Experimental and Numerical Investigations of Erosion on Runner Seal of a Francis Turbine

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Abstract. To suppress sediment erosion in labyrinth seals is an important problem for hydro turbine design and operation. A numerical simulation was carried out to know the flow with solid particles and its influence on the erosion in the labyrinth seal. The result showed that the vortex took place in the intermediate space between the first and the second seal gaps and the solid particles impinged on the runner wall along the vortex. Experiments were also carried out to understand the characteristics of the flow with vortices in the labyrinth seal by changing the flow rate of the leakage through the seal. It was found that the vortex took place stably in the intermediate space regardless the flow rate of the leakage although the Taylor vortex pattern was significantly disturbed as the leakage flow rate increased.

1. Introduction

Importance of renewable energy continues to grow. Hydro energy is one of the most important renewable energy as a base power due to its high energy density and low cost. Therefore, hydro turbines are required to have a long operating life as well as a high efficiency. One of causes to shorten the operating life of the hydro turbines is sediment erosion. The sediment erosion can damage various part of the hydro turbine such as a runner, stay vanes, guide vanes and a draft tube. The erosion in the runner also takes place at various parts such as on blades and in seals. The erosion of the blades can be leaded to decrease of the hydraulic efficiency and power output, and the erosion of the seal can be leaded to increase of the leakage flow, which may reduce the efficiency.

In a working hydro turbine suffered from the sediment erosion in the labyrinth seal on the runner wall as shown in Figure 1. There were two labyrinth seals on this runner: the one was on the back shroud and the other was on the front shroud. The geometry of the flow path in the labyrinth seal was stair-like with two steps as shown in Figure 1. Circumferential grooves were formed as a result of the erosion. In the labyrinth seal, the erosion took place at the inlets of the narrow seal gaps. The depth of the groove at the second seal gap inlet was deeper than that at the first gap inlet. Because of the formation of such deep grooves, the maintenance work must be done frequently. In order to suppress the erosion in the labyrinth seal, it is important to know the flow pattern and erosion mechanisms.

Sediment erosion of the hydro turbine has been a research subject for long time. Although there are many literatures about the erosion of blades, vanes and buckets of Francis and Pelton runners [1-8], there are a few reports about the investigations of the seal erosion. Padhy and Saini [9] reviewed many literatures and a study about the seal erosion was introduced. Mack et al. [10] carried out a simple numerical simulation to evaluate the erosion rate in the seal gap. On the other hand, flows between a
cylindrical rotor in a casing have been carried out by many researchers. The purpose of these studies was to understand the physics of vortices caused by Taylor-Couette instability [11-13]. In these studies, characteristics of Taylor vortex were examined under various conditions. However, authors could not find any literatures which clearly unveiled the flow patterns and mechanisms of erosion in the labyrinth seal. According to the literature survey, authors expected that the vortices in the gap played an important role as a cause of the erosion.

In the present report, a numerical simulation was carried out to know the flow with solid particles in the labyrinth seal. In addition, an experiment was also carried out to know the flow characteristics in the labyrinth seal under various condition. Finally, the mechanisms of the sediment erosion in the labyrinth seal was discussed.

2. Numerical flow simulation in labyrinth seal of hydro turbine

2.1. Numerical method

The CFD simulation of the flow in labyrinth seal was carried to understand the phenomena in the hydro turbine. ANSYS CFX 2019-R1 was used as a flow solver. A steady flow simulation without turbulence model was carried out. The particle distribution was calculated considering the interaction between the motions of liquid and solid particles. The erosion rate was evaluated using Grant and Tabakoff model [14]. Using this model, the erosion rate $E$ was estimated as follows:

$$E = f(\gamma) \left( \frac{V_p}{V_1} \right) \cos^2 \gamma \left( 1 - R_T^2 \right) + f(V_{py}) \quad \ldots(1)$$

$$f(\gamma) = \left[ 1 + k_2 k_3 \sin \left( \gamma \frac{\pi}{2} \frac{V}{V_0} \right) \right]^2 \quad \ldots(2)$$

$$R_T = 1 - \frac{V_2}{V_1} \sin \gamma \quad \ldots(3)$$

$$f(V_{py}) = \left( \frac{V_p}{V_2} \sin \gamma \right)^4 \quad \ldots(4)$$
\[ k_2 = \begin{cases} 1.0 & \text{if } \gamma \leq 2\gamma_0 \\ 0.0 & \text{if } \gamma \geq 2\gamma_0 \end{cases} \quad \text{...}(5). \]

Properties of the particle and the body material are expressed using constants in Eqs. (1-5) and the used values are presented in Table 1. The solid particle and the runner material were assumed to be quartz and steel.

Table 1 Input parameter of Tabakoff erosion model for quartz particle and steel body

| Parameter | Value      |
|-----------|------------|
| \( k_{12} \) | 0.0293328 [-] |
| \( V_1 \)   | 123.72 m/s   |
| \( V_2 \)   | 352.99 m/s   |
| \( V_3 \)   | 179.29 m/s   |
| \( \gamma_0 \) | 30 degree    |

![Computational domain](image1)

(a) Computational domain

![Meridional cross section of the flow path](image2)

(b) Meridional cross section of the flow path

Figure 2 Schematic of computational domain
The computational domain, which is shown in Figure 2, was the same with the geometry of the labyrinth seal of the actual hydro turbine. The domain was assumed 45 degrees periodic in circumferential direction. The computational mesh consisted of hexahedral mesh and the total number of elements was 6,538,410. The labyrinth seal had a step and the sediment erosion was observed at the inlets of the seal gap as above mentioned. The gap between the rotor and stator was 1 mm, and the revolution frequency was 3.57 Hz. In this computation, the leakage flow rate through the labyrinth seal was fixed at the inlet boundary and the normalized axial velocity, $v_z/r\Omega$, was 0.3, which corresponds to 0.15% of total flow rate through the hydro turbine. Here, $\Omega$ is the runner revolution angular velocity of 22.4 rad/s and $r$ is the radius of the runner seal of 1.5 m.

Figure 3 shows instantaneous velocity distribution and velocity vector in a meridional plane. It was observed that the flow impinged on the runner surface around the inlet of the seal gaps.

The volume fraction distribution of the solid particle in the meridional plane and erosion rate density on the runner wall is shown in Figure 4. The erosion rate became large at the inlets of the first and the second seal gaps. It was observed that the solid particle impinged on the runner wall and the erosion rate density became large. Although the results are not presented in the paper, high erosion rate density regions were not found on the stator wall. Comparing the flows and erosion rate distributions between the first and the second gaps, the erosion rate density is smaller at the first gap than that at the second gap. The difference of geometry can be seen around the inlet. At the inlet of the first gap, the runner wall contour is concave, and the particle impingement may be weakened.

According to the numerical results, it was confirmed that the particle impingement on the runner wall cause the sediment erosion on the labyrinth seal. Further investigation of the erosion progress and the method to suppress the erosion are under way and will be reported in near future.

Figure 3 Instantaneous velocity vector field (left: 1st gap inlet, right: 2nd gap inlet)
3. **Experimental investigation of the flow in the labyrinth seal**

3.1. **Experimental method**

Flow patterns in the seal gap were visualized and measured by means of PIV method. Figure 5 shows experimental apparatus. The rotor and stator walls, which simulate the runner and casing walls, were made of transparent acrylic resin to suppress the reflection of the laser light on the surface. The rotor and the stator geometries simulated the labyrinth seal. However, the gap between the rotor and the stator was 5 mm, which was larger than the actual seal, in order to obtain clear velocity fields. The planar laser induced fluorescence (PLIF) technique was used to visualize the flow in the gap. The visualized flow...
patterns were recorded using a high-speed video camera and temporal and time-mean flow velocity fields in meridional plane were obtained. Two kinds of rotor geometries were used, which were the original geometry and the eroded geometry. The eroded geometry had a circumferential groove around the inlet of the second seal gap. The rotational frequency of the rotor was fixed at 0.83 Hz and the leakage flow rate was varied.

3.2. Results and discussion

Flow patterns around the inlet of the second gap were measured. Time-mean fields of velocity vector and axial velocity distributions in the meridional plane are shown in Figure 6, where the original rotor was used, and various leakage flow rates were examined. A counterclockwise recirculation can be in the intermediate space between the first and second gaps. The vortex core of this recirculation took place near the upper wall of the stator at the small leakage flow rate but moved downward as the leakage flow rate increased. The leakage jet from the first gap attached on the stator wall, and then impinged on the rotor wall, which was the same with that observed in the numerical results in Section 2. Around the second gap inlet, clockwise vortex took place for all leakage flow rate conditions. Although the outward radial flow took place downstream of this inlet vortex core, the radial velocity was smaller than that upstream of the vortex core. This should be why the large erosion rate density was not observed on the casing wall in the hydro turbine. Each one counterclockwise and clockwise vortex can be seen alternatively downstream of the inlet vortex at small leakage flow rates, \( Q_z = 0 \) and 1 l/min. This suggests that stable Taylor vortex patterns took place in the second gap. At larger leakage flow rates, \( Q_z = 4 \) and 7 l/min, the vortex structures are unclear downstream of the inlet vortex. Figure 7 shows the results using the eroded geometry. Although similar flow patterns to those with the original rotor, Taylor vortex patterns become clearer than those without the groove on the rotor at the low leakage conditions. Because the flow path became wider, the stagnation point shifted downstream and the impinging angle became smaller.

![Figure 6 Time mean distribution of axial velocity and velocity vector](PIV measurement, without groove)
Figure 7 Time mean distribution of axial velocity and velocity vector (PIV measurement, with groove)

Figure 8 and Figure 9 show time histories of radial velocity distribution on the center line in the second gap obtained by PIV measurement for cases with and without the circumferential groove on the rotor. Stripe patterns of the radial velocity suggests that Taylor vortex takes place. The outlet of the first gap and the inlet of the second gap are at \( z = 50 \text{ mm} \) and \( 67 \text{ mm} \). The circumferential groove on the rotor is at \( z = 68.9 \text{ mm} \). At \( Q_z = 0 \text{l/min} \), the number of the stripe pattern changed between 4 and 5 without the groove as shown in Figure 8. In Figure 9, on the other hand, the number of the stripe pattern was kept at 5. These results suggest that Taylor vortex become stable due to the groove on the rotor. At \( Q_z = 1 \text{l/min} \), the stripe patterns are disturbed by the axial flow for both with and without the groove. At \( Q_z = 4 \text{l/min} \), the stripe pattern distribution becomes oblique and further disturbed patterns take place at \( Q_z = 7 \text{l/min} \). The Taylor vortex patterns changes as the axial flow rate increases, as presented in the previous studies [8-9]. However, the vortex at the gap inlet takes place regardless of the axial flow rate. Therefore, the inlet vortex always takes place in the labyrinth seal of the examined hydro turbine. When the sediment is included in the working water, the runner wall is damaged and finally the groove is formed through a time. Finally, it is necessary to modify the geometry in the labyrinth seal to suppress the sediment erosion. The geometry around the seal gap inlet would be important.
Figure 8 Time history of radial velocity distribution on the centre line in the second gap (without groove)

Figure 9 Time history of radial velocity distribution on the centre line in the second gap (with groove)
4. Conclusion
The mechanism of the sediment erosion was discussed by means of a numerical flow simulation with considering the transportation of solid particles. The most serious erosion was predicted at the inlet of the second seal gap as was observed in the actual hydro turbine. It was found that the vortex took place in the intermediate space between the first and the second gaps and intense impingement of the solid particles took place on the runner wall.

Experiments were also carried out to understand the vortex characteristics in the seal with various flow rates of the leakage flow. It was found that the vortex in the intermediate space took place regardless the leakage flow rate although the Taylor vortex was more disturbed as the flow rate increased.

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