Methodology to Predict Effects of Leakage Flow from Guide Vanes of Francis Turbine

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Abstract. Leakage flow from clearance gap affects the performance of Francis turbines. This study presents the method to predict the effects of leakage flow from clearance gap of GVs. When sediments flow along with water through guide vanes it erodes the guide vane’s surface. Clearance gap of the guide vanes gradually increases due to continuous effects of abrasive wear. This phenomena of abrasion deteriorates the overall performance of the turbine. In this study, the effects of increased clearance gap of GVs of Francis turbine are studied numerically. Numerical models including the clearance gap-size of 0 mm, 2 mm and 4 mm are made to compare the effects. It uses alternative leakage flow approach, whereby current model consisting of 24 GVs contains 12 clearance gaps alternatively. This approach makes it possible to differentiate the amplitude of pressure pulsations contributed either by wakes or vortices due to leakage flow from guide vanes. Comparing the 3 different cases, it was found that increased clearance gap of the guide vanes increases the pressure pulsation at the runner inlet, reducing overall efficiency of the turbine.

1. Introduction

Hydro-turbines exposed to sediment laden projects are severely affected by the combined effect of abrasive wear and erosive wear [1]. Future need and prospect of hydropower development needs to address the operational challenges due sediment erosion effects [2]. Francis turbine that contributes to about 80% of the total prospective sites for hydropower development is severely affected by the sediment erosion. Francis turbine consists of 3 major components i) Distributer ii) Runner and iii) Draft Tube. Distributer of the Francis turbine is composed of inlet conduit with spiral casing, fixed vanes and guide vanes. In guide vanes total available energy is converted partly into pressure energy and kinetic energy. The flow behaviour from GV is highly unpredictable due to leakage flow from clearance gap and wakes and vortices from the trailing edge [3]. Many researches were carried out to predict the behaviour of fluid flow from the guide vanes [4-12]. Thapa [4] performed the experimental investigation of the fluid flow around the guide vanes of the

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Francis Runner. The development of one guide vane test set up showed the behaviour of the flow comparable to the real turbine. Experimental verification was done by the PIV approach to measure the velocity field on the test domain. Chitrakar [5, 10] studied the effects of guide vanes profile on the performance of the Francis Turbine. Pressure difference between adjacent surface decreases for asymmetrical guide vane profiles. Leakage flow in case of symmetric guide vane profile was higher than asymmetrical profiles due to higher pressure difference between the two sides of guide vanes [12]. Thus, sediment erosion was interpreted to become minimum with the use of asymmetrical guide vane profile. Selection of unsymmetrical guide vane profiles to reduce the effect of sediment erosion in Francis turbine was also suggested by Koirala [9] in his study. Quian [6] studied the flow measurement in the distributor of Francis Turbine. Her works were based on the measurements of the instantaneous field. Both instantaneous velocity fields and dynamic pressure measurements were done using PIV approach and miniature pressure sensors. Velocity of the working fluid through the guide vanes was observed. The velocity fluctuations at the outlet of guide vane components are non-uniform at all conditions. These findings were further elaborated by Thapa [7] capturing the wake along the trailing edge of guide vane from the wall to the mid-span using PIV approach and CFD analysis.

It was seen from the previous study [12] that the leakage flow through the clearance gap results in the formation of a vortex filament, which has a tendency to hit the runner inlet. The pressure pulsation contributed by this vortex filament can be studied by conducting transient simulations of the turbine [5]. However, the frequency of resulting vortex through each guide vane coincides with the blade passing frequency. This results in combined amplitudes in harmonics while conducting Fast Fourier Transformation (FFT) of the pulsations. An alternative clearance gap approach has been used in this paper so that the amplitude of the pressure due to leakage flow alone can be studied, as well as compared between different conditions and geometries. In the first part of the paper, it discusses the development of leakage flow in the guide vanes followed by numerical techniques employed to predict the leakage flow. Both steady state and transient blade row model using component modelling of GV, runner and leakage were done that is able to introduce new approach in predicting leakage flow.

2. Development of leakage flow from guide vanes and sediment erosion

A wicket gate consists of a set of guide vane blades capable of rotating in its axis to regulate the required flow into the runner inlet. In order to ensure free rotation of GV blade from its axis, small gap is present in between blade and facing plate. When the flow enters guide vane domain, in the flow path two distinct flows can be observed towards the upper side of blade and lower side characterized as: pressure side and suction side. Pressure difference is thus created in between two sides of the GV blades. The significant build-up of the wake along the trailing edge, pressure difference between two adjacent sides and leakage flow from clearance gap affects the performance of the runner.

Fluid enters the turbine from the inlet of the spiral casing. The flow is axi-symmetrically distributed to the GV’s domain through stay vanes. When the fluid containing sediment particles enters the guide vanes, many undesirable flow phenomena may be observed [10]. The undesirable flow may be the combination of cross leakage flow, vortices through the tip or horse-shoe vortices at the corners. The erosion in the guide vanes are so characterized as Turbulence erosion, Leakage Erosion, Secondary Flow Erosion and Acceleration Erosion [7]. Sediment erosion in the Francis turbine is the combined effect of the different kinds of undesirable flow phenomena in guide vanes. The most common measurable effects of sediment erosion damage in guide vanes of Francis Turbine are the increase in the guide vane clearance gap due to the consequences of these effects that deteriorates the performance of runner. Most affected regions of the guide vanes due to sediment erosion were found to be around the trailing edge due to very high pressure difference compared to the leading edge. This high-pressure difference causes the cross-leakage flow from the clearance gap. Koirala [9], investigated the performance of medium head Francis turbine of Kaligandaki ‘A’ Hydropower Project (48X3 MW) severely affected by sediment erosion. It was reported that the highest concentration of quartz particle in the river causes abrasive erosion in the GV profile. Clearance gap size was reported to be as high as 10 mm at some locations of GV.
3. Numerical Model

Current study uses case for Jhimruk Hydropower Plant, 12.3 MW (4.1X3 MW each unit runner) consisting of 24 guide vanes. Numerical model for runner and guide vanes were created for computational analysis. In this case, leakage is so introduced that 24 guide vanes contain 12 guide vanes with leakage and 12 GVs without leakage alternatively.

![Figure 1. Numerical model of alternative leakage](image)

Reynolds averaged Navier-Stokes (RANS) is used to solve the numerical model for an incompressible flow. The commercial CFD solver ANSYS-18.1 is used for numerical simulations in steady state and transient conditions using high-resolution discretization in advection scheme. Shear Stress Transport (SST) turbulence model was used for the flow. Transient Blade Row model was used for unsteady analysis. The total simulation time was 0.06s, equivalent to 1 revolution of the runner. The convergence criteria for the mass, momentum and turbulence parameters were set to a root-mean-square (RMS) value 1E-4. The inner loop iteration for transients at each time step was selected to be 10.

Model consists of the 3 separate domains i) Guide Vanes ii) Leakage and iii) Runner. Runner domain is rotating with 1000 revmin-1. Separate hexahedral mesh was employed for each domain as shown in figure. At the inlet of the GV, a mass flow rate of 2350 kg/s with the cylindrical vector components (a,r,t) as (0,-0.34,-0.94) was chosen. These components were according to the orientation of stay vanes in the turbine. Average static pressure of 1 atmosphere was specified at the outlet of the runner as the differential pressure was the parameter of interest in this paper. GV blades, runner blades, hub and shroud were specified walls with no slip condition. At the inlet of the domain, 5% turbulence intensity was used.

4. Grid Convergence Test

GCI technique was used for the estimation of the discretization error with three different mesh schemes specified as: Fine (G1), Medium (G2) and Coarse (G3) [13]. Refinement of mesh with different mesh scheme was done with 1.3X grid refinement factor at all the edges of the blocks. Clearance gap was not introduced in the domain for uncertainties measurement. Table 1 shows uncertainties in the measured value of the runner and guide vane. In this case, torque of the runner blades in the direction of rotation and velocity of the fluid at the trailing edge of the GV are chosen.
The numerical uncertainties for the measurement of torque for fine mesh were 0.31% and the velocity at the trailing edge of GV was 11.07%.

**Table 1.** Discretization error for the numerical solution

| Grid Type | Number of Elements | Grid Refinement Factor(r) | Measurement Parameter (φ) | Grid Convergence Index (GCI) |
|-----------|--------------------|---------------------------|---------------------------|-----------------------------|
|           |                    |                           | Torque (Nm) (RV-Blades)   | Torque          | Velocity(m/s) (GV-Outlet) | Velocity |
| Coarse    | 507720             | \( r^{21}=1.32 \)        | 41175.7                   | \( GCI_{fine}^{21}=0 \) | 28.89                     | 41528.2  | 29.31 |
| Medium    | 2091564            | \( r^{32}=1.6 \)         | 41515.6                   | \( GCI_{fine}^{32}=11 \) | 25.09                     |          |      |
| Fine      | 4847309            |                            |                           |                |                            |          |      |

Figure 2 and 3 shows uncertainties in the measurement of the velocity of fluid from the outlet of GV. Near the trailing edge of the GV velocity of the fluid was found to be least and has higher uncertainties. This is because of wake in the trailing edge of GV. At the trailing edge of the GV velocity was uncertainty was measured to be ±2 m/s. The discretization error bars are computed for fine mesh where the uncertainty ranges from 0.14% to 11.07%. Higher error was found at the trailing edge of GV. This is because of wakes travelling from the GV trailing edge resulting higher deviation in the calculated value.

5. Leakage Flow

Four planes were defined in between runner and guide vanes, along 45 degrees of circular span whereby three guide vanes: one without leakage and other with leakage were covered. Plane 4, 3 and 2 respectively lies inside guide vane domain from beneath the trailing edge of the guide vane. In front of the runner blade lies plane 1 where flow is affected by the rotational motion of the runner.
Figure 4. Planes between runner and guide vanes

Figure 5 shows the normalized total pressure contour, which total pressure with respect to the maximum pressure in the domain, at different planes in between GV and runner. In between two guide vanes with leakage lies a single guide vane without leakage. The growth of flow beneath the guide vane trailing edge of 2 mm and 4 mm clearance gap is shown in the figure. It can be inferred that the clearance gap disturbs the main flow in any case for 2 mm and 4 mm leakage. The lowest total pressure was found near the clearance gap region, which represents the vortex filament leaving the GV. In any of the plane representing three GVs, there were two regions with low total pressure representing the effects of clearance gap. In the case of the GV without clearance gap, in between two GVs in the plane, no such region for the development of vortex filament was observed. In the case of 2 mm clearance gap, the strength of the vortex increases while moving from Plane 4 to Plane 3 and decreases slightly while moving from Plane 3 to Plane 2. However, in the case of 4 mm clearance gap, the strength of the vortex increases continuously from Plane 4 to Plane 2. However, between 2 mm and 4 mm clearance gap, using the same range for the legend, the strength of the vortex was not found to be significantly different. This result is in agreement with the past research work [7], which studied from the single GV’s rig that the critical size of the clearance gap is 2 mm, which caused highest leakage flow when compared between 0.5 mm, 1.5 mm, 2 mm and 3 mm gap.
Flow downstream the guide vane domain is affected by the secondary flow from clearance gap. The rotational component of the vortex filament leaving the GV hits the inlet of the runner other than the design angle. When it enters the runner field due to continuous rotor stator interaction and secondary flow from clearance gap, sharp pressure difference is observed along hub and shroud. Since this study only includes clearance gap in the hub region of GV, the pressure difference is observed near hub region. Figure 6 shows the normalized total pressure contour in the plane inside runner domain. With the increase in clearance gap size, difference in total pressure is also observed. The difference observed in this plane is larger than the planes upstream. It shows that the effect of the vortex is predominant inside the regime of the runner. Since the previous study [7] did not contain runner in the rig, this effect was not observed. This disturbance in the main flow results in the unwanted pressure pulsations and vibrations in the turbine. The efficiency the turbine decreases as the size of clearance gap increases.

Figure 5. Normalized total pressure contours at 3 planes downstream of guide vanes

Figure 6. Normalized total pressure contours at runner inlet (Plane 1)
6. Pressure pulsation between rotor-stator components

Figure 7. Points between GV and RV inside rotating domain. To visualize the pressure pulsation in between runner and guide vanes, total pressure during each angular position of runner was observed locating points in front of the runner. Total six points were introduced up from the mid-span between hub and shroud. These points progress towards near hub region with 50% geometric progression of the length along the span.

Figure 8 shows the transient pressure pulsation in between runner and guide vanes at Point 5 (closer to hub). Total pressure during each degree revolution was monitored for three cases viz. No Leakage, 2 mm Leakage and 4 mm Leakage. It is clear from the figure that the increase in clearance gap increases the magnitude of normalized pressure: defined as the ratio of difference in local pressure with maximum pressure. In this case the peak pressure pulsation due to increased clearance gap is due to the increased vortex filament originating from clearance gap. For the current case with 24 GVs the peak frequency pressure pulsation of alternative leakage gives the peak values at 15 degrees of runner revolution.

The time value of total pressure pulsation for different points was transferred to frequency value with corresponding frequency of 1000 Hz. In case of 24 GV system, peak frequency during each runner revolution was observed to be at 400 Hz except for the case consisting of clearance gap alternatively. The alternative clearance gap at all the cases gives peak pressure at 200 Hz i.e. first harmonics of the frequency spectrum occurs at 200 Hz. This gives the indication of the effects of leakage flow runner in comparison to no leakage condition due to peak pressure pulsation compared to no leakage condition.

Figure 9 shows Fourier transformed pressure spectrum for all the points. It is clear from the figure that in case of guide vanes consisting of alternative leakage, first harmonics occurs at 200 Hz whereas for no leakage condition first harmonics occurs at 400 Hz.
Interestingly, in case of Point 3, located 87.5% along the normal line from shroud to hub, peak pressure pulsation at 200 Hz was found to be higher than that of other points which lie closer to the clearance gap. This is because of the shifting of the vortex towards the mid-span while traveling downstream of the GV. A similar pattern of the flow was observed in the single GV rig [12]. The vortex also results in the deviation of the stagnation angle at the inlet of the runner other than the design angle.

**Figure 9.** Frequency spectrum of the pressure pulsation at six points for three cases of the clearance gaps (BPF 400 Hz)

**Figure 10.** Vortex core region at 1000 Hz
When leakage flow leaving the trailing edge of the GV mixes with the main flow, it induces the rotational velocity component developing vortex filament. Figure 10 shows the vortices travelling from alternative clearance gap of 2 mm and 4 mm thickness respectively. Vortex core region is observed at the swirling strength of 1000 s⁻¹. It is evident that the magnitude of the vortex rope is higher for higher thickness of clearance gap. In the GV without leakage no vortex core region due to leakage flow is observed. It can be inferred that the clearance gap of GV is responsible for the wear in the inlet of runner due to very high velocity of the rotating flow.

7. Conclusion

Due to the continuous abrasion of sediment inside the clearance gap, the size of clearance gap increases. Leakage flow with clearance gaps of 0 mm, 2 mm and 4 mm thickness were studied in this paper. With the increase in the clearance gap of GV, the intensity of pressure pulsation inside the runner increases due to the vortices travelling through the gap into the runner. With the introduction of clearance gap alternately in the GV domain, first harmonics of the total pressure pulsation was able to be observed at 200 Hz separately than that of 400 Hz in case of no leakage. Fourier transformed pressure amplitude was able to capture the intensity of pressure pulsation for both no leakage condition and for increased clearance gap. Furthermore, strength of vortices increases for with the thickness of clearance gap, whereby no such vortices were seen from guide vanes without leakage. This study also introduces the prospects of fixed guide vane system to minimize the simultaneous effect of secondary flow and sediment erosion.

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