CFD analysis of flow pattern in S-Shape region for low specific speed Francis turbine

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Abstract. In this research, a Francis turbine with low specific speed was analyzed by unsteady numerical simulation in case of S-Shape region appearing model test. It was found that S-Shape characteristics curve was caused by an increase of head. Firstly, the head was decreased in accordance with a decrease of flow rate. However, once a centrifugal force became larger, then a reverse flow appeared between guide vane and runner and the head was increased. And then, head was decreased with flow rate decreasing. In this research, operating conditions of flow rate were defined as three regions, first half of S-Shape region, just S-Shape region and last half of S-Shape region. The operating condition, where the head was decreased in accordance with the decrease of flow rate, was defined as the first half of S-Shape region. The operating condition, where the head was just being increased in accordance with the decrease of flow rate, was defined as the just S-Shape region. The operating condition after passing of the just S-Shape region was defined as the last half of S-Shape region. It was revealed that those three operating conditions showed a spectrum distribution of pressure fluctuation differently each other. A flow visualization analysis with numerical results was conducted to investigate the difference of pressure spectrum in three operating conditions. At the first half of S-Shape region, two groups of reverse flow were caused at chamber between guide vane and runner and revolving in same direction as runner rotation. At the just S-Shape, the reverse flows were circumferentially connected to build a long curved string. At the last half of S-Shape, the reverse flows were fully connected to build a round ring shape.

1. Introduction
Hydraulic power generation is one of the most commonly used electric power generation by renewable energy and 80% of it is generated by hydraulic power plants. Especially, Francis turbine is one of the major hydropower systems. On Francis turbines including pump turbines, a turbine characteristic curve indicates S-Shape relation at high speed factor and low discharge factor for a constant guide vane opening, in particular for small guide vane opening. Runaway speed point with zero turbine output appears and finally the turbine output changes to be negative, called as turbine brake around this operating region. This S-Shape characteristic is formed by multiple discharge factor $Q_{ED}$ against a given speed factor $n_{ED}$ and causes an unstable operating condition at turbine start and load rejection. When a load rejection is caused in hydro power plant, rotational speed is increased and the guide vane is going...
to be closed. And then, pressure on penstock is increased. If Francis turbine has S-Shape characteristic, it may cause a pressure increase again. There are some cases in which this secondary pressure increase is higher than first one. In worst cases, the secondary peak value becomes higher than penstock design pressure. The aim of this paper is to conduct a comprehensive analysis of flow behavior for S-Shape characteristic by using numerical simulation technology.

At high speed factor and low discharge factor around the turbine brake region, a reverse flow caused by separating flow from runner inlet appears in chamber between guide vane outlet and runner inlet. This reverse flow carries hydraulic energy from runner to guide vane. In case of smaller guide vane opening, the reverse flow does not impinge on guide vane because guide vane outlet diameter is large and distance from runner to guide vane is far. It means shock loss at guide vane outlet is decreased and turbine head can be increased by reverse flow containing energy [1]. This increased turbine head makes speed factor $n_{ED}$ to be smaller, then S-Shape curve appears in 3rd quadrant region of turbine characteristics.

Model test for pump-turbine was conducted with zero condition of turbine discharge in order to measure pressure and radial velocity at chamber between runner blades and guide vanes [1]. It was investigated how turbine head could be affected by guide vane position and guide vane opening. S-Shape region of reversible pump-turbine on turbine mode was analyzed by transient computational fluid dynamics with large grid scale [2]. Turbine characteristics curve, head and torque were predicted well with comparison of experimental results and flow phenomena in runner blade were analyzed in detail. A numerical simulation with steady and unsteady methods were conducted for a low specific speed Francis turbine and the computational result for S-Shape characteristics curve agreed well with the experimental one [3]. It was revealed by the numerical simulations that an increase of turbine head caused the S-Shape characteristics curve and operating conditions were divided into two different regions, which were the first half of S-Shape region and the last half of S-Shape region. The first half of S-Shape region was defined at flow rate condition before the increase of turbine head happened. On the other hand, the last half of S-Shape region was defined at flow rate condition after the increase of turbine head happened. The unsteady numerical simulation indicated that a few significant peaks of pressure spectrum could be seen at the just S-Shape region and only one peak of blade passing frequency could be seen at the last half of S-Shape region [3].

In this paper, the unsteady numerical analysis for low specific speed Francis turbine was descried with a guide vane opening condition of 40% where the S-Shape characteristics curve appeared at model test. Pressure spectrums were investigated in detail at each different flow rate condition around S-Shape point. Moreover, a flow visualization analysis using unsteady numerical results was conducted to demonstrate different flow behaviors at each different flow rate condition.

2. Numerical method

2.1. Computational model

The numerical simulation and model test of low specific speed Francis turbine were carried out. The specification of the model turbine is shown in Table 1. Figure 1 shows computational domain considered in this research. The rotational part of turbine consists of a runner with 17 blades, and the stationary part consists of a spiral casing with 20 stay vanes, 20 guide vanes and draft tube. The guide vane opening condition is 40% explained in Figure 2. It shows that the guide vane end clearance is narrower and the guide vane outlet diameter is larger. Therefore, the distance between runner inlet and guide vane outlet is wider. Pressure was measured at upper wall between guide vane and runner shown in Figure 2 in experiment.

Leakage flow is generated in the back region of runner crown and runner band. The back regions were involved in a numerical domain in order to predict hydraulic performance accurately in this research. Figure 3. indicates the numerical domain of back region. Leakage flows are generated in the seal flow passage with multiple stages.
### Table 1. Specification of model turbine

| Specific speed | $N_{QE}$ (-) | 0.076 |
|----------------|--------------|-------|
| Runner outlet diameter | $D_2$ (mm) | 0.285 |
| Reynolds number | $Re$ (-) | $3 \times 5 \times 10^6$ |

**Figure 1.** Computational domain without back region and side region of runner

**Figure 2.** Guide vane opening conditions

**Figure 3.** Numerical domain for back region of runner crown and side region of runner band

#### 2.2. Computational method

The information of grid number applied in this research is summarized in Table 2. The numerical domain consists of all components of Francis turbine and is divided into six subdomains such as the spiral casing with stay vane, guide vane, runner, back region of runner crown, back region of runner band and draft...
tube. Mixed mesh with tetra and prism topology was prepared for spiral casing and hexahedron topology was prepared for other parts.

| Numerical part                          | Mesh Type     | Grid number (million) | $y^*$ |
|-----------------------------------------|---------------|-----------------------|-------|
| Spiral casing with stay vane            | Tetra-Prism   | 0.3                   | 38    |
| Guid vane                               | Hexahedron    | 4.4                   | 90    |
| Runner                                  | ↑             | 3.7                   | 200   |
| Back region of runner crown             | ↑             | 1.5                   | 475   |
| Back region of runner band              | ↑             | 0.9                   | 137   |
| Draft tube                              | ↑             | 0.8                   | 400   |
| Total node                              | —             | —                     | 11.6  |

Commercial software ANSYS CFX ver. 18 was applied for numerical simulation. Shear Stress Transport model was employed for turbulence model. Steady and unsteady simulations were conducted and the unsteady simulation was conducted with the steady result used as the initial condition. In the unsteady simulation, time step was set to be two degrees of the runner rotation. The interface model between stationary and rotating domains was frozen rotor in steady simulation, transient rotor stator in unsteady simulation. Numerical boundary condition for speed factor and discharge factor is described at Table 3. That condition was located around the turbine brake and including operating conditions in which S-Shape curve was revealed at guide vane opening of 40%. Inlet and outlet conditions were set to be fixed mass flow rate and constant pressure respectively.

| Guide vane opening | GVO (%) | 40 |
|--------------------|---------|----|
| Speed factor       | $n_{ED}$ (-) | 0.293–0.275 |
| Discharge factor   | $Q_{ED}$ (-) | 0.05–0.01 |

3. Numerical results and analysis

3.1. Steady numerical simulation analysis

The 3rd quadrant region in four quadrant characteristics of Francis turbine was simulated in this research. Firstly, the steady numerical simulation was carried out to predict the turbine characteristics quadrant, head coefficient and torque coefficient. The previously reported research concluded that steady numerical simulation could predict those turbine performance curves accurately compared with the experimental results [3]. Numerical analysis revealed that a reverse flow of radial velocity was generated between guide vane and runner at small flow discharges. It was found that the reverse flow caused a head increase and S-Shape characteristics at guide vane opening of 40%.

3.2. Unsteady numerical simulation analysis

S-Shape and turbine head curve predicted by steady and unsteady simulation are shown in Figure 4. $Q$ is volumetric flow discharge, $D$ is outlet diameter of runner, $g$ is gravity acceleration, $H$ is turbine head, $U$ is circumferential velocity based on outlet diameter of runner. In this paper, operating condition was divided into three parts, the first half of S-Shape region, the just S-Shape region and the last half of S-Shape region. Each divided region was explained in Figure 5 and Figure 6 for experiment and unsteady simulation respectively. At the first half of S-Shape, the turbine head was decreasing in accordance with decrease of flow rate. On the other hand, at the just S-Shape, the turbine head was being increased in
accordance with decrease of flow rate. Finally, at the last half of S-Shape, the turbine head was decreasing again in accordance with decrease of flow rate. Just S-Shape was unstable operating condition, so that operation point was rapidly changed from smaller discharge point of last half of S-Shape to larger discharge point of first half of S-Shape and stable value of \( n_{ED} \) and \( Q_{ED} \) for just S-Shape could not be measured in experiment shown in Figure 5. On the other hand, unsteady simulation could predict the turbine performance for just S-Shape shown in Figure 6.
Unsteady pressure fluctuation was measured at the crown wall located between guide vane and runner. Numerical and experimental pressure spectrums were compared with each other at the first half of S-Shape, just S-Shape and last half of S-Shape and indicated in Figure 7, 8, 9 respectively. Transient pressure component fluctuating from time averaged one was taken into consideration by using Fourier analysis. In experiment, stable measurement was impossible on the just S-Shape which was unstable operating condition. For that reason, pressure kept measuring while the operating point was changing from the smaller discharge point on the last half of S-Shape to the larger discharge point on the first half of S-Shape. Peak value indicated by 17 is blade passing frequency, hearafter called BPF, since the runner is consisted of 17 blades. High peak at BPF could be predicted well by numerical simulation compared with experimental results. It was found that all of three operating conditions had the high peaks at BPF. At the first half of S-Shape, another significant peak was revealed at 1.2 other than BPF in numerical simulation. Similar peak in experiment was seen at 1.3. Large fluctuations at broad band frequencies lower than BPF were found in both of numerical simulation and experiment. At the just S-Shape, another significant peaks were found at 0.4 and 4.1 other than BPF in numerical simulation. High peak at 0.4 in numerical simulation was similarly found at 0.5 in experiment. On the other hand, the similar high peak at 4.1 in numerical simulation was not found in experiment. Large fluctuations at broad band frequencies lower than BPF were found in experiment as well as at the first half of S-Shape. However, fluctuations at broad band frequencies other than significant peak frequencies of 0.4, 4.1 and 17(BPF) were clearly reduced in numerical simulation. At the last half of S-Shape, significant peak was only found at BPF in both of numerical simulation and experiment. Fluctuations at broad band frequencies lower than BPF was largely reduced in numerical simulation. On the other hand, experiment had still large fluctuations at broad band frequencies other than BPF.

The first S-Shape and just S-Shape had another significant peaks other than BPF. Flow visualization using radial velocity distribution was conducted to make an animation of flow pattern. A correlating analysis between significant peaks of pressure spectrum and flow pattern was considered to investigate each different characteristic flow phenomenon at three operating conditions respectively.

![Figure 7. Pressure spectrum of first half of S-Shape](image1)

![Figure 8. Pressure spectrum of just S-Shape](image2)
The animation of transiently changing contour of radial velocity at the first half of S-Shape is explained in Figure 10 where the cross section is located at mid span of blade height of runner leading edge. It shows instantaneous velocity and plus value means reverse flow traveling from runner to guide vane. In order to emphasize the reverse flow and plus value means reverse flow traveling from runner to guide vane. In order to emphasize the reverse flow, minus value of forward flow is clipped by zero. It was found in previous research[3] that a reverse flow of radial velocity had strong correlation with pressure spectrum. One of 17 runner blades emphasized using arrow was visualized to demonstrate a runner rotation speed. $T_r$ is one periodic time of runner rotation and six frames during one periodic time are displayed. Two groups of reverse flow, BF-A and BF-B, were caused at chamber between guide vane and runner and revolving in counter-clockwise direction as same way as runner rotation. At time 0, BF-A was located at Phase-A and BF-B was located at 180 degree opposite side to BF-A. At time 0.81$T_r$, revolving BF-B arrived at Phase-A and the inverse of 0.81$T_r$ was corresponding to the significant peak frequency of 1.2 which was found on pressure spectrum of the first half of S-Shape in Figure 7.
The animation of changing contour of radial velocity at the just S-Shape is explained in Figure 11. The reverse flow was also generated between guide vane and runner as well as the first half of S-Shape. However, it expanded circumferentially and was connected to build a long curved string which was revolving in counter-clockwise direction. At time 0, the front head of long curved string was located at Phase-A and revolving with the lower frequency than runner rotation. At time $2.86T_r$, it was traveling round and returned to be at Phase-A again. The inverse of $2.86T_r$ was corresponding to the significant peak frequency of 0.4 which was found on pressure spectrum of the just S-Shape in Figure 8.

Figure 11. Animation of reverse flow of radial velocity at just S-Shape
The animation of changing contour of radial velocity at the last half of S-Shape is explained in Figure 12. The reverse flow was also generated between guide vane and runner, and formed to build a round ring shape. It was revolving with the same frequency as runner rotation as if the round ring was attached to runner blade. Reverse flows represented by blue color were counted as 17, the same number as runner blade and it was relating to the pressure spectrum of the last half of S-Shape in Figure 9 where only one peak was found at BPF.

Figure 12. Animation of reverse flow of radial velocity at last half of S-Shape
4. Conclusion
Unsteady numerical simulation was conducted for guide vane opening of 40% in low specific speed Francis turbine in order to investigate S-Shape characteristics. S-Shape curve predicted by unsteady numerical simulation was matched well with the experimental one. S-Shape was caused by turbine head increase. When the discharge flow rate was decreased and runner rotation was increased, the reverse flow happened at chamber between guide vane and runner. The centrifugal force was getting larger by higher runner rotation and it overcame the main flow momentum going forward from guide vane to runner, then the reverse flow was generated. The reverse flow carried kinetic energy supplied by runner and made the turbine head to be increased.

Operating conditions could be divided into three parts, the first half of S-Shape, the just S-Shape, and the last half of S-Shape around the S-Shape curve was revealed. At the first half of S-Shape, the turbine head was decreasing in accordance with decrease of flow rate. At the just S-Shape, the turbine head was being increased in accordance with decrease of flow rate. At the last half of S-Shape, the turbine head was decreasing again in accordance with decrease of flow rate. Unsteady pressure fluctuation between guide vane and runner was calculated by numerical simulation and pressure spectrum was compared with experimental one at the first half of S-Shape, the just S-Shape and the last half of S-Shape. It was found that all of three operating conditions had the high peaks at BPF in both of experiment and numerical simulation. At the first half of S-Shape, another significant peak was revealed at 1.2 other than BPF in numerical simulation and similar peak in experiment was seen at 1.3. At the just S-Shape, another significant peaks were found at 0.4 and 4.1 other than BPF in numerical simulation. High peak at 0.4 in numerical simulation was similarly found at 0.5 in experiment.

Flow visualization using radial velocity distribution was conducted to make the animation of flow pattern. Correlating analysis between significant peaks of pressure spectrum and flow pattern was carried out to investigate each different characteristical flow phenomenon at three operating conditions respectively. At the first half of S-Shape, two groups of reverse flow, BF-A and BF-B, were caused at chamber between guide vane and runner and revolving in same direction as runner rotation. It was found that reverse flows of BF-A and BF-B caused significant peak frequency of 1.2 which was found on pressure spectrum of the first half of S-Shape. At the just S-Shape, the reverse flow expanded circumferentially and was connected to build the long curved string, which was revolving in the same direction as runner rotation. The rotation flow pattern of long curve string caused the significant peak frequency of 0.4 which was found on pressure spectrum of the just S-Shape. At the last half of S-Shape, the reverse flow was fully connected to build the round ring shape. It was revolving with the same frequency as runner rotation and caused only one peak at BFP for pressure spectrum of the last half of S-Shape.

References
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