RPT Runner Flow Structures Dependence on Guide Vane Opening Angle: A CFD Numerical Simulation

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Abstract. Pumped storage power plants are now honored for different novelties mostly to do with large energy storage ability and electrical grid stabilization capacity. However the control of Reversible pump Turbines (RPT) operations within these plants is still an issue, where the so-called S-shape flow instabilities cause different problems especially when under low discharge operating conditions. Taking from the grounds that these instabilities have been found to mostly be based within the vaneless space between the guide vanes and the runner, this paper intends to investigate the effect of guide vanes opening (GVO) on runner flow characteristics. CFD-backed numerical simulations were carried out on a RPT complete flow passage under different GVOs; namely 17mm, 21mm and 25mm openings. Instabilities were found to take source from low flow conditions where resulting hydraulic losses maybe the trigger of s-shape characteristics appearance. The GVO however, showed the ability to tame the severity of these flow instabilities and associated pressure pulsations.

1. Introduction.

The energy sector has seen big changes in the last decades, where energy actors are now more than ever before, concerned with renewable sources. In line with this, owing to their different advantages; big and long term energy storage capacity, electrical grid stabilization, and operational flexibility among others; Pumped storage power plants have recently seen a very rapid development. In accordance with the electrical grid load-demand situation at hand, Reversible Pump Turbines (RPT) within these plants are subject to quick and frequent switches between the pumping and generating modes with prolonged periods under off design operating conditions, which in turn results into different flow instability occurrences. Trying to tackle the pump turbine generating mode-related instabilities; through many and varied attempts, different investigators have tried to get an understanding as to the cause as well as the onset and development mechanisms of these flow instabilities within RPT flow zones. Zhang et al. [1] noticed the flow unsteadiness increase as the flow decreased where flow vortex structures appeared and blocked some runner channels leading to flow reversal in the guide and stay vanes. Xia et Al. [2] blamed the flow losses within the runner channels to be the triggers of the s-shape characteristics occurrence. As for Histamuchi et Al. [3], the investigated flow blockage at runner flow channels take source from rotating flow separations at the same zones, which gives birth to rotating stall within the vaneless space and associated flow reversal within the inter-guide vane flow areas. Note that the so called “rotating stall” was defined by Frigne [4] as the flow unsteadiness that results into the occurrence of sub synchronous rotating velocity pulsations. In their studies, Widmer et al. [5] and Seidel et al. [6] found this rotating stall to rotate at...
speeds in the range of 50 to 70% of the runner rotational frequency. On the other hand, different studies have emphasized on parameters that influence the s-shape characteristics occurrence, where geometric design modifications such as variations of distributor pitch diameter [7], blade meridional section [8], blade leading edge profile [9] and runner blade number [10]; have made a great deal of change in terms of hydraulic losses occurrence mechanisms and the associated flow instabilities. Though the here mentioned studies and so others, have made a great contribution towards fundamental understanding of the flow unsteadiness onset and eventual development within RPTs, RPT flow instabilities have not yet been fully understood thus still requiring much more research efforts. In line with this, the present study seeks to investigate the influence of guide vane opening (GVO) on flow structures within the RPT runner flow zones for a pump turbine operating under off-design conditions. CFD-backed Numerical simulations are carried out on a high head pump turbine’s complete flow passage, where the guide vanes were successively set to three different openings namely 17mm, 21mm, and 25mm; under which the changes in terms of flow unsteadiness onset and development mechanisms within the runner channels are analyzed.

2. Research object and method.

2.1. RPT geometrical model

The investigated pump turbine model is a single stage centrifugal type with the specific speed Ns: 36.8m³/s. It’s composed of five components namely volute casing, stay vanes, guide vanes, runner, and draft tube. More details on the investigated pump turbine model are given through table 1, while figure 1 displays its external view.

![Figure 1. RPT computational model.](image)

| Parameter                  | Symbol | Value |
|----------------------------|--------|-------|
| Runner Inlet Diameter      | D₂     | 560   |
| Runner Outlet Diameter     | D₁     | 270   |
| Runner Blade Number        | Zᵣ     | 9     |
| GV Distr. Diameter         | Dᵥ     | 662   |
| Guide Vane Height          | Bᵥ     | 37.8  |
| Guide Vane number          | Zᵥ     | 20    |
| Stay Vane Number           | Zₛ     | 20    |
| Stay Vane Inlet Diameter   | Dₛᵢ    | 966   |
| Stay Vane Outlet Diameter  | Dₛₒ    | 763   |

2.2. Turbulence model

The RPT flow turbulence was modeled using Menter’s SST turbulence model[11]. This model is known to combine the advantages of two other k-ε and k-ω models to be able to adequately model wall-bounded as well as free stream flows. Its mathematical expressions are as follows:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_j k)}{\partial x_j} = P - \beta' \rho \omega k + \frac{\partial}{\partial x_j} \left[ \left( \mu + \sigma_{t} \mu_{t} \right) \frac{\partial k}{\partial x_j} \right] \tag{1}
\]

\[
\frac{\partial (\rho \omega)}{\partial t} + \frac{\partial (\rho u_j \omega)}{\partial x_j} = \frac{\gamma}{\nu_t} P - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[ \left( \mu + \sigma_{t} \mu_{t} \right) \frac{\partial \omega}{\partial x_j} \right] + 2(1 - F_t) \frac{\rho \sigma_{t}}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \tag{2}
\]

2.3. Numerical scheme

Using CFD commercial code Ansys CFX 18.0, the 3D flow through the complete flow passage of the RPT model under different operating conditions was modeled. Ansys ICEM was used to generate structured hexahedral grid for most of the model components, at the exception of the volute tongue, where unstructured tetrahedral grid was adopted, due to its sharp shape. After a grid independence test, and in line with the available computational resources, a grid of 7.5 million grid nodes was chosen. Fine mesh was used at walls situated in critical flow zones like guide/stay vanes as well as the runner.

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Table 1. RPT geometry details
blades. The Y+ value globally varied between 20 and 300. Experimentally found inlet flow discharge and outlet pressure values were used as boundary conditions at the same boundaries.

Figure 2. Numerical simulation details. (a) Investigated Operating conditions, (b) Pressure monitoring point locations, (c) investigated runner span positions.

The transient numerical simulations were run for 7 runner revolutions with 1° rotation as the length of 1 time step. Numerical results agreed well with experimental ones with a global error rate less than 3%. Three operating points (OP) expanding from normal turbine conditions to runaway vicinities were simulated for every GVO as shown in Figure 2 (a). Four Pressure monitoring points were also positioned at the runner inlet zone as shown in Figure 2 (b).

3. Results and discussion

3.1. Flow field characteristics

In order to have an understanding on the eventual flow behaviors, flow stream lines at 5 selected runner span positions (See figure 2(c)) are displayed through Figure 3. The analysis is first carried out for three operating points as seen in Figure 2(a) under the GVO of 25mm. At OP4 the flow speed is high with quite ordered streams but also some vortices can be noticed at each blade’s suction side. The flow unsteadiness rises with the flow decrease where the runaway vicinities (OP8) are the most disturbed among the three investigated conditions. As the machine entered the unstable operating zone, the noticed inter-blade vortex flow shifted from the blade suction side to pressure side.
Figure 3. Flow streamlines and pressure contours for the 3 operating conditions under GVO25mm. (a) GVO25mm-OP4: normal turbine conditions, (b) GVO25-OP6: normal turbine conditions, and (c) GVO25-OP8: runaway vicinities.

Moreover, the flow turbulence locus moves from the hub to the shroud vicinities. The low pressure zones at the blade trailing edge were also found to widen up with the flow decrease. The here shown OP8 characteristics mark the beginning of the S-shape characteristics zone. In figure 4, the flow under OP8 conditions, is analyzed for different GVOs. It can be seen that for all GVOs the flow unsteadiness remains within the flow zones in the vicinities of the runner shroud (SP1, SP2 and SP3). However the flow complexity within inter-blade channels get weaker as the GVO increases, leading to conditions with GVO17mm and GVO25mm being the most and least disturbed flow states respectively. This takes source from the guide vanes resistance to vaneless space back flows when under small GVO, which in turn strengthens the vaneless space water ring and the inter-blade vortices.

Figure 4. Velocity streamlines at five runner spans (SP) for three GVOs. (a) GVO17mm-OP8, (b) GVO21mm-OP8, a0.nd (c) GVO25mm-OP8
Therefore bigger GVOs weaken the vaneless space water ring as well as the inter-blade runner vortices, allowing for reverse flow occurrence in the upstream flow zones.

3.2. Pressure pulsation characteristics.

Four pressure monitoring points (GU1-GU4) were located at the vaneless space outlet (runner inlet) to investigate the combinational effect of runner channels back flow and guide vane opening on pressure pulsations at the runner inlet. Figure 5 shows the pressure pulsations under one guide vane opening (25mm), at one monitoring point (GU1), for three operating conditions (OP4, OP6, and OP8). The low discharge conditions (OP6 and OP8) are characterized by high amplitude pressure pulsations, which is the consequence of incurred severe flow separations under these conditions (See Figure 3). For all cases, the dominant frequencies are the blade passing frequency (BPF: 9 fn) and its harmonics (2 to 7 BPF), for which with a gradually decreasing flow, the amplitudes first rose from OP4 to OP6 and then decreased downwards to OP8. However, sub-synchronous frequencies can also be noticed at each OP. These may take source from different flow instabilities be it upstream (guide vanes) or downstream-based (draft tube). Figure 6 shows pressure spectrums at GU3 for the three investigated guide vane openings. The increase of the dominant frequency’s amplitudes as the guide vane opening increases is obvious, which is in good agreement with Figure 4. The increase of GVO destroyed the vaneless space water ring, which caused the emergence of different flow separation zones and associated increased pressure pulsations.
Figure 6. Frequency domain Pressure pulsations at GU3 for three GVOs: GVO17mm-OP8, GVO21mm-OP8 and GVO25mm-OP8.

There was no much change of the available pressure frequencies for the three openings, except the changing sub-synchronous frequencies (0.57/\) where their highest amplitudes were recorded under 17 mm guide vane opening. These maybe related to the draft tube vortex rope effect.

4. Conclusion
In this paper the 3D turbulent flow simulations are performed on an RPT model’s complete flow passage to investigate the flow unsteadiness onset and development, where the effect of guide vane opening on runner flow characteristics is analyzed. A comparatively smooth flow was first noticed under normal turbine operating conditions, which deteriorated as the machine discharge decreased leading to tough flow separations accompanied with inter-blade channels obstruction by the developed vortex flow. The increase of the GVO destroyed the vaneless space water ring, which itself had been enhanced by the small GVO-caused resistance to vaneless space backflows. Therefore with the GVO increase, the inter-blade flow structures improved, whereas different flow separations emerged within the vaneless space. Pressure pulsations at runner inlet were also found very dependent on guide vane opening, where the dominant frequencies were the blade passing frequency and its harmonics. Low flow conditions were characterized by high amplitude pressure pulsations. These ones however, increased with the increasing guide vane opening. Therefore, the RPT flow unsteadiness mainly takes source from the frequently experienced low flow conditions, especially when shifting between operating modes. However, the guide vane opening when adequately controlled can considerably improve these operations thus contributing to the machine operational safety.

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