Reference measurements on a Francis model turbine with 2D Laser-Doppler-Anemometry

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Abstract. To validate the investigations of a high-resolution CFD simulation of a Francis turbine, measurements with 2D Laser-Doppler-Anemometry are carried out. The turbine is operated in part load, where a rotating vortex rope occurs. To validate both, mean velocities and velocity fluctuations, the measurements are classified relative to the vortex rope position. Several acrylic glass windows are installed in the turbine walls such as upstream of the spiral case inlet, in the vaneless space and in the draft tube. The current investigation is focused on a measurement plane below the runner. 2D velocity components are measured on this whole plane by measuring several narrow spaced radial lines. To avoid optical refraction of the laser beam a plan parallel window is inserted in the cone wall. The laser probe is positioned with a 2D traverse system consisting of a circumferential rail and a radial aligned linear traverse. The velocity data are synchronized with the rotational frequency of the rotating vortex rope. The results of one measurement line show the dependency of the axial and circumferential velocities on the vortex rope position.

1. Introduction

The energy transition makes it necessary to switch from power plants with high, constant power output like coal or gas power plants to a wide range of new energy sources. These often have the disadvantage of a fluctuating power supply. Concerning the stability of the electricity grid and a consumer adapted energy production there is an increased demand to operate hydro power plants outside of the optimal operational range. Especially part load operation is associated with dynamic and unsteady flow phenomena. A rotating vortex rope can develop in the draft tube that causes noise, vibration and decline of the efficiency. When the rotational frequency matches the natural frequency of a component it might provoke serious damage. Therefore the reliable prediction of the operating behavior is an important challenge in the process of turbine design as well as in the operation of existing plants.
In a research project, the possibilities of computational fluid dynamics (CFD) simulations to accurately predict the flow in part load operation of a Francis turbine are examined on high-performance computers [1]. To validate mean velocities and velocity fluctuations, measurement data with a demand on maximum precision have to be prepared. For this purpose, a test stand was built. Two dimensional velocity measurements with Laser-Doppler-Anemometry (LDA) are carried out on several positions along the model turbine.

Recent investigations have treated the occurring phenomena in part load, including pressure measurements, LDA measurements and PIV measurements at various positions in the turbine. For example, the Flindt Project [2], [3] and [4] as well as the Francis-99 Project [6] and [7] show significant work on this issue.

The focus of the current investigation is the draft tube cone below the runner. Here, two dimensional velocity data will be measured in a full plane. A key aspect of this work is the phase resolving of the velocity field, so the data will be synchronized with the positions of the rotating vortex rope and, in future work, with the position of the runner. The turbine is operated in cavitation free conditions. In this paper, the measurement and the analysis of one line within the plane is described.

2. Experimental setup and measurement
A Francis turbine with $n_q = 80 \text{ 1/min}$ and an elbow draft tube is used for the investigation. The outlet diameter of the runner is $D = 372 \text{ mm}$. In the investigated operating point the flow rate is $Q = 0.09579 \text{ m}^3/\text{s}$. To gain optical access to the measurement area, several transparent elements consisting of polymethyl methacrylate (PMMA, hereafter called acrylic glass) are installed. A short piece of the inlet pipe right before the spiral case consists of acrylic glass. Here, the velocity profile entering the turbine is validated. In the turbine cover, four windows are installed to access the vaneless space for two dimensional measurements. In the draft tube, several windows are located in the diffusor. In the cone, the velocity field is investigated in a whole plane consisting of several radial lines. For the laser measurements, an optical system of Dantec Dynamics is used. The model turbine setup and the LDA system are shown in Figure 1.

![Figure 1. Left: Test stand before the installation of the traverse system and sight protection for laser safety. Right: Dantec Dynamics LDA system with probe.](image)

2.1. Measurement plane in the draft tube cone
The conical shape of the draft tube cone requires installing an acrylic glass insert with plan parallel surfaces in order to perform two dimensional measurements. Two holes are milled with a diameter slightly larger than the maximum beam space of the laser probe. Two inserts reproduce the conical form on the inside and are used as dummies, when no measurement is performed. For measurement purposes, a plan parallel window is installed, which causes a very small step on the inner surface of
the cone. Figure 2 shows the cone with milled preparation for the inserts. On the right, a dummy window is presented.

![Image](image1.png)

Figure 2. Acrylic glass insert in the cone for a plan parallel beam path when measuring two dimensional.

The measurement plane consists of 16 lines with an angle increment of $\Delta \zeta = 11.25^\circ$, see Figure 3. The measurements are processed in two steps. First, the solid lines are measured. The cone is rotated together with the cage in the bolt circle of the fastening screws. For every position, two lines are measured with the two possible window locations, as pictured in the scheme. Afterwards, the cone is rotated within the cage enabling to measure the dashed lines. In this work, the blue line will be treated. The diameter of the plane from wall to wall is $D_p = 427.33$ mm.

![Image](image2.png)

Figure 3. Measuring positions in the cone, 16 lines in total. The blue line is the first measured reference line.

To position the laser probe around the cone, a traverse system is constructed. A circumferential rail allows adjusting the circumferential position with high accuracy. It also ensures the repeatability of the measurements. On this rail, a radial aligned linear traverse with servomotor is placed to move the probe. To create a measurement line, the circumferential position is adapted to the window insert. The positioning is done automatically by the linear traverse. The laser probe mounted on the traverse system is presented in Figure 4.
2.2. Laser-Doppler-Anemometry
An argon-ion laser is used for the measurements. The two dimensional measurements are performed with the wavelengths 488 nm and 514.5 nm. Per wavelength, the beam is divided again with one beam shifted by a frequency of $\Delta f = 40 \text{ MHz}$. The four beams intersect in a volume with a length of approximately 5 mm. When a tracer particle in the fluid crosses the volume, the light is reflected and captured by an optical sensor in the probe. The burst contains the Doppler shift that is dependent on the sought velocity information. Such an incident is called count and the amount of counts per second is the data rate. To get a reliable measurement at one point, a sufficient amount of counts has to be available. The real velocity can be determined by the statistical distribution of the single count velocities.

In the cone, a relatively high distance has to be overcome. Therefore, the optical signal transmission in the flow is an important factor of the measurements. Low data rates can lead to long measurement durations. For the LDA measurements, hollow glass spheres with a mean diameter of $d = 17 \mu m$ are added to the water.

2.3. Synchronization of the velocity data
To determine the periodic influence of the rotating vortex on the flow, the information about the position of the vortex has to be linked to the velocity measurements. This is done by a trigger signal, which is forwarded to the LDA system.

A pressure sensor, installed in the cone wall, records the pressure fluctuations caused by the circumferential movement of the vortex. To lower the noise and reduce the fluctuation to the sought frequency, the signal is band-pass filtered and amplified. As a TTL-signal is required for the synchronization, the signal is then filtered by a comparator. The signal processing is shown in Figure 5. The range between two raising or falling edges is the period of one vortex revolution.

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**Figure 4.** Traverse system around the cone. Circumferential rail with measure tape and automatic linear traverse.
Figure 5. Signal processing of the pressure, measured on the cone surface below the runner. The shown frequency is the vortex rope rotational frequency.

In the velocity measurements, this period is used to assign each count to a position information $\alpha_{\text{VR}}$ in a range between $0^\circ \leq \alpha_{\text{VR}} < 360^\circ$. The range is divided into equidistant bins with a chosen size of $\Delta \alpha_{\text{VR}} = 2^\circ$. Hence this is the maximum resolution of the following evaluations.

2.4. Phase resolved velocity measurements

For the phase resolved LDA measurement, a mean value is calculated in every bin. The statistical distribution of the counts has to be considered for each bin individually. The development of the mean value depending on the amount of counts shows, that from 100 counts on, no significant change is visible. During measurement, the intersection volume remains in one point until every bin contains at least 100 counts. This makes sure that the statistically determined value is sufficiently converged. A condition for this measurement procedure is, that the velocity value at one position of the vortex rope is composed of several revolutions, always considering the same angle range $\Delta \alpha_{\text{VR}}$.

The data rate differs significantly between the bins. Therefore, some bins contain more counts than others. It was determined that the maximum distinction of the bin with count number 100 and the highest count number was 300 %.

3. Results

In a first investigation, only one measurement line is treated. The line with the reference position $\varphi = 0^\circ$ is located at $x = 0$ and runs along the positive $y$-axis. Hereafter it is called line 1, as the lines are designated by the order of measurements. Figure 6 shows the line relative to the turbine. In Figure 3, the blue line corresponds to line 1.

The pressure signal, used for generating the trigger signal, is recorded at the marked spot, at a distance of 77.5 mm below the runner. The sensor is attached to the cone, so when rotating the cone as described earlier, the pressure signal position changes simultaneously. The lines consist of single measurement points. Between every measurement point, the probe moves by 10 mm. The
measurement volume moves with a slightly different velocity, as the beam path changes due to the deviating refractive indices of the permeated materials. This leads to a point distance of 13.3 mm.

![Figure 6](image)

**Figure 6.** Top view on the CAD model of the turbine. The positive rotation direction of the vortex rope $\alpha_{VR}^+$, the location of the pressure sensor as well as the measurement line 1 with the reference position $\varphi = 0^\circ$ are presented.

In the special case of line 1, the circumferential and radial velocities match the x- and y-axis directions of the Cartesian coordinate system shown in Figure 6. Therefore only the axial and circumferential velocities are considered in the following presented data. The measurement plane is located at a distance of 235 mm below the runner.

### 3.1. Total averaged velocity data

Figure 7 shows the total averaged velocity data of line 1. On the abscissa, the radial measurement point position referred to the cone radius $r_c$ is plotted. The middle of the cone is defined as $r/r_c = 0$. Accordingly, at $r/r_c = \pm 1$ the center of the measuring volume meets the inner cone wall. The velocity data are referred to the reference velocity, defined as

$$v_{\text{ref}} = \frac{Q}{A_c} = 0.6679 \text{ m/s}$$

$A_c$ is the cross-section area of the cone.

The measurement time per point is not less than 300 seconds, assuring a sufficiently high number of vortex rope revolutions. The count number of all points is at least 10000, up to 40000 counts, which makes the total averaged value highly accurate.

The axial velocity profile indicates that the flow in the cone is not symmetric. A bigger part of the fluid runs through the side in positive y-direction, cf. coordinate system in Figure 6. At $r/r_c = -0.3$, the mean axial velocity is nearly zero, while the other side of the core flow reaches $v/v_{\text{ref}} \approx -0.2$. The maximum velocity amounts to $v/v_{\text{ref}} \approx -1.7$.

The swirl component of the velocity is mainly directed in the rotation direction of the vortex rope. This complies with the expectations, as the circumferential velocity at the blade tailing edge matches the rotation direction of the runner.
3.2. Phase resolved data
To make the periodic influence of the rotating vortex visible, the velocities of one vortex rope revolution are plotted for every single measurement point of line 1. The results are shown in Figure 8. Each diagram refers to one radial position along that line. As the circumferential position of the vortex rope is based on the trigger signal in a height different than the LDA measurement plane, the rope position is in no defined relation to the scale. On the ordinate in Figure 8, the relative vortex angle is plotted:

\[ \alpha_{\text{rel}} = \frac{\alpha_{\text{VR}}}{360^\circ} \]

To locate the vortex in the plane, the circumferential velocity is a good indicator. At \( r/r_c = 0.43 \) an enhanced scatter is visible between \( 0.3 < \alpha_{\text{rel}} < 0.55 \), even though the count numbers of the concerning bins are not below the mean value. The measured circumferential velocity is about zero. Therefore, it is assumed that the center of the vortex is located in this area at \( \alpha_{\text{rel}} \approx 0.42 \). When the vortex rope passes line 1, the velocity vectors related to the rotation around the core at \( r/r_c = 0.43 \) are mainly pointing in y-direction. As the 2D-LDA system is aligned to detect the velocities in x- and z-direction, the radial velocity is not measured. The vortex position in the cone is presented schematically in Figure 9. The scheme is an assumption and will be verified by the velocity data of the whole plane.

The averaging performed within the binning leads to a high variation of the mean values in this area. It is assumed, that this is a consequence of the velocity fluctuations near the vortex rope core (\( 0.3 < \alpha_{\text{rel}} < 0.55, r/r_c = 0.43 \)). Another possible reason is the shape of the vortex rope, which is not necessarily circular. As the vortex rope does not cross the measurement plane orthogonally, the cross section is distorted. At \( r/r_c = 0.31 \), the circumferential velocity distribution has a minimum, when the vortex angle reaches \( \alpha_{\text{rel}} = 0.42 \). At \( r/r_c = 0.56 \), a maximum is visible at the same vortex angle. Those velocities might be related to the self-rotation around the vortex rope core. The same phenomenon is visible on the other side of the cone around \( r/r_c = -0.44 \). The vortex core position is shifted by \( \Delta \alpha_{\text{rel}} = 0.5 \), so the center of the vortex can be found at \( \alpha_{\text{rel}} \approx 0.92 \), see Figure 9, right.

![Figure 7. Mean axial and circumferential velocity on measurement line 1.](image-url)
Figure 8. Phase resolved results on different positions along line 1.
The axial velocity is nearly zero in the center of the vortex rope. The flow is rapidly slowed down before and accelerated after the vortex core passes the point. The influence is most intense in the assumed vortex core position at \( r/r_c = 0.43 \) (0.3 < \( \alpha_{rel} < 0.55 \)). It is also visible in the adjacent positions at \( r/r_c = 0.31 \) and \( r/r_c = 0.56 \) in Figure 8. A more detailed investigation shows, that the influence is visible from approximately \( r/r_c = 0.12 \) to \( r/r_c = 0.68 \), which covers a range of \( \Delta r/r_c = 0.56 \) or \( \Delta y = 120 \) mm. Before and behind this range, meaning \( r/r_c = 0 \) and \( r/r_c = 0.81 \) in Figure 8, the axial velocity has a smoother distribution. On the other side of the cone, the same phenomenon is visible (0.7 < \( \alpha_{rel} < 1 \), \( r/r_c = -0.44 \)).

The main vortex in the cone is caused by the remaining swirl downstream of the runner in part load operation. It is significantly influenced by the vortex rope movement. In Figure 9 the assumed path of the vortex core is indicated by the dashed arrow. The maximum circumferential values occur at positions where the vortex rope core is on line 1, see Figure 9. This happens two times in one vortex rope revolution, reaching values of approximately \( v_{circ}/v_{ref} = 1.2 \) and \( v_{circ}/v_{ref} = -1.2 \). At the angular positions, shifted by \( \Delta \alpha_{rel} \approx \pm 0.25 \), the circumferential velocity distribution at \( r/r_c = 0 \) crosses the zero line. Here, the circumferential component points in \( y \)-direction and is therefore not measured in line 1. At \( r/r_c > 0.43 \), the circumferential velocity stays positive and is accelerated, as the vortex passes by. Accordingly, at \( r/r_c < -0.44 \) the velocity is negative. In the range between those areas, meaning the area within the dashed circle in Figure 9, the circumferential velocity constantly changes its sign.

**Figure 9.** Assumed flow in the measurement plane (not to scale). **Left:** Vortex meets line 1 at \( r/r_c = 0.43 \). **Right:** Vortex meets line 1 at \( r/r_c = -0.44 \).

### 4. Conclusion
A model turbine was installed in our laboratory enabling precise velocity measurements in a high specific speed Francis turbine. The traverse system makes the positioning of the laser probe around the draft tube cone possible. A first attempt to measure one line showed, that the applied concept is sufficiently precise for the repeatability of the measurements. The presented triggering procedure has been successfully used to filter the data generated by the 2D-LDA system in terms of the periodic influence of the rotating vortex rope. This influence is visualized by means of velocity trend during one vortex rope revolution at every measurement point. The results show the periodic behavior of the velocity components in axial und circumferential direction.
The investigation of the whole plane will complete the perceptions. Measurements in the draft tube diffuser will be carried out with the same triggering as within the cone. The acrylic glass cone at the spiral case inlet will be used to measure a detailed inlet profile. In the vaneless space, 2D velocity data will be provided as a reference for the flow conditions before entering the runner. Additionally, the triggering procedure will be used for analyzing the influence of the runner rotational frequency on the flow.

5. References
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