where an object oscillates about an equilibrium point, (Sena, *et al.* 2016). The causes of imbalance runner in hydro turbines are blow holes in castings of cups, runner disc and journal, eccentricity in runner, addition of keys and keyways, distortion caused by stress relief, clearance tolerances, corrosion or wear, deposit build up, manufactured unsymmetrical configurations and hydraulic imbalance resulting for trapped oil on wheel and cavitation (Amit and Mubarish, 2013).

Pico-hydro usually refers to the smallest scale or division in a hydropower plant, (Lahimer, *et al.* 2012; Bhusal, *et al.* 2007; Green, *et al.* 2005; Howey, 2009; Mapher and Smith, 2001; Paish and

Green, 2003 and William, 2007). It has a capacity of less than 5 kW [Green, *et al.* 2005; William, 2007, Mapher and Smith 2001, Meier and Fischer, 2011): Pico-hydro is also known as family hydro in some countries, because it can be owned by a single household (Green, *et al*. 2005; Howey, 2009; Paish and Green, 2003; Meier and Fischer, 2011).

When a machine is operating normally and according to design, it will produce a certain vibration signature. Vibration is always present when a machine is converting energy into useful work. Vibration, in simple terms, is the motion of the machine, or machine part, moving about its position of rest. The total measurement is known as the peak to peak displacement and the number of complete cycles per second is the frequency of the vibration. The position of the part at any instant in time with respect to its rest position is the phase of vibration and the rate of change of position with respect to time is the velocity of the vibration (Hitchen, 1980) and (Pain, 2005).Vibration is any periodic process, especially a rapid linear motion of a body about an equilibrium position (Pain, 2005).

LITERATURE REVIEW

A Pelton turbine essentially consists of a Pelton wheel with blades of the bucket form and one or more injectors that generate the high-speed jets when leaving the nozzle. The energy transfer from the high-speed jet onto the Pelton wheel is performed through the interaction between the jet and the rotating buckets. Pelton runners exist in all size classes, from very small Pico hydro applications, e.g. to use tap water from water delivery systems, to the larges units with capacities of more than 400 MW like in the Swiss Bieudron hydropower scheme with a current world record head of 1883 meters, (Zhang, 2016).

(Smith and Qin, 2012) reported that Pelton turbine runners are typically manufactured as one piece either as a casting or as a welded fabrication. The olden days runners (i.e., early 1900’s or before) were cast from cast iron or bronze and later replaced with cast carbon steel. Today, runners are either cast or fabricated from carbon steel or stainless steel. Just as materials have improved for modern turbine runners, so has the design and manufacturing to provide enhanced performance for power, efficiency, and reduced cavitations damage. Zhang, (2016) buttressed the fact, that earlier Pelton wheels were almost all made of cast steel or the Pelton buckets were screwed on a wheel disk and the rotating masses of the buckets were not considered. Pelton wheels nowadays are often directly machined from a forged stainless steel disk. A significant increase in the resistance capability of Pelton buckets against fatigue cracking and therefore in lifetime has, thus, been achieved.

Zhang, (2016) revealed, that one of the biggest problems in the operation of Pelton turbines is fatigue of the material, unnoticed vibration and cracking of the Pelton buckets in the root region, where the greatest material stress is recorded as a result of the largest periodic bending moment. The advent of computerized design and manufacturing which occurred in the late 1970’s and 1980’s made many of the advancements of today possible. Modern Computational Fluid Dynamics (CFD) flow analysis, Finite Element Analysis techniques (FEA) for engineering and Computer Numerically Controlled (CNC) in manufacturing have significantly improved turbine efficiency and production accuracy, (Smith and Qin, 2012). The condition for dynamic balancing and inertia equation can be complicated to drive and computed (Volkert and Just, (2009). This study therefore is aimed at investigating the effect of Pelton bucket masses on runner balancing, using statistical quality control with derived control limits and developed software called PELWHELPRO1 with displayed graphic user interface (GUI).

METHODOLOGY

Pelton turbine runners are typically manufactured as one piece either as a casting or as a welded fabrication using a cast iron or bronze and later replaced with cast carbon steel. However, this work adopted a different approach by sand casting the runner disc and buckets separately using aluminium because of its local availability, castability, machinability and good resistance to corrosion. The individual masses of the bucket were measured using weighing scale and statistically selected for use in dynamic balancing.

Sixty (60) Pelton buckets were cast. There were variations in the masses of these cast product, ranging between 95.10 and 117.80g, as a result of variation in the production and finishing processes. All the cast buckets were weighed on a weighing balance and twenty-four (24) buckets of closely related masses were selected into six groups of four buckets each. The twenty-four buckets were statistically analyzed in order to select the final sixteen (16) cups as required by design, (Montgomery, 2012). The balancing process was carried out using a developed software application called PELWHELPRO1. This software application was developed, for quick computation of balancing angle, masses, centrifugal force and rotational angular speed.

Balancing of Rotating Masses

The balancing of the rotating masses was carried out using the developed software. The PELWHELPRO1 was developed using the parameters listed in Table 1. It was used for calculating required balancing masses required for equilibration of rotating masses of Pelton cups along a common axis. The advantage of this software application is that it automatically generates boxes for inputted masses and various angles to hang the Pelton Cups around the circumference of the runner disc.

Table 1: Parameters used for PELWHELPRO1

Parameters	Equations
Mass of the cup	M
Vertical Component	$Mr\, sin\theta$
Horizontal Component	$Mr\, cos\, \theta$
Resultant Force	$\sqrt{M\, r\, Sin\theta - M\, r\, Cos\, \theta}$
$\tan \theta$	$\sum V / \sum H$
θ_1	$\tan^{-1} \frac{\sum V}{\sum H}$
θ_2	$180 + \theta_1$
Centrifugal Force	$m\, r\, \omega^2$
Angular speed (ω)	$\frac{2\, \pi\, N}{60}$

Application of Statistical Control Analysis

There are two types of control charts namely: (1) Variable Control Chart; and (2) Attribute Control Chart. A variable control chart portrays measurements. A variable control chart requires the interval or the ratio scale of measurement. An attribute control chart classifies a product or service as either acceptable or unacceptable. It was based on the nominal scale of measurement, as presented by Heizer and Render, 2014; Montgomery, 2012.

Variable Control Chart

The development of control charts for variables, The required sample mean in each subgroup $\bar{x}_1$, $\bar{x}_2, \bar{x}_3, \ldots\ldots\ldots \bar{x}_n$, then the grand mean of mean is designated by $\bar{\bar{x}}$ and k is used to show the number of sample means as shown in equation (1)

$$Grand\ Mean = \bar{\bar{x}} = \frac{summation\ of\ Means\ of\ the\ subgroups}{Number\ of\ sample\ Means}$$

$$\bar{\bar{x}} = (\bar{x}_1 + \bar{x}_2 + \cdots \ldots . \bar{x}_n)/k \qquad (1)$$

The standard error of the distribution of the sample means is designated by $S_{\bar{x}}$. This was found using the equation (2).

$$S_{\bar{x}} = \frac{s}{\sqrt{n}} \qquad (2)$$

These relationships allow limits to be set up around the sample means to show how much variation can be expected for a given sample size. These expected limits are called the upper control limit (UCL) and the lower controls limit (LCL) and are computed using equations (3) and (4)

$$UCL = \bar{\bar{x}} + 3\frac{s}{\sqrt{n}} \qquad (3)$$

$$LCL = \bar{\bar{x}} - 3\frac{s}{\sqrt{n}} \qquad (4)$$

where s is an estimate of the standard deviation of the population . There are 3 levels of confidence; 99.74, 95 and 90 percent. The 99.74 percent, called the 3-sigma limit has a constant relationship between the range and the standard deviation. Therefore, equation (5) and (6) can be used to determine the 99.74 percent control limits for the mean of the Upper Control Limit (UCL) and Lower Control Limits (LCL) respectively.

$$UCL = \bar{\bar{x}} + A_2\bar{R} \qquad (5)$$

$$LCL = \bar{\bar{x}} - A_2\bar{R} \qquad (6)$$

where A_2 is a constant used in computing the upper and the lower control limits. It was based on the average range $\bar{R}$, the factors for various sample sizes can be found in the Table of Factors for Constructing Variables Control Charts (Appendix I).

$$UCL = D_4\bar{R} \qquad (7)$$

$$LCL = D_3\bar{R} \qquad (8)$$

RESULTS AND DISCUSSION

Table 2 shows the results obtained by weighing each of the hemispherical cups on a weighing balance.

Table 2: Individual Masses of the Finished Pelton Buckets with Computed Average and Range.

Group No	1	2	3	4	Total	Mean	Range
1	95.80	96.50	98.30	95.60	*386.20*	***96.55***	***2.70***
2	95.40	97.10	96.40	95.70	*384.60*	***96.15***	***1.70***
3	97.20	98.10	95.40	96.20	*386.90*	***96.73***	***2.70***
4	96.20	96.80	97.50	95.20	*385.70*	***96.43***	***2.30***
5	97.30	99.20	98.10	96.30	*390.90*	***97.73***	***2.90***
6	95.70	96.80	95.50	95.10	*383.10*	***95.78***	***1.70***
						579.35	***14.00***

From equation (6):
$\bar{\bar{x}} = (\bar{x}_1 + \bar{x}_2 + \cdots \ldots . \bar{x}_n)/k$

Central Limits or Control Limits = $\bar{\bar{x}} = 96.56\text{g}$

The Mean Range is designated

$$\bar{R} = \frac{\textit{summation of the range of subgroup}}{\textit{Number of group sample}} \quad (9)$$

From Table 2, the summation of the subgroup range is 14.00g while the total number of group under consideration is six (6), the values of A_2, D_3 *and* D_4 were obtained from Table of Factors for Constructing Variable Control Charts. (Appendix I)

$\bar{\text{R}} = 2.33 \text{ g}$

From equation (5) was used in getting the Mean Upper Control Limit (UCL) and equation (6) was used for the Mean Lower Control Limit (LCL)

$UCL = \bar{\bar{x}} + A_2\bar{R} = 97.69\ g$

$LCL = \bar{\bar{x}} - A_2\bar{R} = 95.43\ g$

The mean Upper Control Limit was 97.69 g while the mean lower control limit was 95.43 g. The average mass of the sixteen (16) hemispherical Pelton buckets are 96.56 g. The mean control chart is presented in Figure 1.

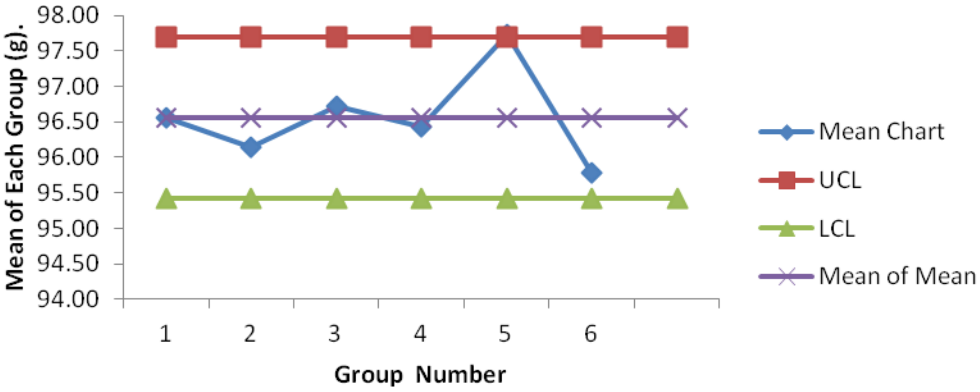


Figure 1: Mean Control Chart.

The interpretation of mean upper control limits (UCL) and lower control limits (LCL) depicted in Figure 1 was 97.69 and 95.43grams respectively. The average masses of twenty four (24) cups were 96.56 gram. The group 5 shows a large deviation from the mean masses. It means that only one or two of the cups in this group can be selected while a major number cups can be selected from other groups (1, 3 and 4) whose masses fall within the control area. Some cups in group 6 whose masses are close to mean of the mean may be selected. The mean control chart may not be sufficient to take decision; this may require the use of range control chart for confirmation and further evaluation of decisions taken against group 5 items.

From equation (7) for computing the upper control limit for range and equation (8) is used for the lower control limit for the range.

$$UCL = D_4\bar{R} = 4.68\ g$$

For lower control limit for the range:

$$LCL = D_3\bar{R} = 0$$

The range control chart is plotted in Figure 2,

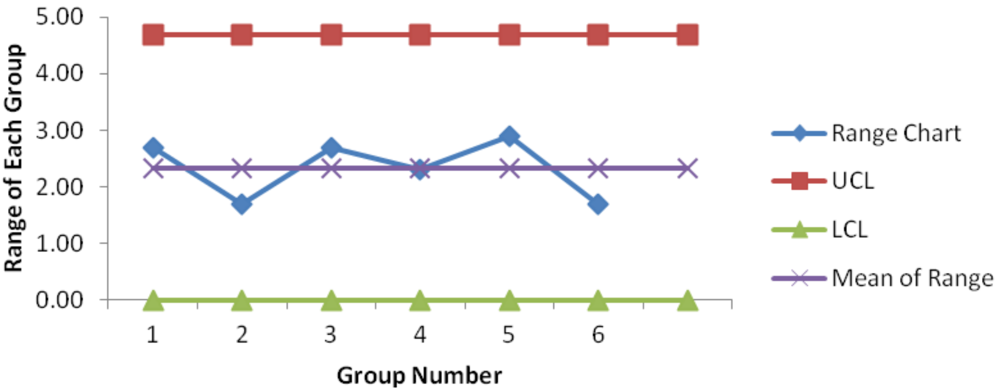


Figure 2: The Range Control Chart.

The Range Control Chart (RCC) depicted in Figure 2 shows that all the six (6) group falls within the control limits which implies that items in (Group 1, 3 and 4) were very close to the mean of the range should first be selected and part of the cups in group 5 or other groups can selected for use as long as they fall within mean control chart. The importance of the Variable Control Chart (VCC) is better understood with the use of the developed software called PELWHELPRO1. The input interface is shown in Figure 3.

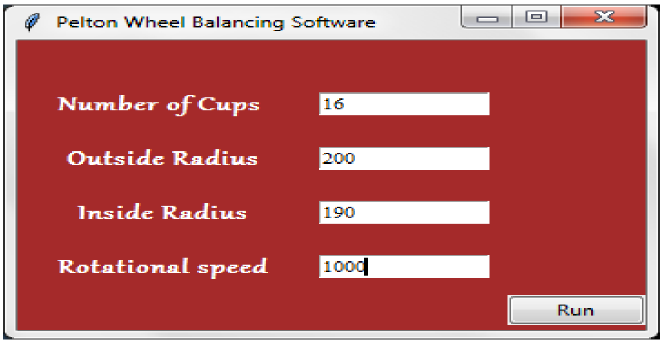


Figure 3: Graphic User Interface with required inputs.

The input interface requires the numbers of Pelton Cups, outside radius, inside radius and the rotational speed as input to automatically generate the number of boxes inputted as shown in Figure 3, to be filled with various statistically selected masses as shown in Figure 4.

It was observed that all the masses selected were of close values to the calculated mean and when the program is run on computer system the result obtained is displayed in Figure 5.

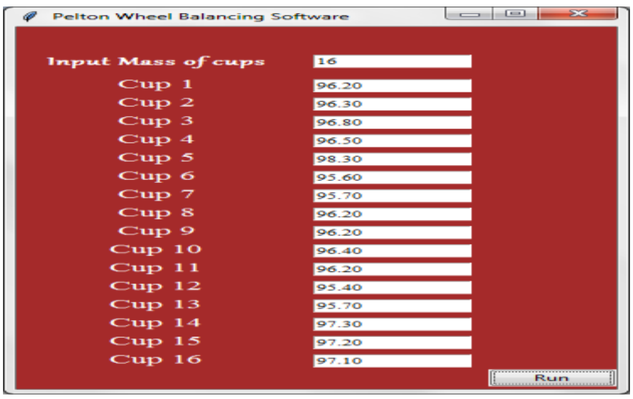
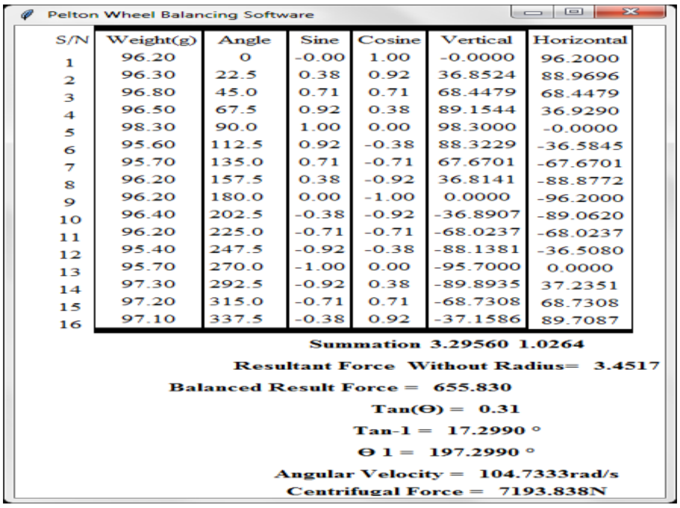


Figure 4: Automatically Generated GUI for Pelton Cups with Statistically Selected Masses.


Pelton Wheel Balancing Software

S/N	Weight(g)	Angle	Sine	Cosine	Vertical	Horizontal
1	96.20	0	-0.00	1.00	-0.0000	96.2000
2	96.30	22.5	0.38	0.92	36.8524	88.9696
3	96.80	45.0	0.71	0.71	68.4479	68.4479
4	96.50	67.5	0.92	0.38	89.1544	36.9290
5	98.30	90.0	1.00	0.00	98.3000	-0.0000
6	95.60	112.5	0.92	-0.38	88.3229	-36.5845
7	95.70	135.0	0.71	-0.71	67.6701	-67.6701
8	96.20	157.5	0.38	-0.92	36.8141	-88.8772
9	96.20	180.0	0.00	-1.00	0.0000	-96.2000
10	96.40	202.5	-0.38	-0.92	-36.8907	-89.0620
11	96.20	225.0	-0.71	-0.71	-68.0237	-68.0237
12	95.40	247.5	-0.92	-0.38	-88.1381	-36.5080
13	95.70	270.0	-1.00	0.00	-95.7000	0.0000
14	97.30	292.5	-0.92	0.38	-89.8935	37.2351
15	97.20	315.0	-0.71	0.71	-68.7308	68.7308
16	97.10	337.5	-0.38	0.92	-37.1586	89.7087

Summation 3.29560 1.0264
Resultant Force Without Radius= 3.4517
Balanced Result Force = 655.830
Tan(Θ) = 0.31
Tan-1 = 17.2990 °
Θ 1 = 197.2990 °
Angular Velocity = 104.7333rad/s
Centrifugal Force = 7193.838N

Figure 5: GUI Output display for Sixteen (16) Pelton Cup Selected.

The result displayed a balanced force with a value of 655.83 N at the first angle of 17.30^{o} and balanced (second) angle of 197.30^{o}, The Pelton Turbine runs with an angular velocity of 104.73 rad/s and a centrifugal force of 7193.84 N. The implication of this result is that positive angles were obtained, because the masses used were within six sigma control. The case is different when sixteen (16) masses of large discrepancies were used in the next evaluation as shown in Figure 6.

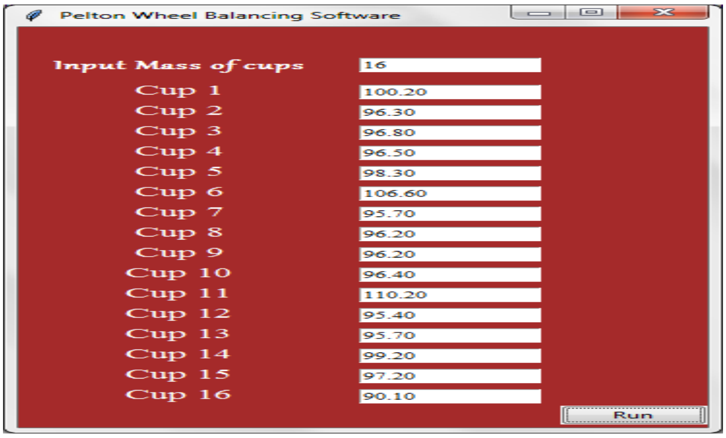
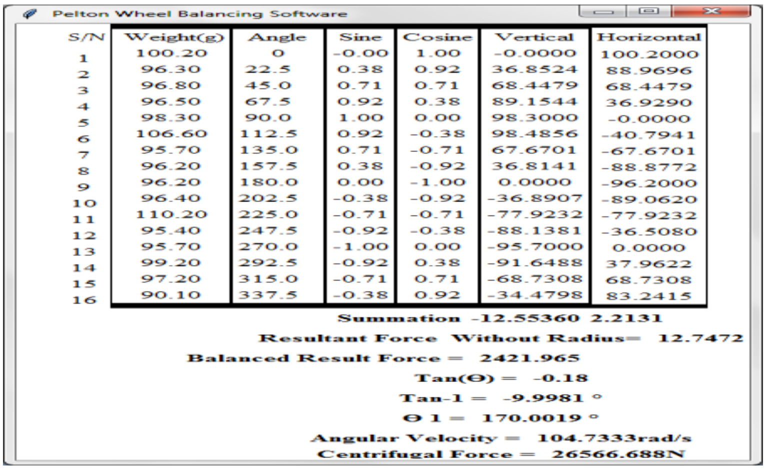


Figure 6: Automatically Generated GUI for Pelton Cups with Out of Control Masses


Pelton Wheel Balancing Software

S/N	Weight(g)	Angle	Sine	Cosine	Vertical	Horizontal
1	100.20	0	-0.00	1.00	-0.0000	100.2000
2	96.30	22.5	0.38	0.92	36.8524	88.9696
3	96.80	45.0	0.71	0.71	68.4479	68.4479
4	96.50	67.5	0.92	0.38	89.1544	36.9290
5	98.30	90.0	1.00	0.00	98.3000	-0.0000
6	106.60	112.5	0.92	-0.38	98.4856	-40.7941
7	95.70	135.0	0.71	-0.71	67.6701	-67.6701
8	96.20	157.5	0.38	-0.92	36.8141	-88.8772
9	96.20	180.0	0.00	-1.00	0.0000	-96.2000
10	96.40	202.5	-0.38	-0.92	-36.8907	-89.0620
11	110.20	225.0	-0.71	-0.71	-77.9232	-77.9232
12	95.40	247.5	-0.92	-0.38	-88.1381	-36.5080
13	95.70	270.0	-1.00	0.00	-95.7000	0.0000
14	99.20	292.5	-0.92	0.38	-91.6488	37.9622
15	97.20	315.0	-0.71	0.71	-68.7308	68.7308
16	90.10	337.5	-0.38	0.92	-34.4798	83.2415

Summation -12.55360 2.2131
Resultant Force Without Radius= 12.7472
Balanced Result Force = 2421.965
Tan(Θ) = -0.18
Tan-1 = -9.9981 °
Θ 1 = 170.0019 °
Angular Velocity = 104.7333rad/s
Centrifugal Force = 26566.688N

Figure 7: GUI Output display with masses out of control chart used.

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The result depicted in Figure 6 and Figure 7 implies that when masses that are out of range were used, a large balanced resultant forces and centrifugal force were obtained negative angles. It implied that the balancing of such systems will be difficult to achieve. A runner with sixteen known masses is shown in Figure 8.

Figure 8: Pelton Turbine Runner with 16 selected known

CONCLUSIONS

Statistical Quality Control and PELWHELPRO1 software were used for dynamic balancing of a Pelton wheel turbine runner. It was concluded that the Pelton turbine runner should be produced in separate pieces so that the masses of individual component and bucket are known. This would allow buckets whose masses are very close to the mean of the mean value to be selected in order to obtain reasonable balancing masses and angles. This would greatly minimize vibration and damages of bearings of the turbo machinery.

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