Analysis of pressure pulsations during the fast transition of a pump turbine from pumping to generating mode

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Abstract. Variable speed motor-generators based on full size converter offer new options for operation of reversible pump-turbines. To explore the challenges related with this new technology a specific test rig configuration is developed to perform such transition with a PT reduced scale model. Transition from pump to turbine and vice versa are performed with various guide vanes opening and transition time. In order to validate the predictive capabilities of state-of-the-art CFD methods to predict the flow field under fast transition through off design operating conditions, pressure pulsations are measured as well in the rotating as in the stationary frame. Since some phenomena are likely to occur only for short periods of time, wavelet transformation methods are used to compare the pressure pulsations occurring during the transitions for different times of transition ranging from 20s to 4s.

1. Introduction
Variable speed motor-generators based on full converter solutions offer new options for operation of reversible pump-turbines (PT) [1], including fast transition from pump to turbine mode, where the pump is operating in pump-brake mode for a while. To explore the challenges related with this new technology a specific test rig configuration is developed to perform such transition with a PT reduced scale model. Transition from pump to turbine and vice versa are performed with various guide vanes opening and transition times ranging from 4s to 20s. Dynamic pressure sensors have been installed to capture transient flow phenomena and various mechanical components have been instrumented to evaluate their loadings. Amongst the available measurements, pressure fluctuation measurements represent the most direct means of validation for Computational Fluid Dynamics (CFD) simulations of such transitions. Furthermore, the hydraulic phenomena occurring during the fast transition through the pump brake quadrant of the 4-Quadrant characteristic are the main source of dynamic loads on the machine components and direct pressure measurements constitute the first step in understanding the characteristics of the loads before its consequences on the structure are further investigated.

2. Experimental setup
The overall setup of the test is obtained by modifications on an universal test rig at ANDRITZ Hydro Hydraulic Laboratory in Linz, which was initially designed for testing hydraulic machinery in steady conditions in all four quadrants. This setup is allowing for a direct transition from pumping to generating mode and vice versa while maintaining a head which is comparable to what would be expected on a prototype implementation as described in [2] The setup and its validation by 1-D simulations is described in more detail in [3]. Challenges in implementation encountered are the time-accurate measurement of flow rate, where finally a correction based on numerous pressure measurements available had to be considered for
further data analysis, as well as the implementation of the variable rotation rate in the digital control system which is initially aimed at constant condition operation. Finally the implemented control parameters induced strong torque fluctuations in the shaft line, that are clearly visible in the overall representation of a typical transition manoeuvre in Figure 1.

Figure 1. Transition from pumping to generating mode as measured and simulated. Left: Time history of Head, Discharge Torque and rotation rate for a transition forth and back, right: Transition from pumping to generating mode in the dimensionless 4-quadrant representation.

The instrumentation considered in this paper consists of:

- Five miniature piezoresistive pressure sensors located on the runner as shown in Figure 2, sensors 16, 19 failed early, sensor 20 also before completing measurements
- Four piezoresistive pressure sensors located between the guide vanes as shown in Figure 3 (left)
- Four quartz crystal pressure sensors in the draft tube cone as shown in Figure 3 (right)

Figure 2. Position of the dynamic pressure sensors on the pump turbine runner

Figure 3. Position of the dynamic pressure sensors in the head cover (left) and draft tube (right), spiral case flange to the upper left, draft tube to the right

The data of all channels in rotating and stationary part are recorded simultaneously and stored with a raw sampling frequency of 5kHz respectively 1kHz for the rotating frame.

3. Results
In the following, the measurements obtained from transitions at constant guide vane opening of 15° and under 12 m Head are presented. A slow transition (20s), which is relatively close to quasi steady, the transitions which have been shown to be corresponding to what could be feasible at prototype scale with respect to the waterways (8s) and a very fast transition (4s) are compared.
Figure 4. Pressure in stationary components for different transitions from pump to turbine and vice versa. Top: 4s, Middle: 8s, Bottom: 20s, left: Between guide vanes pm06, right: Draft tube, pm 05

Figure 4 displays the time history of pressure in stationary parts and shows that, although qualitatively similar there is a clear difference in pressure fluctuation occurring during a fast transition versus a slower one, and not only by difference in the number of cycles the structure is undergoing. In the fastest transition, it seems that the nonuniformities in the flow do not build up as intensely than in the slower and quasi-steady case.

Figure 5. Pressure on runner blades for different transitions from pump to turbine and vice versa. Top: 4s, Middle: 8s, Bottom: 20s, left: pm17 pressure side, right: pm 18 suction side

Figure 5 displays that pressure fluctuations on the runner leading edge display a similar behaviour showing that remaining in the off design conditions by an extremely slow transition induces more cycles and even of higher amplitude than a faster transition.
4. Wavelet Analysis of pressure fluctuations

For time signals with quickly varying frequency content, the proven tools for frequency analysis such as simple Fourier transforms and even short time Fourier transforms lack flexibility in tuning of frequency versus time resolution. Wavelet transforms give more flexibility, but are still lacking a common best practice in the use of various mother wavelet functions and interpretation. The following figures have been obtained using a Morlet 5 continuous wavelet transform with the aforementioned time series data. Figure 6 is showing that the pressure recorded between the guide vanes (pm06) is dominated by the interaction with the runner when the unit operates in pump brake conditions, the linear slopes of the runner revolution rate as imposed is outstanding all other phenomena. The impression from timeseries that the interaction is more intense in slower transition scenarios than in faster ones is confirmed by the obtained convolution. The draft tube pressure fluctuations represented on the right show only slight differences, as could be interpreted in the time series already.

![Figure 6. Morlet Continuous wavelet transform of pressure during mode transitions](image)

Figure 6. Morlet Continuous wavelet transform of pressure during mode transitions
Top: 4s, Middle: 8s, Bottom: 20s, left: Between guide vanes pm06, right: Draft tube, pm 05

Figure 7 displays the pressure fluctuations on the runner periphery, consistently with the results obtained between the guide vanes, excitations with frequencies evolving with the runner rotation rate are seen. In the acceleration towards pump mode (last part of the sequence) high contribution from higher frequencies are seen. The used Morlet 5 wavelet (and wavelet methods in general) resembles a strongly windowed sine of only 5 periods so its frequency resolution is rather poor. Using a variable type of wavelet for different frequencies could improve this situation, and reaching a good resolution of low frequency phenomena presenting only very few periods and higher frequency excitations often showing a more consistent periodicity over a significant duration.
Figure 7. Morlet Continuous wavelet transform of pressure during mode transitions. 
Top: 4s, Middle: 8s, Bottom: 20s, left: pm17 pressure side, right: pm 18 suction side

5. Conclusion and outlook

The measurements of pressure fluctuations during fast transition and their simple display as timeseries as well as their wavelet transformed representation show that the intensity of the pressure fluctuation in the hydraulic unit does not increase with the speed of the manoeuver and that there is even a trend to lower pressure fluctuations the faster the manoeuver is executed. The presented measurements were made at constant guide vane opening for sake of simplicity of the first of its kind measurement in reduced model scale. Including a variation of a guide vane control sequence into such kind of transition adds a consequent number of additional degrees of freedom but from the difference in pressure fluctuations that are seen between fast and slow transitions, it seems conceivable that optimum sequences can be found that are allowing for fast transition while reducing the dynamic load on the components and providing fast response time and also inertia response to the grid. Numerical simulations of the transition manoeuvres represent a challenge in terms of computational resources and analysis, first implementations, results and interpretations were presented shortly after the measurements [4]. Given the non-stationary character of the results, further detailed analysis will be needed to fully assess the capabilities and shortcomings of numerical methods to predict flow under quickly varying off-design conditions.

6. References

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Acknowledgments
The research leading to the results published in this paper is part of the HYPERBOLE research project, granted by the European Commission (ERC/FP7-ENERGY2013-1-Grant 608532). The author would like to thank the colleagues in Linz for performing the test rig measurement.