Velocity Measurement with PIV in a Straight Cone Draft Tube

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Abstract

Since the deregulated energy market, hydropower plants are increasingly operating at off-design conditions in order to follow the demand in the electrical grid. In this context, the ability of handling the operation in a wide range of off-design conditions has become more important for hydropower plants. But one of the major difficulties in hydraulic turbines is the rotating vortex rope in the draft tube, especially for Francis turbines running in part load.

This is one reason for the great interest in mitigation and prediction of the vortex rope phenomenon over the past few years. The numerical prediction of unsteady flow structures and flow phenomena like a vortex rope by using CFD became possible with the fast development of computer performance. Previous simulations show that complex models are necessary, in order to describe the phenomena correctly. Simulation results with new models e.g. VLES are promising. However this approach must be further tested and detailed comparisons with measurements are necessary /1/. For validating these models, measurements on a model pump-turbine with a simplified straight cone draft tube, instead of the usual used elbow draft tube, are accomplished. The results from different operating points are taken as reference for the validation of CFD-simulations.

For five operating points Particle Image Velocimetry measurements were done. For these operating points time averaged velocities are presented. In the velocity measurements with PIV the radial and axial components of the velocities were measured in one longitudinal cross section for the different operating points.

Introduction

The draft tube, which is in fact a diffuser, is an important part of a hydraulic turbine /2/. It converts kinetic energy at the runner outlet into pressure energy. In this way it increases the head of the runner /3/. When a turbine operates at off-design conditions the flow in the draft tube has not only a transport component, which determines the flow rate, but also a circumferential component. The appearance of the vortex rope is in correlation with the strength of the swirl at the runner outlet /4/. The rotation of the vortex rope causes a rotating pressure oscillation. In elbow draft tubes also a synchronous pressure oscillation can occur, i.e. a pressure oscillation of the whole level at in a respective cross-section of the draft tube. The frequencies are relatively low and could be in the range of the eigenfrequency of the water passage. If the frequency of the synchronous pressure oscillation correlates with the eigenfrequency of the water passage, there could be an unacceptable amplitude in the pressure oscillation /1, 5, 6/.

Many numerical investigations have been done over the last years by researchers in the whole world. But there are only a few detailed experimental investigations of the unsteady velocities in draft tubes using laser optical methods, like LDA or PIV. All these measurements /7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17/ were done in conventional draft tubes with an elbow. In this investigation a simplified test case is used with a straight cone draft tube, in order to reduce the complexity of the flow field.
Particle Image Velocimetry

Particle Image Velocimetry (PIV) is a laser-optical measuring method, where the velocity in an entire plane is detected at the same time. Today PIV is widely spread in the flow measuring technique. All Laser-optical measuring procedures have the advantage – compared to measuring methods with hot wire or multi-hole probes – that the flow field is not affected by bringing in a transducer.

For a PIV-measurement a laser beam is expanded to a light-sheet with a thickness of approx. 1mm. Thus planes in a flow can be illuminated (see fig. 1a). Polyamide powder was added as seeding particles to the water in the test rig. Since the velocity of the added scattered light particles is measured, it is provided that the particles follow the flow slip-free. From this it is a requirement that the particles are small enough to follow the flow well. The polyamide particles have nearly round shape and an average size of 90 μm. With the density of the particles of 1,016 kg/m³ at 23°C the seeding should follow the flow well. To describe the displacement of the seeding particles two successive exposures of the light-sheet are required. From the time between the two exposures and the displacement the velocity can be calculated. In this way it is possible to measure at the same time the two-dimensional velocity vectors in the illuminated plane.

A PIV system of the manufacturer TSI is used. The PIV system consists of a double-pulsed Nd:YAG-laser (TSI model Y25-20 MiniLase II, manufacturer: New Wave Research) with 25 mJ per pulse and a maximum repetition rate of 20 Hz. The laser beam has a wavelength of 532 nm (green). The laser light is coupled via a light arm to the optics. The photos were taken with a CCD-camera (PIVCam 13-8) with a resolution in space of 1280 x 1024 pixel² and a 12 bit brightness resolution by a repetition rate of 8 Hz. A synchronizer (model 610032) and a PC with the software Insight PIV version 6.1.1.0 control the components of the system. For processing the cross-correlation an interrogation area of 64 x 64 pixel² with 50% overlapping is used. The time between two exposures varies with the operating point between 70 μs and 140 μs. The filter adjustments are also adapted to the respective operating point. For the time-averaged results at least 20,000 velocity vector fields are averaged for one camera position.

With the experimental setup all sources of error of an optical picture recording have an influence on the measuring accuracy, i.e. refraction at phase interfaces, characteristics of the optical components and positioning accuracy of the camera. A further source of error is the
evaluation with the cross-correlation and the computation functions for the post processing /18, 19/.

Due to the conical shape of the draft tube and the coupled different angle of refraction a correction of the optical distortion is necessary. The calibration relation is obtained acquiring images of a plane acrylic glass target with an equally spaced grid of black dots. The dots have a diameter of 2 mm and the space between the dots is 6.5 mm. The target is placed in the respective measurement plane and photographed by the camera of the PIV system (see fig. 1b). During the calibration the camera is exactly at the same position as later in the measurement. In a first step the positions of the points of the calibration grid on the distorted image are determined. A self-written program corrects the positions and the size of the velocity vectors by means of a transfer matrix. The individual entries in the matrix are produced by bi-linear interpolation depending on the location.

Due to the optical calibration one additional effect is not taken into account. The pictures of the seeding particles are not a parallel projection, as most assumed. In reality, the pictures of the seeding particles are a perspective projection of the particles. In a strong three-dimensional flow the measurement of the two components of the velocity in the illuminated plane get a systematic error by the out of plane motion [20]. In fig. 2 a scheme of this effect is presented. At every measurement section the camera was placed at two positions to correct this effect. The second position is the mirrored position to the measurement plane from the first position of the camera. By averaging the results of the two positions the error should be eliminated.

![Fig. 2: Influence of the out of plane movement on calculated displacement of the particle](image)

**Experimental Setup**

The measurements were carried out at the large closed-loop test rig of the IHS (see fig. 3). The test rig is equipped with two pumps, which can operate in parallel or serial, depending on the requirements of the respective experiment. In this experiment the pumps operate in serial. A speed-regulated direct current motor drives the pumps. The pumps deliver the water to the upper water vessel. The water flows from the vessel to the pump-turbine model. The pump-turbine is also connected to a speed-regulated direct current motor-generator. A straight acrylic glass cone is built into the pump-turbine representing the draft tube. The cone has a diameter of 182 mm at the inlet and a diameter of 400 mm at the outlet. The cone
angle is 2° 10'. Behind the acrylic glass cone a straight pipe with a nominal diameter of 400 mm and a length of approx 2.4 m is installed. Afterwards the water flows into the tailwater vessel, which is built with an air-subjected dome, in order to vary the pressure level of the test rig. The water flows from the vessel back to the pumps passing a magnetic inductive flow meter.

**Fig. 3:** Scheme of the test rig and sectional drawing of the pump-turbine

On the right in fig. 3 the longitudinal cross section of the pump-turbine is depicted. The guide vane opening can be adjusted via hand wheel. The straight diffuser is made of transparent acrylic glass, in order to ensure the accessibility for the laser-optical measuring procedures.

**Selected operating points**

In order to specify suitable operating points for detailed investigations, the turbine characteristics was measured. The measured values were transformed into specific values. Fig. 4 represents the hill chart in a $Q_{11}$ against $n_{11}$ diagram. The points 4, 5, 6, 9 and the best efficiency point were selected for the velocity measurement. Afterwards special measurements for pre-selected points were made. The focus was on unsteady pressure measurements at the draft tube wall and to identify different structures of the vortex rope in the diffuser. Therefore the vortex rope in the diffuser was visualized by cavitation in the core of the rope. In fig. 5a and fig. 5b the rotating vortex rope at part load conditions is shown. Fig. 5c shows a central vortex shape at an overload operation point. Fig. 5d displays the rotating vortex rope at high overload conditions. In this case the direction of the corkscrew shape and the direction of the rotation is opposite to the direction of curvature and rotation in the part load operation points.
Results of the PIV Measurement

In this section the results of the before mentioned error elimination by averaging the results of the two positions is shown. The area of the results presented here is marked in fig. 6 with a rectangle. All results are preliminary analyzed without filtering the PIV-data.

Specific discharge:

\[ Q_{11} = \frac{Q}{D^2 \cdot \sqrt{H}} \]

Specific speed:

\[ n_{11} = \frac{n \cdot D}{\sqrt{H}} \]
Fig. 6: Photograph of the draft tube with a vortex rope at operation point No. 4

In the Fig. 7 to 11 the velocity field of the two mirrored positions (left and middle pictures) and the averaged velocity field (right picture) are shown. As can be seen, the differences between the two mirrored positions depend on the swirl strength of the respectively operating point. In case of strong swirl the two velocity fields differ considerably.

Fig. 7: Velocity-field at operation point No. 4

Fig. 8: Velocity-field at operation point No. 5
Fig. 9: Velocity-field at BEP

Fig. 10: Velocity-field at operation point No. 6

Fig. 11: Velocity-field at operation point No. 9
Compared to the discharge measured with the electromagnetic flow meter the integrated discharge from the PIV-measured velocity field shows deviations in axial direction (fig. 12). One reason for the discrepancies between the measured and the calculated discharge is that the regions near the wall could not be acquired by the velocity measurement. In the calculation of the discharge this values are set to zero. Therefore the discharge is calculated to low, especially for operating points with strong swirl.

![Graph showing discharge discrepancies](image)

**Fig. 12:** Discharge discrepancies

**Conclusion**

For five operating points Particle Image Velocimetry measurements were done. For these operating points time averaged radial and axial components of the velocities in one longitudinal cross section are presented. Additionally a correction of the systematic error created by the out of plane motion in a strong three-dimensional flows is introduced.

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**References**


