Abstract: This paper shows some aspects regarding the Kaplan type hydraulic turbine runner optimization, using the Modal analysis software ANSYS, starting with runner blade design, using geometric airfoil technique and Matlab programming software and AutoCAD software. In practical, it have 10kW turbine output under 3m net head, the flow rate is 0.587 m³/sec to produce required power. For the given capacity, the diameter of the Kaplan turbine blade is 0.39m and the number of blade is 4. In this paper, the 3D model of runner blade has been established in ANSYS by importing the blade model created previously. Modal analysis was carried out to check whether it can be matched with strength of the material to be used the vibration characteristic of the blade meet certain safety requirements.

Keywords: Kaplan Turbine, Vibration Characteristic, Matlab Programming, ANSYS Software, Modal Analysis 3D View Of Runner Blade.

I. INTRODUCTION
Hydropower has been one of the most variable sources of renewable energy. The low cost of hydropower is competitive with more conventional sources of energy. There are many types of the turbine blade for using hydropower plants, but Kaplan turbine is the most suitable type for low head and small power plants. Kaplan turbine is an axial flow reaction turbine. The basic Kaplan turbine consists of a propeller, similar to a ship’s propeller. The Kaplan turbine usually has three to six blades. This kind of Kaplan turbine is known as an adjustable blade axial flow turbine.[1]

The main aim of this paper is to improve the design of runner blade profile, to distribute the technologies about micro hydropower to remote or rural areas, and to survey how to operate the Kaplan turbine coupled with the generator which can be developed 10kW output power.

The calculations of the blade included the following steps:
- Firstly to consider the design procedure of Kaplan turbine and runner blade profile;
- Detailed calculations of the runner blade profile, using the numerical calculations;
- Checking of the required blade profile data from Matlab programming;
- Detailed drawing for the 3D solid modeling of the runner blade using Auto Cad software;
- Identified natural frequencies, especially low-order frequencies and vibration modes of Kaplan turbine blade.[2]

II. BASIC CONFIGURATION OF KAPLAN TURBINE
The basic Kaplan turbine consists of five main parts. They are: 1.Direct Drive Shaft 2.Casing 3.Runner 4.Guide Vane 5.Draft Tube [2]. The technical specifications for Kaplan turbine are:

The required generator output power, \( P = 10 \text{ kW} \)

Generator efficiency, \( \eta_g = 0.8 \)
Generator speed, \( N_g = 1500 \ \text{rpm} \)
Design head of turbine, \( H_d = 3 \ \text{m} \)
Mechanical efficiency, \( \eta_m = 0.85 \)
The required shaft power, \( B_P = \frac{\text{generator Output}}{\eta_m \eta_g} \)
= 14.7 kW

**B. Type of Hydraulic Turbine**

Hydraulic turbines are the machines which use the energy of water and convert it into mechanical energy. A turbine converts energy in the form of falling water into rotating shaft power. Turbines are divided by their principle way of operating and can be either impulse or reaction turbine [3].

<table>
<thead>
<tr>
<th>Type of Turbine</th>
<th>Turbine type</th>
<th>Head Range(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impulse</td>
<td>Pelton</td>
<td>50 &lt; H &lt; 1300</td>
</tr>
<tr>
<td></td>
<td>Turgo</td>
<td>50 &lt; H &lt; 250</td>
</tr>
<tr>
<td></td>
<td>Cross – Flow</td>
<td>3 &lt; H &lt; 250</td>
</tr>
<tr>
<td>Reaction</td>
<td>Francis</td>
<td>10 &lt; H &lt; 350</td>
</tr>
<tr>
<td></td>
<td>Kaplan</td>
<td>2 &lt; H &lt; 40</td>
</tr>
<tr>
<td></td>
<td>Propeller</td>
<td>2 &lt; H &lt; 40</td>
</tr>
</tbody>
</table>

**III. DESIGN CONSIDERATION OF BASIC PARAMETERS FOR 10KW KAPLAN TURBINE**

**A. Design Procedure**

The power developed by a turbine is given by the following equation.

\[
P = \gamma Q H_d \eta_o\]

(1)

The speed of the turbine can be calculated from the following equation.

\[
N = \frac{N_s \sqrt{H_d}}{\phi}\]

(2)

The runner discharge diameter can be known from the peripheral coefficient.

\[
\phi = 0.0242 \times N_s^{2/5}\]

And then,

\[
D = \frac{84.5 \times \phi \times \sqrt{H_d}}{N}\]

(5)

According to the specific speed, the number of blade and the ratio of hub and outer diameter of Kaplan turbine can be read from Fig 4. The number of blade is four [5].

---

**TABLE I: CLASSIFICATION OF TURBINE TYPE**

<table>
<thead>
<tr>
<th>Type of Turbine</th>
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<tr>
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<td></td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>Propeller</td>
<td>2 &lt; H &lt; 40</td>
</tr>
</tbody>
</table>

**Application Range for Kaplan Turbine**

- Head: 1 m to 10m
- Discharge: 0.1 to 1.5 m³/sec
- Turbine specific speed: 300 to 1100
- Low head – High flow rate

---

**Fig.2 Main Components of Kaplan Turbine [3]**

**Fig.3 Selection of Type of Turbine [4]**
Design and Vibration Characteristic Analysis of 10kW Kaplan Turbine Runner Blade Profile

B. Design Calculation of Guide Vane

The function of the guide vanes is to regulate the quantity of water supplied to the runner and direct water onto the runner at an angle appropriate to the design. The flow velocity can be determined from the following equation.

\[ A = \frac{\pi}{4} (D^2 - d^2) \]  
\[ Q = A \cdot V_f \]  

The magnitude of the whirl velocity can be obtained by the following formula.

\[ C_{ul} = \eta_h \cdot g \cdot H_d \]  
\[ U \]

Fig. 4. Design Consideration of Basic Parameters For 10kw Kaplan Turbine

C. Design Theory of Spiral Casing

Dimensions of spiral casing are related to the runner discharge diameter and relations are illustrated in fig 6. A = 1.45D, B = 1.5D, C = 1.9D, E = 2.05D, F = 1.6D, G = 1.25D, H = 1.85D, I = 0.4D, J = 0.7635D, K = 0.38D.[5]

Fig. 5 Inlet and Outlet Velocity Diagram of Kaplan Turbine [5].

The guide vane angle,

\[ \alpha = \tan^{-1} \frac{V_f}{C_{ul}} = 74.6^\circ \]  

Fig. 6 Dimension of spiral casing [5].

D. Design Theory of Draft Tube

The detail dimensions of the draft tube at the flange angle which is approximately equal to a 6 degree are as below,

\[ T = D \]  
\[ Y = 3D \]  
\[ D_{out} = D + 2Y \tan \alpha \]  
\[ \text{Exit area of Draft Tube} = 3.3D \]

Fig. 7 Draft Tube[5].

E. Geometric Characteristics of Airfoils

The most important geometric characteristics of the airfoil which is shown in Fig 8 is taken from the profile N.A.C.A (National Advisory Committee for Aeronautics) 2412. In this series, the geometric characteristics are shown in the following relation.

\[ \frac{m}{l} = 0.02 \quad \frac{L}{l} = 0.40 \quad \frac{t}{l} = 0.12 \]  

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IV. DESIGN PROCEDURE OF BLADE PROFILE

In the space of the runner, it can be divided into five cylindrical sections. These sections are can be calculated by the following equation. Fig 9 shows five sections of the blade.

For section I,
\[ r_1 = \frac{d}{2} + 0.015d \]  
(11)

For section III,
\[ r_3 = \frac{D}{2} \sqrt{\frac{1+D_2^2}{2}} \]  
(12)

For section II,
\[ r_2 = r_1 + \frac{r_3 - r_1}{2} \]  
(13)

For section V,
\[ r_5 = \frac{D}{2} - 0.015D \]  
(14)

For section IV,
\[ r_4 = r_3 + \frac{r_5 - r_3}{2} \]  
(15)

Calculation of runner angle at outlet and inlet blade at various diameters, tangential speed and whirl velocity must be known in [5]. The tangential speed at the hub diameter,
\[ U = \frac{\pi r N}{30} \]  
(16)

The blade inlet angle,
\[ \tan \beta_1 = \frac{V_{f1}}{U - C_{u1}} \]  
(17)

The blade outlet angle,
\[ \tan \beta_2 = \frac{V_{f2}}{U} \]  
(18)

The spacing of the blade can be determined by the following equation.
\[ t = \frac{2\pi r}{z} \]  
(19)

Circulation can be determined by the following equation.
\[ \Gamma = t (C_{u1} - C_{u2}) \]  
(20)

The average angle \( \beta_a \) can be known from Figure 10.
\[ \tan \beta_a = \frac{V_{f1}}{W_{al}} \]  
(21)

\( W_{al} \), can be obtained by the following equation.
\[ W_{al} = U - \frac{C_{u1}}{2} \]  
(22)

The average relative velocity \( W_a \) can be determined by equation (23).
\[ W_a = \frac{W_{al}}{\cos \beta_a} \]  
(23)

Fig 10 shows velocity triangle of Kaplan turbine. Figure 11 shows circulation around the blade. [5]
The high of the hub or boss of the runner can be known from \( h_1 \) and \( h_2 \) as shown in Fig. 12.

\[
\frac{h_1}{D} = 0.094 + 0.00025 N_s \tag{24}
\]

\[
\frac{h_2}{D} = \frac{1}{3.16 - 0.0013N_s} \tag{25}
\]

Fig. 12 Section View of Kaplan Turbine [5]

The high of the hub or boss = \( 2(h_2 - h_1) \) \( \tag{26} \)

Distance between the inner edge of the guide vane and center of the runner blade \( \lambda \), \( \lambda = 0.25 D \)

The height of guide vane, \( B = 0.4 D \)

V. DESIGN THEORY OF DRIVE SHAFT

To determine the drive shaft diameter for solid shaft is subjected to combine bending, torsional and axial load.[6]

\[
d = \sqrt[3]{\frac{16}{\pi S_s}} \left( K_0 M_B + \frac{2 F_a}{S} \right) + \left( K_t M_T \right) \tag{27}
\]

and

\[
d = \frac{16K_t M_T}{\pi S_s} \tag{28}
\]

where,
- \( S_s \) allowable stress (MPa)
- \( \alpha \) column-action factor
- \( K_0 \) combined shock and fatigue applied to bending moment
- \( K_t \) combined shock and fatigue applied to torsional moment
- \( M_B \) bending moment (N-m)
- \( M_T \) torsional moment (N-m)
- \( F_a \) load (N)
- \( d \) drive shaft diameter (m)

TABLE II: CALCULATED RESULTS FOR PARAMETERS 10kW KAPLAN TURBINE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Calculated result</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_s )</td>
<td>Synchronous Speed</td>
<td>750</td>
<td>rpm</td>
</tr>
<tr>
<td>( P_t )</td>
<td>Turbine Output Power</td>
<td>10</td>
<td>kW</td>
</tr>
<tr>
<td>( Q )</td>
<td>Flow Rate</td>
<td>0.587</td>
<td>m³/s</td>
</tr>
<tr>
<td>( N_s )</td>
<td>Specific Speed</td>
<td>673</td>
<td></td>
</tr>
<tr>
<td>( N )</td>
<td>Turbine Speed</td>
<td>693</td>
<td>rpm</td>
</tr>
<tr>
<td>( D, d )</td>
<td>Runner Outlet Diameter</td>
<td>0.39</td>
<td>m</td>
</tr>
<tr>
<td></td>
<td>Runner Hub Diameter</td>
<td>0.16</td>
<td>m</td>
</tr>
<tr>
<td>( T )</td>
<td>Draft Tube Dimensions</td>
<td>0.39</td>
<td>m</td>
</tr>
<tr>
<td>( Y )</td>
<td></td>
<td>1.17</td>
<td>m</td>
</tr>
<tr>
<td>( A, \delta )</td>
<td>Outlet Diameter</td>
<td>0.6027</td>
<td>m</td>
</tr>
<tr>
<td></td>
<td>Exit Area of Draft Tube</td>
<td>0.4508</td>
<td>m²</td>
</tr>
<tr>
<td></td>
<td>Drive Shaft Diameter</td>
<td>0.026</td>
<td>m</td>
</tr>
</tbody>
</table>

TABLE III: COMPARISON OF THE DESIGN DATA AND EXITING DATA OF KAPLAN TURBINE

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Design data</th>
<th>Existing data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runner diameter</td>
<td>0.396 m</td>
<td>0.35 m</td>
</tr>
<tr>
<td>Hub diameter</td>
<td>0.161 m</td>
<td>0.14 m</td>
</tr>
<tr>
<td>Number of blade</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Flow rate</td>
<td>0.587 m³/s</td>
<td>0.675 m³/s</td>
</tr>
<tr>
<td>Turbine speed</td>
<td>693 rpm</td>
<td>750 rpm</td>
</tr>
<tr>
<td>( \beta_1 )</td>
<td>68°</td>
<td>-</td>
</tr>
<tr>
<td>( \beta_2 )</td>
<td>42.2</td>
<td>-</td>
</tr>
<tr>
<td>Number of guide vane</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Table III is the comparison of the design data and exiting data of Kaplan turbine. After calculating the blade profile, three dimensional runner blades are drawn by AutoCAD software.
VI. VIBRATION CHARACTERISTICS OF SINGLE KAPLAN TURBINE BLADE

To understand the vibration characteristics of Kaplan turbine blade, the natural frequencies and mode shapes of single Kaplan turbine blade are calculated. The Commercial software ANSYS Workbench (ANSYS Multiphysic) is used to calculate the natural frequency and mode shapes of Kaplan turbine blade. Modal analysis is used to identify natural frequencies, and its mode shape. From the modal we can learn in which frequency range the blade will be more sensitive to vibrate[7].

A. Modal Analysis of Single Kaplan Blade.

The finite element analysis of blade is carried out in ANSYS software. In the modal analysis of ANSYS Workbench, the Automatic Method is used for the meshing of solid model and Structural Steel is used for the material of blade. The first 6 natural frequencies and modes shapes of single Kaplan turbine blade are shown in Table IV.

B. Modal Vibration Characteristics Analysis

Fig.14 Solid and Meshing model of Kaplan Turbine Blade.

Fig.15 Directional deformations and mode shape model along x, y and z-axis of Kaplan turbine blade with Normal Condition.

Modal analysis is the basis need to find Natural frequency and vibration characteristic. Modal analysis does not provide the value of stress by mere learning mode shape and Natural frequency. Therefore a special procedure for natural frequencies calculation was developed [8]. If deformation has to be calculated, total deformation and directional deformation must be worked out.

TABLE IV: FIRST 6 NATURAL FREQUENCIES OF KAPLAN TURBINE BLADE

<table>
<thead>
<tr>
<th>Mode</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [Hz]</td>
<td>558.53</td>
<td>1074.5</td>
<td>1571</td>
<td>2678.2</td>
<td>2885</td>
<td>3632.9</td>
</tr>
</tbody>
</table>

TABLE V: DIRECTIONAL DEFORMATIONS IN THE X, Y, Z- AXIS OF EACH CONDITION OF KAPLAN TURBINE BLADE

<table>
<thead>
<tr>
<th>Condition</th>
<th>X-axis</th>
<th>Y-axis</th>
<th>Z-axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal condition</td>
<td>-0.64672m</td>
<td>-1.03016e-02m</td>
<td>-9.391e-03m</td>
</tr>
<tr>
<td></td>
<td>0.42994m</td>
<td>1.3016m</td>
<td>0.9108m</td>
</tr>
<tr>
<td>One degree Clockwise</td>
<td>-0.6467m</td>
<td>-1.0468e-002m</td>
<td>-9.2141e-003m</td>
</tr>
<tr>
<td></td>
<td>0.42994m</td>
<td>1.315m</td>
<td>0.8909m</td>
</tr>
<tr>
<td>One degree Counter clockwise</td>
<td>-0.6467m</td>
<td>-1.0196e-002m</td>
<td>-9.5647e-003m</td>
</tr>
<tr>
<td></td>
<td>0.42992m</td>
<td>1.2878m</td>
<td>0.9305</td>
</tr>
</tbody>
</table>

By examining the above Fig15. It can be seen in which place deformation take place in a small amount or in which place, a greater amount. In Modal Analysis, it can be seen out whether deformation takes place in a small amount, by checking their corresponding frequencies. But directional deformation had been calculated in x, y and z axes Has to be shown. From the following illustrations, directional deformations along the x, y and z- axes can be learnt. A small deformation changes into a greater one, and vice versa, as while there appears a change in clockwise, counterclockwise and revolutions. Depending on the stress, directional deformation occurs in the blade with normal condition at y-axis, but in the least amount, at x-axis in above Table V. And the natural frequencies, mode shape and its deformations in the x, y, z- axis of original blade found in normal condition, in the clockwise one degree and counter clockwise one degree direction are described in...
Design and Vibration Characteristic Analysis of 10kW Kaplan Turbine Runner Blade Profile

the above table. So, as soon as a blade is tilted in an angle from its own weight in the clockwise direction, it is found how much its natural frequency and total and directional deformation has been changed.

C. Static Analysis with Variable Revolution

The vibration characteristics analysis of the single Kaplan blade is mainly involved in the calculation about natural frequency and modal shape. The objective to calculate the natural frequency and modal shape of the single Kaplan blade is to modulate those frequencies and avoiding resonance at rotational speed. There are many methods to compute the natural frequency of the single Kaplan blade. Depending on the revolution effect, we can learn how much the value of the stress is. According to the static analysis of Fig 16, as soon as the revolution changes, its stress value and the result also change. How the stress changes in accordance with the change in revolution.

Fig.16. Value of Equivalent vomiss Stress with variable revolution.

TABLE VI: EQUIVALENT VOMISS STRESS WITH VARIABLE REVALUATION NORMAL CONDITION OF KAPLAN TURBINE BLADE

<table>
<thead>
<tr>
<th>Type of Condition</th>
<th>Rotational Velocity (RPM)</th>
<th>Tensile Ultimate Strength Used in Material(Pa)</th>
<th>Value of Equivalent vomiss Stress(Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Condition of Blade</td>
<td>750</td>
<td>4.6e+08</td>
<td>1.2683e+07</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>4.6e+08</td>
<td>1.1048e+07</td>
</tr>
<tr>
<td></td>
<td>650</td>
<td>4.6e+08</td>
<td>9.5263e+06</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>4.6e+08</td>
<td>8.1171e+06</td>
</tr>
</tbody>
</table>

VII. DISCUSSION AND CONCLUSION

By studying this, we have learnt that directional deformation occurs in the greatest amount in which place or in the smallest amount, in which place. So, if we use this blade, we are to make a fit one, withdrawn all these. To say clearly, normal condition blade has the greatest deformation at y-axis, and the smallest deformation at x-axis. Likewise in the clockwise one degree and counter clockwise one degree direction condition blade, the place of the smallest deformation and the place of the greatest deformation can be seen. It can be also that there is no change in some places. By looking at this, when a design is to be produced, to resist all these, the material to be used and the Modal have to be chosen only from this field.

VIII. ACKNOWLEDGMENT

The author would like to thank Professor Dr. Myint Thein for his patience, understanding and guidance, for his help preparing for the technical necessary for this analysis. I also would like to thank all my family members, teachers and friends for their motivation and continuous support to my education.

IX. REFERENCES


