Hydrodynamics of a Pump-Turbine under Off-Design Operating Conditions in Generating Mode

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Abstract. The experimental investigation of the hydrodynamics of a reversible pump-turbine reduced scale model in off-design operating conditions is presented. The onset and development of flow instabilities outside the "normal" operating range, in generating mode, involving runaway and "S-shape", are described. Wall pressure measurements, in the stator, are performed with the help of miniature piezoresistive sensors synchronized with high speed flow visualizations in the vaneless gap between the impeller and the guide vanes by air bubbles injection. The detailed analysis reveals that a rotating stall arises at runaway and increases in amplitude while the discharge is decreasing, reaching its maximum value near zero discharge. The pump-turbine experiences in the vaneless gap between the impeller and the guide vanes one rotating stall cell at sub-synchronous speed.

Keywords: Off-design, Pump-turbine, Generating mode, Hydrodynamics, Instability, Experimental investigation
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INTRODUCTION

Pump-turbine technology is widely seen as having great potential in storing large amounts of electrical energy. It is also an enabling technology, and gives a way in which to control the European power grid with respect to the development of new renewable modes of energy production. Not only are pumped-storage power plants a key element in efforts to develop renewable, CO2-free primary energy sources, but they also hold great promise in terms of improving the security of national electricity supplies. With concern widespread over the sustainability of current methods of energy production, as well as the monopoly some countries hold on supply, the development of renewable methods is a real priority. Turbine technology plays a crucial role in electrical power production and

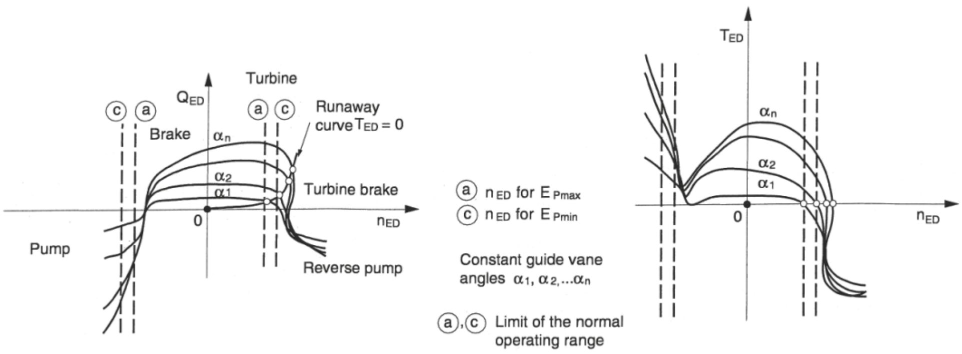

FIGURE 1. Example of four quadrants operation of a radial-type pump-turbine, Ref. [1].

storage. Wind and solar energy, and other renewable sources, generate energy on quite an irregular basis, and when storing that energy certain aspects need to be controlled, largely because of the random nature of both the supply and the demand. The grid authority is requiring maintaining the electricity network at a stable frequency, a function which can be performed by reversible pump-turbines. However, for this function, a rapid switching between the pumping and generating modes is required, and then technical challenges need to be taken. In particular, during the start-up procedure, the synchronization process of the machine requests to be at runaway operation, no-load condition, at constant frequency in safety conditions. Depending on the specific speed of the pump-turbine, the discharge-speed as well as torque-speed characteristics at constant guide vane opening can be “S-shaped”, see FIGURE 1. Therefore, a strong instability of the machine at these points represents sometimes an obstacle in the synchronization success. Moreover, unwished phenomena as structural vibrations, noises and cavitation occur at off-design conditions. These instabilities were studied in Refs. [2] - [7]. Technical solutions to render the machine stable in off-design conditions are presented in Refs. [8] - [11].

DISCOVERY EXPERIMENTS

The case study is a reduced scale of a radial pump-turbine from the HYDRODYNA project, see FIGURE 2(a), installed in the EPFL PF3 test rig. It is a low specific speed machine with 9 impeller blades and 20 guide vanes. Off-design conditions, involving runaway and “S-shape” turbine brake curve, are investigated. Starting from nominal operation at fixed guide vane opening, 5° and 10°, the rotation speed is gradually increased until the point corresponding to a zero torque value, i.e. the runaway conditions. At this point, the operation becomes unstable and the machine may switch back and forth from generating to reverse pumping modes. A specific procedure, commonly used in model testing of pump turbines, Dörfler [10], is followed to stabilize the machine operation by forcing the flow through a restriction, bypassing the upstream butterfly valve once the runaway condition is reached. Wall pressure measurements are performed with 30 piezoresistive pressure sensors flush mounted at the walls of the spiral casing, stay and guide vane channels as well as of the draft tube, see FIGURE 2(b). The pressure measurements are synchronized with the high speed flow visualizations of air micro-bubbles motion in the vaneless gap between the impeller and the guide vanes, see FIGURE 2(c).

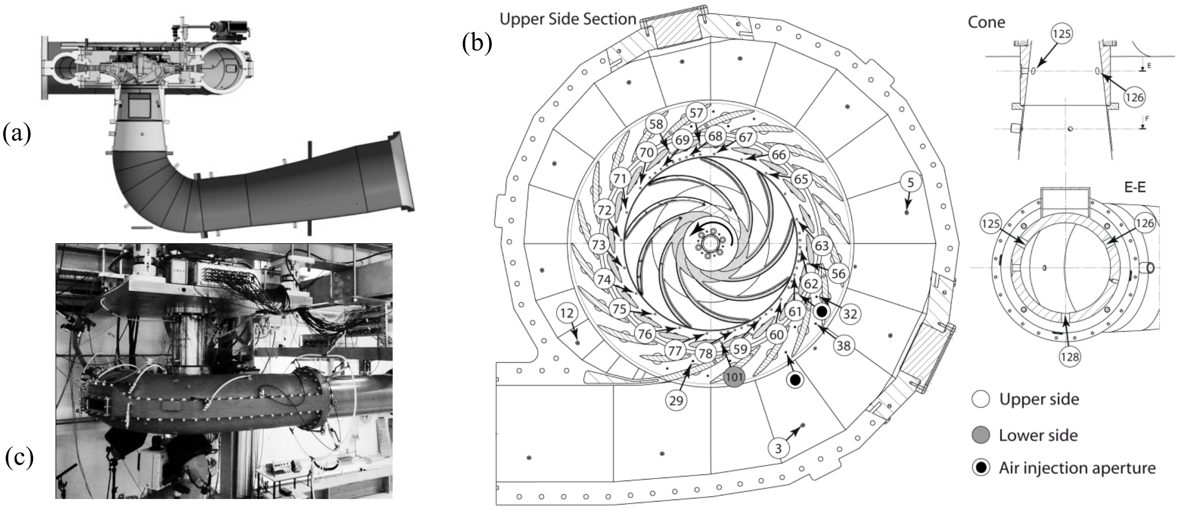

FIGURE 2. (a) Pump-turbine reduced scale model; (b) Pressure sensors location on the model, 10° guide vanes opening; (c) Pressure measurements and high speed flow visualization experimental setup.

RESULTS

The speed, discharge and torque factors are defined respectively by Eq.(1) - (3). The discharge – speed and torque – speed turbine characteristics (FIGURE 3(a), (b)) for 10° guide vane opening exhibits a positive slope after the runaway speed, OP. #3. When a pump-turbine prototype is operated in such a condition, the operation suddenly switches to reverse pumping mode. The discharge as well as torque and power are reversed with a substantial increase of structural vibrations driven by flow instabilities.

$n_{ED} = \frac{nD}{\sqrt{E}}$ - speed factor (1) $\qquad Q_{ED} = \frac{Q_1}{D^2\sqrt{E}}$ - discharge factor (2) $\qquad T_{ED} = \frac{T_m}{\rho D^3 E}$ - torque factor (3)

In our case, the use of the stabilizing procedure prevents such unstable operation and let us exploring the positive slope part of the characteristic curve. Once is in reverse pumping quadrant, an increase of the rotation speed, OP. #6, leads to important cavitation development on the impeller blades as illustrated by the photograph. For this operating point, a large fluctuation of the guide vane opening and discharge is also observed.

To provide a global view of the flow unsteadiness at 5° and 10° guide vane openings, we have superposed on the n_{ED}-Q_{ED} characteristic curves, the standard deviation of the pressure fluctuation in the guide vanes, see FIGURE 3(c); the diameter of the circles being proportional to the standard deviation of the pressure fluctuation. It can be observed that the pressure fluctuation in the guide vane channels, close to rotor/stator interface are increased for low rotation speed, around the "S-shape" and in reverse pumping mode. At these conditions, a substantial increase of the structural vibration is observed. It should be noticed that in the particular case of guide vanes, the maximum pressure fluctuation is at least 25 times larger than in normal operating conditions.

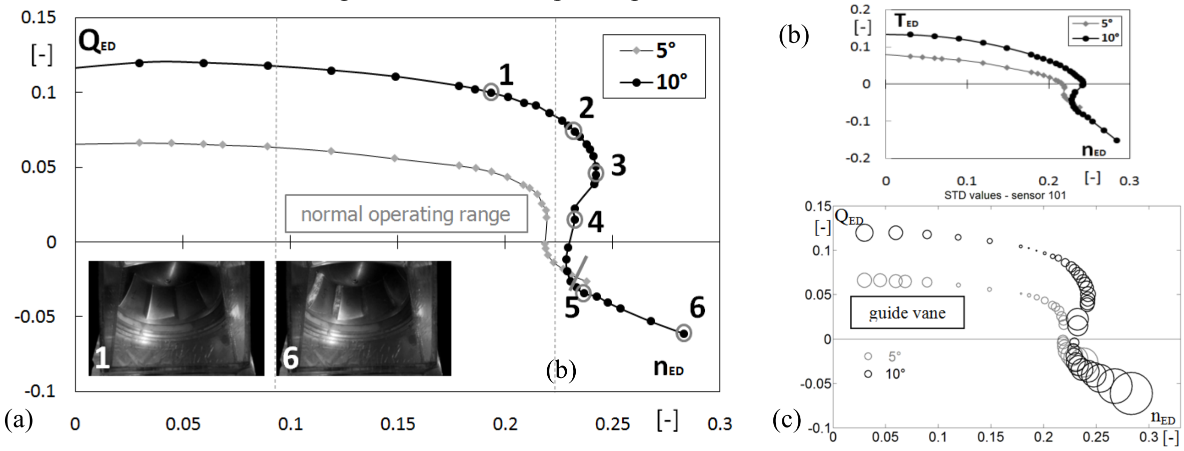

FIGURE 3. (a), (b) Resulting "S-curves" in generating mode; (c) Pressure fluctuations STD in the guide vanes region.

The spectral analysis of the pressure fluctuation time signals in the guide vane channels evidences the blade passing frequency and its first harmonic with lower amplitude, $f = 9 \cdot f_n$ and $f = 18 \cdot f_n$, except at low discharge operating point. However, a low frequency component, ~70% of the impeller rotational frequency, arises at runaway, OP. #3, which further increases in amplitude as we approach the zero discharge condition, OP. #4. At this point it even represents the dominant frequency and is found to modulate the blade passing frequency, see FIGURE 4(a). The low frequency component is also visible in the spiral casing, where it becomes dominant in turbine brake mode, OP. #3 ÷ OP. #5.

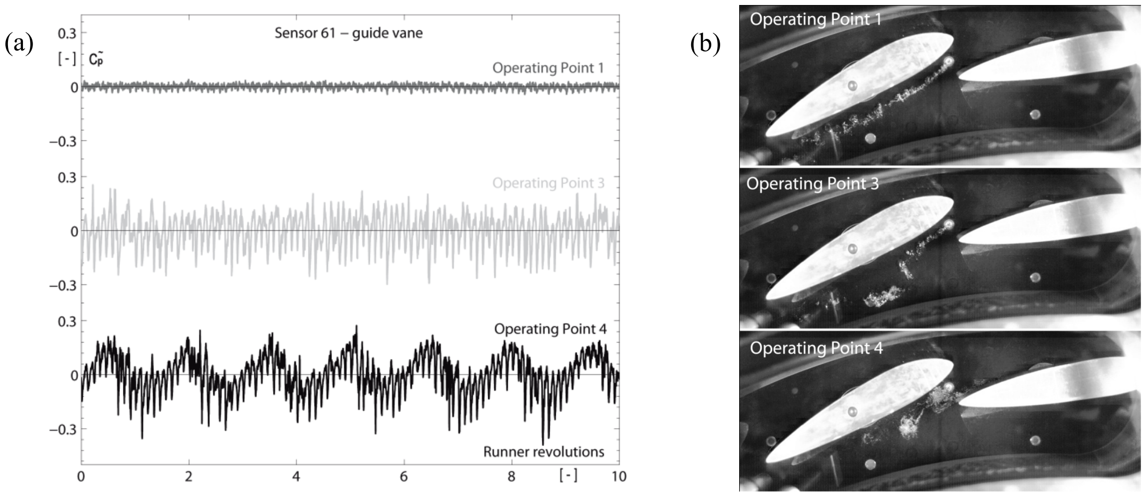

FIGURE 4. Pressure fluctuations (a) and flow visualization (b) in the vaneless gap.

Surprisingly, at zero discharge condition, the pressure fluctuations at this very unstable operating point are not random but exhibit a remarkable periodicity. Their amplitude is 10 times higher than at nominal conditions. The phase analysis, derived from cross correlation between the signals in the vaneless gap, indicates that one instability source, stall cell, rotates with the impeller at sub-synchronous frequency. Vesely et al. [12] tested a medium head pump-turbine model and also found that a rotating stall with a frequency of propagation about 60% of the impeller speed arises at brake and reverse pumping conditions having only one stall cell. In FIGURE 4(b), the flow visualization in the vaneless gap shows a quite uniform flow pattern at the normal operating range, OP. #1, whereas at runaway, OP. #3, the flow is disturbed by the rotating stall passage. The situation is even more critical near zero discharge, OP. #4, where backflow and vortices in the guide vane channels accompany the stall passage. Staubli et al. [13], concluded that local vortices formed at the inlet of the impeller channels represents the source of the unsteady in- and outflow from the impeller in the vaneless gap between the impeller and the guide vanes.

CONCLUSIONS

The present work is focused on the investigation of a centrifugal pump-turbine at reduced scale under off-design operating conditions. The experiment, carried out in the EPFL PF3 test rig, involves wall pressure measurements in the stator with the help of miniature sensors synchronized with high speed flow visualizations in the vaneless gap between the impeller and the guide vanes by air bubbles injection. The onset and development of flow instabilities outside the normal operating range, in generating mode, involving runaway and "S-shape", are described. Starting from the best efficiency point, the impeller speed is gradually increased until the flow is totally reversed. The detailed analysis reveals that a rotating stall arises at runaway and increases in amplitude with the discharge decreasing, reaching its maximum value near zero discharge. Containing one stall cell, the instability rotates with the impeller at sub-synchronous speed in the vaneless gap between the impeller and the guide vanes. It is the effect of rotating flow separations developed in several consecutive impeller channels which lead to their blockage.

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NOMENCLATURE

n_{ED}	[-]	speed factor	T_m	[N m]	mechanical torque
Q_{ED}	[-]	discharge factor	ρ	[kg m^-3]	water density
T_{ED}	[-]	torque factor	f	[Hz]	frequency
n	[rot s^-1]	impeller speed	f_n	[Hz]	impeller frequency
D	[m]	impeller outlet diameter	p	[Pa]	wall pressure
E	[J kg^-1]	specific energy	$\bar{p}$	[Pa]	time average wall pressure
Q_I	[m^3 s^-1]	discharge	$\tilde{c}_p$	[-]	pressure coefficient fluctuation

REFERENCES

1. International Standard, "IEC 60193 Second Edition 1999 – 11", 1999
2. Pejovic, S., Krsmanovic, L., Jemcov, R. and Crnkovic, P., "Unstable Operation of High-Head Reversible Pump-Turbines" in *Proceedings of the 8th IAHR Symposium on Hydraulic Machinery and Cavitation*, Leningrad, 1976, pp. 283-295.
3. Tanaka, H. and Tsunoda, S., "The Development of High Head Single Stage Pump-Turbines" in *Proceedings of the 10th IAHR Symposium on Hydraulic Machinery and Cavitation*, Tokyo, 1980, pp. 429-440.
4. Oishi, A. and Yokoyama, T., "Development of High-Head Single- and Double-Stage Reversible Pump-Turbines" in *Proceedings of the 10th IAHR Symposium on Hydraulic Machinery and Cavitation*, Tokyo, 1980, pp. 441-452.
5. Martin, C. S., "Stability of Pump-Turbines during Transient Operation" in *The 5th International Conference on Pressure Surges*, Hannover, Germany, September 22-24, 1986.
6. Martin, C. S., "Instability of Pump-Turbines with Shaped Characteristics" in *Proceedings of the 20th IAHR Symposium on Hydraulic Machinery and Systems*, Charlotte, USA, 2000.
7. Nicolet, C., "Hydroacoustic Modeling and Numerical Simulation of Unsteady Operation of Hydroelectric Systems", Ph.D Thesis No. 3751, EPFL, Lausanne, Switzerland, 2007.
8. Huvet, P., "Steady Oscillatory Conditions between Pump-Turbine Operating at Partial Flow and Surge Shaft" in *Proceedings of the 16th IAHR Symposium on Hydraulic Machinery and Systems*, Sao Paulo, Brazil, September 14-19, 1992.
9. Billdal, J. T. and Wedmark, A., "Recent Experiences with Single-Stage Reversible Pump Turbines in GE Energy's Hydro Business" in *Hydro 2007*, Granada, October 15-17, 2007, Paper No. 10.3.
10. Dörfler, P. K., "Stable Operation Achieved on a Single-Stage Reversible Pump-Turbine Showing Instability at No-load" in *Proceedings of the 19th IAHR Symposium on Hydraulic Machinery and Systems*, Singapore, September 9-11, 1998.
11. Kuwabara, T., Katayama, K., Nakagawa, H. and Hagiwara, H., "Improvements of Transient Performance of Pump Turbine upon Load Rejection" in *Power Engineering Society Summer Meeting*, Seattle, WA, USA, 2000, Vol. 3, pp. 1783-1788.
12. Vesely, J., Pulpitel, L. and Troubil, P., "Model Research of Rotating Stall on Pump-Turbines" in *Hydro 2006*, Porto Carras, Greece, September 25-28, 2006, Paper No. 3.5.
13. Staubli, T., Senn, F. and Sallaberger, M., "Instability of Pump-Turbines During Start-up in the Turbine Mode" in *Hydro 2008*, Ljubljana, Slovenia, October 6-8, 2008, Paper No. 9.6.