Experimental investigation of the turbine instability of a pump-turbine during synchronization

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Abstract. Although the technology of pump-turbines is generally well known the operation is still affected by flow phenomena that are quite complex and not fully understood. One of these phenomena is the S-shape instability which occurs in turbine mode at low load operation, close to runaway conditions. The instability results in an S-shape of the turbine characteristics and complicates the synchronization of the machine. Numerical investigations performed in the past indicated that the occurrence of turbine instabilities is connected with the appearance of rotor-stator interactions, and backflow regions in the vane less space between guide vane and impeller. This paper presents the results and conclusions of experimental investigations of pump-turbine instabilities carried out to find a practical explanation for the flow phenomena responsible for the appearance of the S-shaped characteristics. In the scope of a joint research project with Andritz Hydro, the Institute for Hydraulic Fluidmachinery at Graz University of Technology optimized an existing 4-quadrant test rig for an experimental investigation at off design conditions featuring the possibility for adjusting stable operation of instabilities. All the experimental investigations were based on IEC60193-standard using a pump turbine model provided by Andritz Hydro AG. In addition to the standard measurements of flow rate, head and efficiency the interaction between model and its hydraulic environment were analysed by dynamic pressure sensors. Additional pressure sensors integrated in the guide vane apparatus were used to investigate pressure distributions in the model. Particle Image Velocimetry (PIV) allowed the measurement of the velocity field in the vane less space between impeller and guide vanes and in the environment of two single guide vanes. The experimental investigations were focused on operation points in the S-shape region of the characteristics. For each operation point 190 double images for 20 rotor-stator positions were taken which allowed an analysis of a complete blade channel. The combination of PIV and pressure measurements in the model enabled a structured experimental analysis of the flow phenomena at low load off-design operation and allowed an improved understanding of the physical background of the occurrence of the instability in turbine mode.

1. Introduction

The nuclear phase out in the middle of Europe increases the gain of energy from the renewable sources such as solar and wind power plants. Due to this fact the electrical grid needs an improved regulation of its energy balance which leads to significant challenges in the production and the storage of electrical energy. Nowadays, the only commercial possibility to handle this situation in an efficient way is given by pump storage power plants. Reversible pump turbines offer the opportunity of fast
start-up times and fast switching between pumping and generating mode and therefore have substantial advantages in case of reacting on the demand of the electrical grid within a short period of time. Therefore the machines are operated in off-design conditions, like runaway more often. The start-up procedure of reversible pump turbines is affected with the occurrence of stability problems. In this case the characteristics at constant guide vane opening are S-shaped in the region of no load condition and the process of synchronization may become complicated. As a consequence thereof expensive modifications have to be done or limitations of the operating range have to be set.

Numerical flow simulations of the S-shaped region of the characteristics predicted the emergence of a vortex formation. This vortex formation spreads against the usual flow direction in turbine mode and against the pressure gradient. An associated recirculation at the inlet area of the runner gives a possibility to explain the physics of the flow field in the unstable operation range.

In the last decade a few publications described the S-shaped characteristics. The present publication can be separated into different aspects of the instability. The first aspect is the startup condition of a pump turbine with a very small guide vane opening of 6° to 8°. A further aspect is the dynamic behavior and the system interaction with the penstock system. By operating several guide vanes independently from the rest of the guide vane apparatus, the synchronization procedure can be stabilized (Klemm et al. [2], Billdal and Wedmark [3]). An alternative way to significantly improve the hydraulic stability is the throttling an inlet valve and thereby increasing the head loss, which was proposed by Dörfler et al. [4]. Some papers discuss the comparison between the S-shaped characteristic and the rotating stall phenomena, which is necessary for the dynamic prediction of runaway in case of rolling blackout. Widmer et al. [5] attempts to detect first coherences between the vortex formations in the vane less space between rotor and guide vane and the S-shaped characteristics. In 2008 the first validation of CFD simulations of a pump turbine was done by Staubli et al. [6], with the goal of the numerical prediction and analyzing of the S-shaped characteristics during start-up conditions.

Another aspect of the stability is the interaction of the leading edge and the main flow, which has been the topic of the work published by Grunde Olimstad et al. [7]. The paper shows that a minimal adaption of the leading edge of the runner has a high influence on the stable operation of the runner.

2. Experimental set-up and investigated pump turbine model

The reversible pump turbine model was provided by Andritz Hydro AG and installed in the closed circuit 4-quadrant test rig at Graz University of Technology. The speed-regulated model, consisting of a runner with 9 blades and a guide vane apparatus with 20 guide vanes, was equipped with a 200 kW motor/generator (Figure 1 (a)). The experimental set up and the measurement instruments were based on the IEC60193-standard [1] providing an measurement accuracy of 0,2%. Miniature pressure transducers were flush mounted in the region of the guide vanes at different circumferential angle and radius. The measurement range extends from zero to 500 kPa with a linearity lower than 0,5% FS. Additionally, piezo-resistive pressure transmitters were positioned in the piping system surrounding the model to separate the influence of the test rig and the feed pump. Signal recording was done at a sample rate of 10 kHz with a measurement time of 25 seconds. The combination of the absolute pressure sensors located all over the pump turbine model allowed the performing of an equilibration of the pressure distributions over the particular components of the pump turbine model (Figure 1 (b)).

The characteristics were investigated in the full range from overload to deep part load and finally to zero discharge at different guide vane openings. Between the guide vane openings of 5° to 15° the operation of the pump turbine model became unstable in the region of the runaway curve. It suddenly switched to reverse pumping mode by passing the turbine brake mode in a completely autonomous way. In the reverse pumping quadrant the operation stabilized without changing any control. By shutting a plunger valve located in the upstream to an almost closed position a stable machine operation was achieved even in the S-Shape region of the $K_{cm}$-$K_u$-characteristics. The stabilization is caused by an additional resistance in the hydraulic system.
3. Implementation of PIV-method and test execution

As initially mentioned the numerical flow simulations predicted the occurrence of a backflow region at the inlet area of the runner. Therefore two dimensional ensemble averaged Particle Image Velocimetry (PIV) was used to visualize the velocity field in the vane less space between impeller and guide vanes. To implement this optical measurement method an appropriate design of the parts enclosing the pump turbine runner was necessary, without changing the geometry and taking care of the IEC60193-standard [1]. To gain a radially oriented optical access to the requested area of the machine the original spiral casing was substituted by a new one made of a milled two-piece Aluminium-casing which was equipped with an optical access made of acrylic glass (PMMA). Furthermore two guide vane-bodies retaining the hydraulic shape were also made of acrylic glass. For an axial view into the area between the guide vanes and the runner an additional window was integrated into the support ring of the guide vanes. The modifications of the pump turbine model finally provided access for the measurement of velocity fields in one radial and three axial normal planes (Figure 2 (a)). While the axial optical access allows the observation of the velocity field in a plane normal to the rotation axis of the rotor (at 25%, 50% and 75% channel height), the radial optical access allows the observation of the velocity field in a plane tangential to the outer diameter of the rotor (D=0.35 m).

Figure 1 (a) Pump turbine model; (b) Experimental setup for pressure measurements

Figure 2 (a) Measurement planes; (b) PIV setup for visualisation
Figure 2 (b) shows a view into the safety-related housing from the pressure side of the model. The figure visualizes the placement of the PIV-laser, the light guide arm and the cylinder lens creating a thin laser light section (thickness was around 1 mm) for the illumination of tracer particles carried with the fluid flow. The new螺旋 casing containing the original parts of the pump turbine model appears in black colour due to its black anodic coating, which avoids any distracting reflections of the laser beam within the spiral casing. At the top of the spiral casing a traversing unit and the camera is located.

The specifications of the used PIV-equipment are:
- Camera: DANTEC 80C60 HiSense, 1280x1024 Pixel @ 12 bit grey scale, double frame sensor
- Laser-System: New Wave Research, Nd:YAG-Laser, pulsed, 15 Hz maximum repetition rate, energy 120 mJ, wavelength 532 nm
- Tracer: Polyamide seeding particles, diameter of 5-50 µm, estimated volume fraction 45 ppm

In order to calibrate the camera system in a way that the real velocity of flow is determined, a calibration target with a grid of points having a defined distance had to be placed exactly there where the laser light sheet was directed into the fluid flow. Figure 3 shows a photograph taken for the radial (a) and axial (b) direction of view for an operation point on the runaway curve. The trailing edge and the pressure side of one single blade of the runner are clearly visible on the left hand side. The picture on the right hand side shows the axial direction of view with two guide vanes made of acrylic glass. Additionally, the pictures show a homogenous distribution of tracer-particles. The dotted lines highlight the laser light planes investigated in course of the measurement program. The blurred and black areas needed to be masked in course of the PIV-evaluation process.

For each operation point investigated with PIV-measurements 190 single velocity fields were created for one rotor- / stator- position. In combination with 21 different rotor- /stator- positions for the investigation of one full blade channel the PIV-measurements at one single operation point results in 190 x 21 = 3990 velocity fields. To verify the periodicity of the velocity fields the first and the last phase position were measured twice. In this way up to five operating points at different guide vane positions were investigated. The whole measurement program included four measurement planes (one radial normal and three axial normal planes; see Figure 3).
4. Results

The operation points chosen for the detailed investigation in turbine mode, the “S-shape” and the turbine brake mode are presented in the $K_{cm}$-$K_u$-characteristics in Figure 4 for constant guide vane openings. Every characteristic curve was measured with a constant head of 10 m. With the help of an automatic pressure control a constant level of absolute pressure has been set. In this way a cavitation free operation was ensured. The runaway curve, which separates the turbine mode from the turbine brake mode, is also indicated in the characteristics. Starting with a guide vane opening of 6° the $K_{cm}$-$K_u$-characteristics exhibits a positive slope after the runaway curve. All the detected areas of unstable behaviour are presented with a dotted line. A stabilisation of the characteristics was necessary to obtain steady state conditions even in the unstable branch of the $K_{cm}$-$K_u$-characteristics. This was a basic aspect to realise ensemble averaged PIV measurements.

\[ K_{cm} = \frac{4Q}{D^2 \pi \sqrt{2gH}} \quad K_u = \frac{\pi \rho D}{\sqrt{2gH}} \]  

(1)

![Figure 4](image.png)

**Figure 4** Operation points investigated in course of the pressure and PIV-measurements

4.1. Pressure measurements

At different guide vane positions an operating point dependent static pressure distribution in the pump turbine model was analysed. The measurement was performed over the entire operating range with the main focus on the S-shape of the characteristics. The differential pressure values were determined between the measurement positions presented in Figure 1 (b) and defined in Table 1.

| Differential Head          | Measurement position |
|---------------------------|----------------------|
| $H_{static-runner}$       | 3 – 4                |
| $H_{static}$              | 1 – 4                |
| $H_{static-guide_vane}$   | 2 – 3                |
| $H_{static}$              | 1 – 4                |
| $H_{static-spiral_casing}$| 1 – 2                |
| $H_{static}$              | 1 – 4                |
The values of differential static head for the single components were normalized with the overall static head \( H_{\text{static}} = \Delta p_{1-4} / (\rho g) \). In this way a comparison of the pressure distribution for the investigated guide vane positions was realised. The behaviour of the normalized static differential head measured at the spiral casing, the guide vanes and the runner are presented in Figure 5. The static head is plotted by a bold line in the diagrams - obviously having the value of “1” by normalizing it with itself. The static differential head of the runner scaled by the machine head is named reaction type and defined in Table 1. \( H_{\text{static-runner}} \) also includes most of the draft tube.

![Figure 5](image)

**Figure 5** Static differential head as function of normalized \( K_u \) at 8° (left) and 15° guide vane opening (right)

The measured differential pressure is presented as a function of \( K_u \) in the diagrams shown above. Statistical convergence was achieved for the presented results. The behavior in the S-shaped area was repeatable. The sum of all of the values of the normalized differential head always amounts to 1. At a guide vane opening of 8° the reaction type increases from 0.58 \( H_{\text{static-runner}} / H_{\text{static}} \) at over-load up to 0.85 \( H_{\text{static-runner}} / H_{\text{static}} \) in the region of the instability (Figure 5 left hand side). Thus, an increased runner speed (higher \( K_u \)) is related to a rising reaction type. Reaching the instability (\( K_u / K_u_{\text{ref}} \approx 1.08 \)) the reaction type steeply increases to “1”. The total static head is decreased in the runner. This can be related to an increased influence of the rotation field which goes along with the increasing reaction type. Minor-inverted to this the normalized differential head measured at the guide vanes decreases. Starting with a value of 0.3 \( H_{\text{static-guide vane}} / H_{\text{static}} \) at \( K_u / K_u_{\text{ref}} = 0.45 \) the differential head becomes negative in reverse pumping mode. The normalized differential static head in the spiral casing nearly remains unchanged over the entire operation range.

In contrast to the guide vane position of 8° the position of 15° shows a different behaviour of the static head. Both, the reaction type as well as the differential head measured at the guide vanes change less than 10 % in a range of 0.45 to 1.19 of \( K_u / K_u_{\text{ref}} \). Reaching \( K_u / K_u_{\text{ref}} = 1.18 \) the reaction type increases to 1 while the normalized differential head measured at the guide vanes is already negative when crossing the runaway curve at \( K_u / K_u_{\text{ref}} = 1.16 \). Additionally, the level of the normalized differential head in the spiral casing is higher than the one of the guide vanes over the entire operating range. The distribution of the static head in the components has changed considerably (see Figure 5 right hand side).

At lower guide vane positions the static differential head measured at the guide vanes gets negative near \( K_{cm} = 0 \) while at larger guide vane openings the normalized differential head already changes its sign near runaway (see Figure 4). The S-shape characteristic of the \( K_{cm} / K_u \)-characteristics is also visible in the static differential pressure behavior of the runner or the guide vanes.

Also dynamic analysis of the pressure signals were made because of the unsteady nature of the instability, but will be presented in a separate paper.
4.2. PIV

For the post processing a tool was created in MATLAB environment which gives the opportunity to visualize the PIV results. The recorded velocity fields were averaged to obtain more valuable results and to separate the stochastically component from the mean value of the flow. The averaging of the measured velocity fields was done for each operating point. The result was a global averaged velocity field consisting of 20 rotor-/stator- positions or rather 3800 single flow fields. According to Gersten and Schlichting [8] the velocity is computed with eq. (2).

\[
\bar{c}(\bar{x}) = \frac{1}{3800} \sum_{i=1}^{20} \sum_{j=1}^{190} c(\bar{x}, t_j)
\]

The velocity contours in Figure 6 present the global averaged PIV-results for five different operation points at a guide vane position of 8° marked also in Figure 4. While the y-axis represents the channel height of the runner, the x-axis refers to the extension of the blade channel in circumferential direction. In order to enable a comparison of PIV-results for different operation points a normalization, defined by eq. (3), was carried out by referring the measured velocity field \(\bar{c}(\bar{x})\) to the circumferential velocity \(u_1\) at the inlet of the runner. The velocity illustrated in following diagrams is the absolute value of the normalized velocity field \(\bar{c}^+\).

\[
|\bar{c}^+| = \frac{|\bar{c}(\bar{x})|}{u_1} = \frac{|\bar{c}(\bar{x})|}{D \cdot n \cdot \pi}
\]

![Figure 6 Globally averaged PIV-results at different operation points](image)

The global averaged velocity contour plot referring to the local best efficiency point looks widely homogenous – especially as far as it concerns the velocity distribution in respect to the height of the blade channel. A completely different distribution of velocities is shown in the S-shaped area of the \(K_m-K_u\)-characteristics. The ratio between measured projection of the absolute velocity and the
circumferential velocity becomes smaller and the velocity distribution appears more inhomogeneous with maximum values that are located in the middle of the pictures. Furthermore, strong pronounced inhomogeneities are shown with the pictures which refer to the turbine-brake-mode of the pump-turbine-model. Compared to the runaway points the mean value of normalized measured velocity shown in the contour plots increased although the measured flow rate significantly decreased.

This finding compares quite well with the pressure measurements. The static pressure in the vane less space between rotor and guide vanes increases with a rising influence of the rotational field. The inhomogeneous velocity distribution may act as flow resistance and can therefore be interpreted as local blockage region. As the presented results refer to two dimensional PIV measurements carried out for a tangential normal plane with a radial direction of view it is not possible to verify whether the inhomogeneous flow distribution indicates recirculation regions or not. This issue is examined with Figure 7 where the results for the axial normal measurement plane for a channel height of 50% are presented by superposing the velocity contours with the radial velocity vectors. The plot represents the results of the turbine brake mode (OP 5) including a detailed view of a section.

![Figure 7](image)

**Figure 7** Superposition of velocity contours with the radial velocity vector component at a guide vane opening of 8° in turbine brake mode – channel height: 50%

Applying a special evaluation technique made it possible to detect recirculation regions for the axial direction of view where the velocity field is mainly dominated by the circumferential velocity. A coordinate transformation consequently enabled a splitting of the circumferential and radial components of each velocity vector. The visualization of the radial velocity components on the three different measurement planes for the axial direction of view enabled the detection and localisation of recirculation and back flow regions, respectively. Additionally it has to be pointed out that the inner boundary of the measurement plane for the axial direction of view is around 10 mm away from the leading edge of the runner. Therefore the recirculations are only visible in an attenuated form. Despite of this problem it was partially possible to detect recirculation regions. At a channel height of 25% and 75% no back flow regions could be detected in this operating point.

To get a global view of the complex flow phenomena and to compare the different operating points with each other the velocity fields had been fit to a three dimensional interactive model (Figure 8). Also the runner and the guide vanes had been placed in the model to get a better understanding of the flow. The results feature a good accordance of the single planes to each other.
5. Conclusion
The results of the PIV experimentally confirm a complex flow field between the rotor and the guide vanes with high velocities in the centre of the channel between two single blades. Beside the normal discharge through the pump turbine model it shows a secondary flow, which is driven by the high speed factor \( K_u/K_{u,\text{ref}} \) and can be interpreted as local blockage region in the rotational system of the rotor. The secondary flow has a centrifugal acceleration which can cause backflow. As a result the discharge of the pump turbine is reduced.

The secondary flow influences the static pressure in all parts of the pump turbine and especially in the vane less space between rotor and guide vanes. In areas where the local centrifugal acceleration is higher than the local pressure gradient a backflow emerges as a consequence of the high centrifugal acceleration. The static pressure in the vane less space between rotor and guide vanes increases with a rising influence of an increasing speed factor. Additionally the S-shape of the characteristic is clearly visible in the normalized static differential head. The global averaged velocity field measured with the PIV gives an insight of the behavior of the flow field in the region of the S-shaped characteristics.

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Nomenclature

\[ \bar{c} \quad \text{Global averaged velocity field [m/s]} \]
\[ \bar{c}^{+} \quad \text{Normalized velocity field [-]} \]
\[ D \quad \text{Runner inlet diameter [m]} \]
\[ H_{\text{static}} \quad \text{Static Head [m]} \]
\[ K_{cm} \quad \text{Discharge factor [-]} \]
\[ K_{u} \quad \text{Speed factor [-]} \]
\[ n \quad \text{Runner speed [1/s]} \]
\[ Q \quad \text{Discharge [m}^3\text{s}^{-1}] \]
\[ p \quad \text{Pressure [Pa]} \]
\[ r_{\text{static}} \quad \text{Reaction type [-]} \]
\[ t_{j} \quad \text{Timestep j [s]} \]
\[ u_{1} \quad \text{Reference circumferential velocity [m/s]} \]
\[ \hat{x} \quad \text{Position vector [m]} \]

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