Velocity Measurements in Kaplan and Propeller Turbines: a review

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Abstract. Complex geometry and flow regimes are present in different sections of hydraulic turbines and most operating conditions. In the past two decades, many pressure measurements have been performed on different sections. Such measurements do not reveal the details of the flow distribution. Velocity measurements are needed to obtain more detailed information. The aim of the present paper is to review the velocity measurements performed in hydraulic turbines, especially axial turbines, and highlight the remaining challenges according to the operating condition.

1. Introduction

Hydraulic turbines are widely used for electricity production. The load variations and operations at off-design are growing because of the introduction of intermittent renewable energies [1]. Such operations lead to instabilities that decrease the turbine’s efficiency and increase the risk of fatigue and resonance in the turbine [2]. Unforeseen pressure pulsations and velocity oscillations are the causes of instability at off-design and during transient operations. Pressure sensors are usually used on the walls of turbine components [3], but instantaneous velocity measurements are less common. Velocity measurements are needed at various operating conditions in different sections of the turbine to analyze the flow stability and the losses [4-14]. Computational Fluid Dynamics (CFD) simulations are also required with such measurements to obtain more details about the turbine performance. They need trustful boundary conditions and validation data, which can only be provided from experiments [15-18].

Kaplan turbines are different from other turbines in terms of design and operational conditions because of double regulation. Therefore, the challenges are different. The initial measurements in Kaplan turbine’s draft tube revealed the difficulties to get accurate results due to blade wakes, turbulence, strong adverse pressure gradient, vortex break down, separation and unsteadiness [19-21]. Besides, although it was shown that the head losses predominantly occur due to turbulent kinetic energy dissipation in the draft tube cone of the turbine [18], the rotor stator interactions and the interblade instabilities are still an important source of turbulence production and instabilities in the turbine [7,14]. Thus, it is important to perform experimental measurements not only in the draft tube, but also in the inlet pipe and the vaneless space of the Kaplan turbine in order to account the combined effect of all instabilities. The aim of this paper is to review the velocity measurements performed on Kaplan and propeller turbines and address the remaining challenges with possible solutions function of the operating conditions. In the present paper, the different velocity measurements performed in different sections of the turbines are stated. This paper covers simple methods such as flow visualization to more advanced methods such as Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV). In the final
section, a discussion is presented to underline the challenges and address the remaining questions that are required to be answered.

2. Performed velocity measurements

2.1. Flow visualization

Flow visualization is a method used to investigate the flow field. The vortices can be visualized with the aid of cavitation [16], air bubbles injection [22] or using tufts on the surfaces [22]. Through optical access with proper lightening and observation, the generation, development, and dissipation of the vortices can be visualized. There are different methods used in hydraulic turbines to provide the lightening and record the observations in different sections such as borescopes, stroboscopic light sources and high-speed filming. In the following, different visualization methods that had been applied to the vaneless space, between the runner blades, and in the draft tube are presented.

2.1.1. Flow visualization in the vaneless space

In a hydraulic turbine, by installing fluorescent monofilament wires, known as a tuft, to the impeller outlet, and to the Guide Vanes (GV), the near wall flow has been visualized, as the tuft follows the flow streamlines. A window on the bottom part of the stator and a transparent conical section of the draft tube provided the optical access to the GV region and propeller outlet, respectively. The installed tufts on the GV section from the bottom view and the superposition of them in low discharge condition are shown in figure 1 (a) and (b), respectively. This method is limited to the flow close to the walls and cannot be applied to the flow far from the wall [22].

In the same turbine, a needle valve was designed on the surface to insert air bubbles to the flow field. Assuming the air bubbles follow the streamlines without any effect on the flow itself, the bubbles were used to visualize the flow streamlines around the GV at different operating conditions. The obtained results at low discharge condition are presented in figure 2. In the presence of a rotating stall, the bubbles were found upstream of the injection point, showing the existence of backflow. Although air injection can give good insight regarding the flow structure, it is not always practical because of two main challenges. First, the level of the pressure inside the turbine depends on the operating condition and the air pressure should be high enough to insert bubbles into the desired region. The second challenge is that a minimum volume of gas should be inserted to the flow field to give optimum visibility [22].

One of the methods to visualize the flow in the turbine sections is to lower the pressure in the test loop, so cavitation occurs at low-pressure areas. By this way, the low pressure of the vortex is visible and the origin of the vortex can be located. This method was used in the vaneless space of a turbine to observe cavitation on the runner. Transparent hollow GV with a borescope inserted in the middle of them was used. The borescope is a combination of light and camera attached together. The sketch of the hollow guide vane and the schematic of the borescope are shown in figure 3 (a) and (b), respectively [23, 24].

In order to improve the measurement quality, the amount of light in the vaneless space was increased with neighboring hollow and transparent GV allowing to deliver more light. In this method, some lines were also sketched on the runner blades surfaces to help the observation of the detected vortices. This method is shown in figure 4 [25].

Figure 1. Applying the tuft visualization (a) the position of the fluorescent wires on the midspan of one GV as well as on the top cover in the adjacent GV channels and the vaneless gap and (b) superposition of tuft visualizations in the GV during 3 impeller revolutions at low discharge condition at 10° GV opening [22]
2.1.2. Flow visualization through the transparent conical section. A transparent cone in the draft tube is the most used optical access to observe the flow inside a turbine. A wide range of flow regions from the runner blade to the flow inside the draft tube can be accessed with a transparent conical diffuser. Also, the inter-blade channel vortices and the vertical structures in the draft tube are important since they have a large impact on the turbine overall performance. In this section, some examples of such measurements are presented.

A stroboscopic light with high-speed filming was used in a Kaplan model turbine to investigate the cavitating tip vortex formation in the runner blades. In this case, the discharge ring was made of plexiglass to provide optical access to the runner blades. They observed that cavitating tip vortices separate from the runner blade and re-attach to it in a place that most of the erosion on the runner blade is reported [24]. In another study, the volume-variation of the RVR was investigated with a single-camera to demonstrate the breathing pattern of the RVR [16]. As measurements with a single camera is biased, another study used two synchronized high-speed cameras with 90° angle apart. The first signs of instability and, cavity volume pulsations as well as cavitation collapse were observed in this study [26]. To give an insight regarding the measurement setup, figure 5 shows one of the single-camera setups, where two light sources illuminate the measurement section.

Figure 2. Instantaneous air bubbles flow visualizations in one GV channel at a low discharge conditions with a 10° GV opening [22]

Figure 3. Setup for flow visualization in the vaneless space, (a) sketch of the hollow guide vane equipped with a transparent acrylic glass window, and (b) general layout of the borescope [23, 24]

Figure 4. GV with windows (a), and grid pattern to support flow observations (b,c) [25]
2.2. Laser Doppler Velocimetry (LDV)

LDV is a non-intrusive measurement technique to determine the velocity on a point over time. LDV can be performed in different sections of the turbine, from the runner inlet to the draft tube outlet. To perform LDV measurements, particles are added to the water and optical access to the measurement sections is necessary. LDV does not need large windows or a special direction to perform the velocity measurements. The drawback of this method is that it gives information only on a specific point during the period of measurement and necessitate a large amount of time to get a comprehensive information in the sections of interest.

This method had been widely used in hydraulic turbines to measure the velocity [4, 5, 27]. In some cases, LDV was used to validate PIV measurement or numerical simulations [10]. The LDV was used at the inlet section of a turbine, in the draft tube [10] and even between the runner blades [16]. By combining the obtained results from LDV and pressure sensors mounted on the rotor and stator sections of the turbine, the flow field inside the turbine can be estimated. The fluctuations obtained from axial and tangential velocity components can estimate the dynamic pressure in the turbine [5]. Also, the velocity can be used to calculate the amount of the pressure recovery in the draft tube of the turbine [5]. In addition to mean velocity profiles at different operating conditions, Reynolds stress can be calculated [5].

In figure 6, a sketch of three LDV measurement lines in a draft tube is shown. In this study, the velocity results and the pressure measurement along the draft tube were used to investigate the flow at Best Efficiency Point (BEP) and off-design operating conditions [4, 5].

In another study, through small windows on the distributor’s wall, a two component LDV measurement on a propeller was performed near the cone wall and around the hub region to evaluate the draft tube inlet flow. The measurements were done in two planes, one under the runner blade and the other under the runner hub, as shown in figure 7 [6].
Figure 7. Position of the axes of the LDV measurement in the turbine: (a) Axis A and B positions in the turbine with the coordinate systems and (b) Axis C position in the turbine with the coordinate systems [6].

2.3. Particle Image Velocimetry (PIV)

PIV is another non-intrusive method that determines the instantaneous velocity mostly on a planar light sheet. In the case of hydraulic turbine, PIV is used mostly in the draft tube to obtain the velocity field, whether 2D or 3D. To perform PIV measurement, after adding the particles to the water, there should be at least two windows for 2D PIV, one for the laser sheet and another for the camera. The windows should be large enough to avoid interference with the camera and the laser sheet. For 2D PIV, the angle between the camera and the light sheet should be as close as possible to 90° to minimize errors. In stereoscopic 3D PIV, a third window is needed for the additional camera and the angle between the two cameras should be close to 90°, the laser sheet should be placed at the middle point of the cameras, facing the cameras. The 90° between the cameras is to lessen the out of plane velocity error in the measurement. Also, the light sheet in the middle of the cameras is to lessen the errors of mismatching magnification of the two cameras.

The time resolved PIV method was used in a propeller turbine to estimate the flowrate at the inlet pipe of the turbine during start up. The test rig and the location of the PIV measurements on the inlet pipe are shown in figure 8. The flow in the inlet pipe was assumed 2 dimensional and thus, a two-component PIV measurement was performed on a 2D plane, parallel to the flow direction. Also, to compensate the effect of the refractive index difference on image deformation, the outer surface of the pipe was equipped with flat windows. Firstly, the accuracy of the results obtained from time resolved PIV was confirmed by checking their results from an electromagnetic flowmeter during steady state operation. Then, the time resolved PIV was used during transient operation, since the electromagnetic flowmeter measurements is not reliable in this case [8].

In another study, the flow in the vaneless space of a pump turbine, operating in pump mode, was investigated with windows on the spiral casing and on the wall of the vaneless space. They did the 2D PIV measurements on 3 horizontal and 1 vertical plane in the vaneless space [28]. In another pipe turbine, a 2D PIV measurement was performed by removing 2 stay vanes to provide a larger optical access. Also, a mirror was used to redirect the optical path horizontally toward the camera. They also did the 3D PIV measurements in the draft tube to investigate the detected vortices, wake propagation and dissipation and rotor stator interactions. This measurement setup is shown in figure 9 [29].

Vincent et al. performed stereoscopic PIV measurements in the inter-blade channel of a propeller runner in 2013. Because of the limited optical access, the cameras were placed underneath the runner, with a relative angle of 45° between the cameras, leading to some negative effects on the accuracy of the results. A view from the underneath is shown in figure 10 that shows the cavitating leading edge vortices during the Part Load (PL) operation. The other challenge was to fit the calibration target in the inter-blade channel of the runner blades, considering that the blade shadow reduces the valid measurement area depending on the runner angular position. To overcome this, a custom calibration target was used.
As a result, by reconstructing the averaged 3D velocity field, the tip leakage vortices at the conical section are related to the velocity field at inter-blade channel of the runner [14].

3-D stereoscopic PIV measurements were performed in the draft tube of a propeller turbine to investigate the conical diffuser flow dynamics. In this measurement, as shown in figure 11, the angle between the cameras was 90°. The measurement plane is shown in figure 12, which covers 70% of the conical cross section. The results obtained by PIV were validated with LDV measurements on 3 lines across the PIV measurement section, see figure 13. The results showed that the flow separations are strong and the periodic and non-axisymmetric fluctuations are present in the hub wake, with a frequency equal to the runner rotational frequency [10].

![Figure 8. Schematic of the test rig and location of the PIV measurements [8]](image)

![Figure 9. Top and side views of the measurement sections and laser sheet positions for the PIV experiments in the guide-vanes channel of a pump-turbine [29]](image)

![Figure 10. Visualization of the cavitating leading edge at PL [14]](image)
3. Discussion

This paper presents a review on the velocity measurements that had been done on Kaplan and propeller turbines. In the second section, the measurements that were performed are reviewed. Generally, the measurements are done only on model, not prototype of the turbine, which shows the difficulty to perform the measurements in the prototype. Also, most of the measurements were performed on the propeller type, instead of the Kaplan one, since the measurement in the Kaplan version is more complicated. A brief review of the second section and explanation of the pros and cons of each method are tabulated in Table 1.

According to the different flow regimes in different sections of the turbine, it can be stated that the measurements should be performed on three sections, including turbine inlet, the vaneless space between the GV and runner, and the conical section of the turbine. Each section is discussed more in the following:

1. The velocity at the inlet pipe of the turbine provides information about the flow field entering the turbine during steady and transient operation. So far, most of the numerical simulations in hydraulic turbine make an ideal assumption about a symmetric and close to fully developed turbulent flow entering the spiral casing. Such flow does not reflect the
presence of bend or contraction found upstream the spiral inlet. A more realistic discharge distribution at the spiral inlet is of interest for turbine performance estimation by numerical simulation.

2. The vaneless space, the passage between the GV to the rotating runner, is of great interest for velocity measurements. This section is a subject of interest due to the Rotor-Stator Interaction (RSI) phenomena that occurs at this section in different operating conditions. The larger vaneless space in axial turbines compared to other reaction turbines make this region prone to large instability at low discharge.

3. The measurement in the conical section of the draft tube should be considered as well. According to turbine’s operating condition, the flow at the draft tube inlet can be turbulent or laminar, dominated by swirling or axial flow, with or without backflow and on the walls or far from the walls. The exact velocity profile at the runner outlet can be used to calculate the pressure recovery of the draft tube and thereby overall losses of the turbine more precisely.

Table 1. An overview on the velocity measurement methods in hydraulic turbine.

| Method     | Benefits in hydraulic turbines                                      | Challenges in hydraulic turbines                                      |
|------------|---------------------------------------------------------------------|-----------------------------------------------------------------------|
| Flow visualization | • Different creative ways to visualize the flow                      | • Limited to flow close to the wall (for measurement with tufts)       |
|            | • Not always hard to implement in the turbine                        | • Different level of air pressure to be inserted in the turbine       |
|            |                                                                     | according to operating condition (in bubble insertion)               |
|            |                                                                     | • Optimum visibility is hard to be achieved (in bubble insertion)     |
|            |                                                                     | • Cavitation is not always happening in the turbine according to the  |
|            |                                                                     | loading (measurement based on cavitation)                             |
|            |                                                                     | • Reveals a limited amount of information                             |
| LDV        | • Easy optical access to perform measurements                       | • Velocity measurement only on 1 point over a period of time          |
|            | • Can be used to validate other measurements                        | • Large amount of time is needed to get comprehensive information     |
| PIV        | • Velocity profile, whether 2D or 3D, mostly on a 2D plane          | • Placing the calibration target in each section                     |
|            |                                                                     | • Limited optical access to each section                              |

Although it is valuable to know the important sections to perform the measurements, it is still quite a challenge to perform the measurements. Initially, an appropriate method for measurement should be chosen and then, the problems associated with each method should be addressed and the solution presented. Since PIV is able to get the information on an illuminated plane instead of some specific points, like in LDV, or in regions close to the wall, like the tufting method, PIV is a better choice to obtain the velocity profile in the aforementioned sections of the turbine. However, each section is associated with specific challenges. Some of the problems that can make the measurement challenging are mentioned:

1. One of the main challenge is the limited optical access. Although having a transparent glass at the conical section of the draft tube and at the inlet pipe is feasible, accessing the vaneless space is not as easy as the two others because of mechanical limitations.

2. Calibration of the PIV system is essential for good measurements. Specific solutions needs to be developed for each region of the turbine.
3. The existence of vortices reflects the light sheet. This may cause error due to the illumination of the particles that is not necessarily located in the original measurement plane. Consequently, in the picture taken in this situation, some additional data points may exist far from the observed limit of the vortex rope edge [30].

The future works can focus on performing the PIV measurement during different loading scenarios of the turbine on the sections mentioned above. The measurements can ease the way to find new methods of decreasing the losses and increasing efficiency.

4. References

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