Influence of guide vane opening on the flow phenomena in a pump turbine during a fast transition from pump mode to generating mode

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Abstract. Due to a more fluctuating energy production caused by renewable energies such as wind and solar power, the number of changes between operating points in pumped storage power plants has increased over the last years. To further increase available regulating power, it is desirable to speed up these changes of operation conditions in Hydro units. Previous studies showed that CFD is well capable of predicting the flow phenomena in the machine under unsteady conditions for a large guide vane opening angle. The present paper investigates the benefits of nearly closed guide vanes during the transition. Results are compared between the two different angles as well as between simulation and measurement.

1. Introduction
Pumped storage power plants can be used to resolve imbalances in the grid by providing energy or storing excessive power as required. For reversible pump turbines, the change from one operating mode to the other is equivalent to a change in rotational direction. With the development and improvement of doubly-fed induction machines, machines can run at variable speed and additional brake torque can be provided for slowing down the rotation in pump mode. Apart from a regulation of power consumption or output via rotational speed, this enables a faster transition from pump mode to generating mode. However, this manoeuvre requires knowledge about flow phenomena in the machine to avoid damages.

CFD has been used by various authors to analyse unsteady conditions in Francis and pump turbines, such as runaway (e.g. [1-3]) start-up [4], speed no load conditions [5] or load rejection [6]. In previous work, the authors investigated the transient for a relatively large guide vane opening angle of 25° and compared simulated results to measured data [7, 8]. Generally, a good agreement between simulation and measurement was achieved. Severe pressure fluctuations were found especially in pump brake mode. In practice, the guide vanes may be closed to a smaller angle before the transient is started. However, this prolongs the time of the process.

The present paper aims at determining whether a smaller guide vane angle significantly reduces the fluctuations. Furthermore, it serves as a second validation case for CFD methodology for highly dynamic flow conditions.

2. Simulation setup
Simulations are carried out using OpenFOAM® 2.3 and guide vane angles of 5° (y5) and 25° (y25). The meshes contain approximately 20M nodes distributed over four domains which are connected via
arbitrary mesh interfaces. Time step is constant and k-omega-SST-model is used for turbulence. Flow rate is taken from experiment and prescribed at the respective inlet, i.e. at the draft tube in pump mode and at the spiral case in generating mode. As the measured signal of flow rate was found to be delayed compared to all other acquired data, it was shifted in time by a defined value. However, further investigations of experimental data indicated that this time shift is smaller than assumed in previous work [7, 8]. This paper uses flow rate based on the latest findings, so that results for y25 differ slightly from earlier results.

Transition time is 8 s for both opening angles and change in rotational speed is linear. This leads to a steep decrease of flow rate in pump mode. In pump brake mode, flow rate rapidly increases in the opposite direction. For y5, flow rate stays nearly constant for the rest of the process, independently of the still increasing rotational speed. For y25, flow rate continues to increase slowly until the end of the transient.

For comparison with experiment, pressure is evaluated at certain points in the machine, where pressure sensors were located during measurement. The positions of the sensors are described in [9].

3. Global results

Figure 1 presents the comparison between simulated and measured results in a four quadrant plot. The smaller guide vane angle is characterized by a nearly constant \( Q_{ED} \) over a wide range of \( n_{ED} \) in pump brake and generating mode, while the discharge factor \( Q_{ED} \) for the larger opening angle continuously increases. The agreement between simulation and experiment is very good for both cases and improves the results found with the different flow rate in [8], supporting the assumption that the previous flow rate was delayed with respect to rotational speed.

Figure 2 shows the evolution of head over time. At the beginning of the transient, the head difference between measurement and simulation is comparable for both guide vane openings. The largest deviations are found in pump brake mode, where CFD for the smaller angle severely overestimates the head rise after the reversal of flow direction. For y5, the deviation in the four quadrant plot translates to a significant difference in simulated head in pump brake and generating mode of approximately 20% of reference head between 3 s and 5 s. For the larger angle, a similar deviation appears at 5 s, but with lower amplitude.

![Figure 1](image1.png)

**Figure 1.** Comparison of simulation and measurement in a four quadrant plot.

![Figure 2](image2.png)

**Figure 2.** Simulated vs. measured head over time.

4. Results in the guide vane channels

Figure 3 shows the comparison of the pressure signals between simulation and experiment for both opening angles together with a moving average with a sample length of 0.01 s. Over large parts of the transient, simulation accurately captures both mean values and amplitudes of the fluctuations between
the guide vanes. The deviation in head for y5 in pump brake mode is reflected in the signal, as well as the differences at the beginning and the end. For the larger angle, amplitudes in measurement are significantly higher than in simulation at the start of generating mode. Compared to flow rate used in previous work [8], agreement is improved until 7.1 s, where the difference between simulation and experiment increases.

Generally, the amplitudes of the pressure fluctuations are visibly larger for the smaller angle than for the larger in pump brake mode. In generating mode, they quickly fade out and reach a level that is below the one for y25. This is correctly captured by simulation. Via FFT, the dominating frequency can clearly be identified to be the blade passing frequency. In pump brake mode, additional frequencies are found for both cases, but they randomly appear and disappear over time.

Higher fluctuations in pressure translate to higher fluctuations in guide vane torque, especially in pump brake mode and at the beginning of generating mode. Additionally, the general level of guide vane torque increases for a smaller opening angle.

In previous work, rotating stall was identified at the end of pump mode for y25. This is not found in the guide vanes for the small guide vane angle, where only a short channel exists between adjacent guide vanes. However, a non-uniform velocity distribution between the channels as well as over the channel height is found in both cases. Near the end of pump mode at 2.6 s and with y5, all channels experience backflow or zero flow near the hub and the shroud, while flow direction in the middle of the channels is outward. This is consistent with the behaviour for the larger angle shortly before flow rate reverses.

At 4 s, time of high deviation from measured head for y5, flow is found to be stable from the stay vanes up to the guide vane channels. In the vaneless space between runner and guide vanes, only small vortices exist near the top and bottom of the twin cascade, while flow in the middle of the channel is stable.

Figure 3. Pressure between the guide vanes for both opening angles.

5. Results in the runner
In the runner, two pressure sensors are positioned near the turbine leading edge of the blades, one on suction side and one on pressure side. The corresponding signals over time are presented in figures 4 and 5. Like the signal from the guide vane sensors, the pressure side signal reflects the findings from the head curve, i.e. the values are overestimated in pump mode, underestimated in generating mode and show the peak in pump brake mode at 4 s for y5.

Results on suction side are in good agreement with measured data. For the larger opening angle, high amplitude fluctuations appear between 3.5 s and 8.5 s which are not reproduced in simulation. For a smaller guide vane opening, fluctuations are reduced, but simulated amplitudes are still slightly lower than measured ones.
Although fluctuations at the pressure sensors are comparable for both openings, a smaller guide vane opening causes large fluctuations in the torque contributions of each runner blade during pump mode, especially at the beginning. Vortices are found in the runner channels close to the suction side at approximately 50% of chord length at \( t = 1 \) s, the start of the transient, where flow is stable for a larger guide vane opening. Vortices appear and disappear without systematically rotating through the runner channels.

Apart from the single monitor points where a comparison with measurement is possible, simulated pressure on the runner blades is evaluated along a line on pressure side at 50% span and analysed over time. Overall maximum and minimum values for \( y_5 \) are found at 4 s, the time of maximum deviation in head between simulation and measurement. This leads to a steep pressure gradient from 25% to 45% of chord length for this operating point.

For \( y_{25} \), maxima and minima are less pronounced and the maximum is flatter. The difference in head and pressure on the pressure side for \( y_{25} \) around 4.8 s also coincides with the highest maximum pressure and pressure gradient over time for this configuration. This leads to the conclusion that simulation overestimates the pressure maxima and pressure gradient in the runner under certain flow regimes and maximum deviation from experiment coincides with maximum pressure and maximum pressure gradient on the pressure side of the blades.

For the larger angle, stable flow establishes after the end of the transient. However, simulation overestimates measurement. For \( y_5 \), simulation predicts fluctuations on pressure side even after the end of the transient, caused by vortices in the runner channels. Although the flow is more complex, a better agreement with measurement is obtained.

**Figure 4.** Pressure on the leading edge for \( y_5 \) on pressure side (top) and suction side (bottom).

**Figure 5.** Pressure on the leading edge for \( y_{25} \) on pressure side (top) and suction side (bottom).
6. Results in the draft tube
In pump mode, stable upwards flow establishes in the draft tube under the runner for y25. For y5, flow rate is too low for stable flow, so that flow is detached from the walls with downward flow close to the walls and upward in the middle. The fluid rotates with the runner direction in pump mode and dissipation mode and reverses the direction of rotation at 8 s. At this point of time, the upwards flow shortly collapses and axial flow direction is downward in the complete cross section. As the fluid resumes its rotation, the upwards flow in the middle of the draft tube is re-established.

The detached flow at the beginning of the transition leads to larger fluctuations in the pressure signal. However, the fluctuations seen between 4 s and 8 s for y25 are significantly reduced in both measurement and simulation. With the corrected flow rate, simulation is still not capable of resolving the low frequency fluctuations from the vortex rope seen in measurement for the larger angle; however, some improvement is achieved.

7. Conclusion and outlook
A comparison of a fast transient of a reversible pump turbine from pump mode to generating mode with two different guide vane angles shows how the angle affects pressure fluctuations and flow phenomena in the machine. By taking the additional time to close the guide vanes before the transient, fluctuations in the draft tube are significantly reduced. A small reduction is also visible on the suction side of the runner blades. On the other hand, a smaller guide vane angle increases fluctuations in the guide vanes, especially in pump brake mode. This causes a higher torque on the guide vanes.

Generally, CFD shows a good agreement with measurement for both cases. Differences appear in pump brake mode, where high maximum pressure values and gradients are found on the pressure side of the runner blades. Compared to previous results for y25 obtained with a time shifted flow rate, the current work shows a better agreement. From a CFD point of view, the time shift used in the current work is thus more probable than the older value.

Future work will investigate a coupling of CFD with a 1D method to simulate the complete test rig. This allows deriving flow rate independently of measurement.

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