Preliminary Measurements of the Radial Velocity in the Francis-99 Draft Tube Cone

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Abstract. Two-dimensional particle image velocimetry (PIV) measurements in the draft tube cone of the Francis-99 model have been performed to complete the actual experimental data set with radial velocity data. The velocity profiles obtained presented some variation, which reason has not yet been identified. The presented results are therefore presented as preliminary until the reason is assessed. The axial velocity profiles corroborate well with the ones previously measured with laser Doppler velocimetry (LDV) for all operating points investigated. The radial velocity measured is small in magnitude for all operating points compared to the axial velocity. A gyroscopic effect induced by the swirl leaving the runner and the draft tube bend seems to induce an asymmetry in the draft tube cone.

1. Introduction
Francis-99 is a series of upcoming workshops aiming at determining the state-of-the-art in simulation of high head Francis turbines. For that purpose, the geometry, meshes and experimental results of a high Francis model, the Tokke turbine, were made available to the public at three different operating points: best efficiency point (BEP), part load (PL) and high load (HL), see www.francis-99.org and Chirag et al [1] for more information. The goal of the workshop is to promote the development of numerical tools for the design of high head Francis turbines. The experimental results made available to validate the numerical results comported efficiency, time dependent pressure measurements and velocity measurements. The velocity measurements were acquired in the draft cone at two different locations with laser Doppler velocimetry (LDV), see Figure 3. The measurements comported the axial and the tangential velocities, Sundström et al. [2]. The radial velocity component in high head draft tube cone is small but none the less of importance to assess correctly eventual separation regions. Its determination with optical instrument such as LDV and particle image velocimetry (PIV) is delicate.

PIV and LDV are well-established methods for velocity measurement and have been applied in several turbine-related applications in recent years. PIV is not yet as widespread as LDV, due to its high demand for optical access. PIV has some substantial advantages over LDV, especially for transient phenomena, due to its ability to simultaneously capture a large velocity field with a high data rate. Furthermore, the radial velocity is easily obtained with PIV compared to
LDV. Several set-up configurations of 3D spectroscopic PIV have been investigated by Ciocan [3], with extensive investigation of the data to correct for optical distortion, overlapping of two cameras and set-up for data synchronization. Inter-channel flows in propeller turbines have been investigated by Aeschlimann et al. [4] by the use of stereoscopic PIV in order to obtain 3-component velocity fields. The flow in a Francis turbine draft tube has been investigated by Iliescu et al. [5] using a combination of 3D PIV and LDV.

In the present paper, PIV measurements performed on the Francis-99 test case are presented to complete the actual data set available to validate the numerical simulations. The objectives are to determine the radial velocity in the draft tube cone at the location where the axial and tangential velocities were determined by Sundström et al. [2] with the help of LDV. The axial velocity is also measured with the radial velocity allowing investigating the repeatability of the measurements. Furthermore, contour plots of the meridional velocity are made available for qualitative comparisons.

2. Experimental Setup
The experiment was carried out on a 1:5.1 model Francis turbine of a prototype found at a Norwegian hydropower plant called Tokke. The prototype runner has an inlet diameter of 3.22 m, outlet diameter of 1.78 m, a nominal head of 377 m, and a nominal power output of 110 MW. The distributor is composed of a spiral casing with 14 stay vanes and 28 guide vanes. The runner has 15 full-length blades, and 15 half-blades, also known as splitter blades.

2.1. Test rig
The test rig was operated in a closed-loop configuration, where the pressure and the flow rate are controlled by setting the speed of the pump. The system is fitted with a high-pressure water reservoir upstream the turbine, and a low-pressure reservoir downstream the draft tube. The gauge pressure in the low-pressure reservoir can be independently controlled from 0 down to approximately −9 m, to trigger or prevent cavitation. The experiments were performed under cavitation free conditions. A sketch of the test rig is shown in Figure 1.

![Figure 1. The Francis test rig when operated in closed loop configuration.](image)

The measurements were performed in the draft tube cone. This section is made of Plexiglas for optical access. The draft tube cone was fitted with an index-matching box made of glass and filled with water, to reduce optical distortion.

The operating conditions investigated by Trivedi [1] are listed in Table 1. The specific speed and the specific flow listed in Table 1 are dimensionless numbers defined by Equation 1 and Equation 2.

$$n_{ED} = \frac{n \cdot D}{\sqrt{g \cdot H}} \tag{1}$$
Table 1. Operating conditions as provided by Trivedi [1].

| Operating Point | Head (m) | Flow Rate (m³/s) | Runner frequency (Hz) | n<sub>ed</sub> | Q<sub>ed</sub> | Hydraulic efficiency |
|-----------------|----------|-----------------|-----------------------|------------|------------|---------------------|
| BEP             | 11.91    | 0.203           | 5.59                  | 0.18       | 0.15       | 92.6                |
| HL              | 11.84    | 0.221           | 6.16                  | 0.20       | 0.17       | 90.6                |
| PL              | 12.29    | 0.071           | 6.77                  | 0.22       | 0.05       | 71.7                |

However, upon reaching the proposed operating points, a small but clearly visible instability in the generator torque was detected. The operating conditions were slightly shifted while maintaining the values for n<sub>ed</sub> and Q<sub>ed</sub>, see Sundström et al. [2], giving the operating conditions listed in Table 2.

Table 2. Operating conditions used in this paper.

| Operating Point | Head (m) | Flow Rate (m³/s) | Runner frequency (Hz) | n<sub>ed</sub> | Q<sub>ed</sub> | Hydraulic efficiency |
|-----------------|----------|-----------------|-----------------------|------------|------------|---------------------|
| BEP             | 12.77    | 0.208           | 5.74                  | 0.18       | 0.15       | 92.4                |
| HL              | 12.61    | 0.228           | 6.34                  | 0.20       | 0.17       | 91.0                |
| PL              | 12.30    | 0.072           | 6.77                  | 0.22       | 0.05       | 72.5                |

In order to assess the variation on the velocity profiles of these new operating conditions, a sensitivity analysis was performed, by measuring the time-averaged velocity profiles for the given BEP and the shifted BEP (see Sundström et al. [2]). The velocities are scaled with the bulk velocity leaving the runner, for comparison purposes. These are presented in Figure 2. The velocity difference between the two operating heads is considered relatively small.

2.2. LDV and PIV setup

The LDV used is composed of a Spectra-Physics Model 177G, equipped with a Burst Spectrum Analyzer (BSA) from Dantec Dynamics. The LDV probe was mounted on a traverse table with the probe perpendicular to the glass wall of the index matching box [2]. The perpendicularity was checked with optical methods with an accuracy of 0.2°. The measurement positions are presented in Figure 3. The front lens had a focal length of 310 mm. The seeding particles used were of the type Expancel 46 WU 20 with an average diameter of 6 µm. The axial end tangential velocities were recorded at each coordinate for 720 s, resulting in 70 000-2 000 000 samples, depending on the measurement point location and the operating point. Each velocity profile was investigated with 16 measurement points along the radius for BEP and HL, and at 26 points for PL. The large number of measurement points at PL was necessary to capture the high velocity gradients. The recording time was reduced to 600 s for the last measurements.

A 2D PIV system from TSI was used to measure the axial and radial velocity components in the draft tube cone. Pulse light sheets with a thickness of about 3 mm were generated by
Figure 2. Sensitivity analysis for axial velocity (left) and tangential velocity (right). The velocities are reduced by the bulk velocity leaving the runner.

a Litron Laser NANO L100-50PIV. The illuminated field was recorded by a 4 Mpixel camera (VC-4MC-M180). TSI seeding particles, with a density of 1.016 g/cc, refractive index of 1.52 and mean diameter of 55 µm were used during the measurements. The PIV measurements were performed with an acquisition frequency of 40 Hz. 750 paired images with a time difference of 200 µs were recorded at each measurement section. The velocity profiles measured by PIV were measured in a near-perpendicular direction to the measurement direction of the LDV system, as shown in Figure 3. The axial velocity profiles measured by the PIV and LDV systems can therefore be used to evaluate the flow asymmetry. The PIV system was calibrated using a 2D calibration target. The calibration was performed ex-situ due to the practical limitations associated with the in-situ calibrations.

The velocity profiles measured with the LDV system were measured at two axial positions, as indicated in Figure 3. The PIV system measured velocity in a zone including these two axial coordinates. Note that the measurement axis of the LDV measurements is not parallel with the inlet pipe axis, see Figure 3. The repeatability of the PIV measurements were checked along the radius at a third axial position, indicated as section III in Figure 3.
3. Data Analysis

The velocity measurements from the LDV were time-averaged in each measurement point to give a velocity profile. The velocity was then made dimensionless with the bulk velocity downstream the runner for the given operating point, for comparison purposes. The values for the bulk velocity were 0.75 m/s for PL, 2.18 m/s for BEP, and 2.39 m/s for HL. The radial coordinate was made dimensionless with the runner outlet diameter. For the contour plot, the y-coordinate was made dimensionless with the runner outlet diameter, and the zero value was set to the runner outlet. In the results, the radial velocity ($u_r^*$) is positive in the direction away from the draft tube center, and the axial velocity ($u_z^*$) is positive in the stream wise direction.

The commercial PIV software, DynamicsStudio, from Dantec dynamics was used for image processing and PIV data analysis. Adaptive correlation scheme with two refinement steps and 50% overlap between the adjacent windows was applied on the acquired data after performing the 2D calibration. The averaged velocity vector maps at each operating point are presented in this paper. The velocities for the PIV were measured in two overlapping sections. In reconstructing these, each data set was re-sampled at uniform intervals in the non-overlapping sections. The overlapping sections were re-sampled using data from both set, before they were weight-averaged using a sine half-wave distribution weighing, giving a transition from the upper window to the lower window. In doing this, the data from the upper window will dominate the overlap close to the upper window, while the data from the lower window will dominate the overlap close to the lower window. The weighing method was chosen on qualitative assessment of the velocity contour plots.

4. Repeatability of the measurements

In order to evaluate the repeatability of the measurements, axial and radial velocity profiles in section III, at the overlapping region of the two measurement windows, are investigated. The velocity profiles at the BEP are presented in Figure 4. The measurements were performed three times at each window. Some discrepancy exists between the upper and lower window measurements, both in axial and radial velocities. The measurements for each window were
performed on different days while the test rig was operating continuously. The highest level of discrepancies in both components is found close to the central part of the draft tube where the velocity is higher than close to the wall region. The measurements performed by Sundström et al. [2] indicate the presence of a free vortex in the central region rotating in the opposite direction of the runner. The vortex seems sensible to initial conditions.

Figure 4. Mean axial (left) and radial (right) velocity profiles at section III for BEP operation. The red lines are data from the lower measurement window and the blue lines are data from the upper measurement window.

Figure 5 presents the velocity profiles at section III for HL operation. The velocity profiles are similar to the BEP case. A larger discrepancy appears in the central region of the draft tube. At this operation point, the swirl leaving the runner is larger than at the BEP point, see Sundström et al. [2].

Figure 6 presents the velocity profiles at section III for PL operation. In this figure, the measurements obtained with the full measuring window are included. At this operating point, a large recirculation region appears below the runner in the central region of the draft tube. The axial velocity, as well as the radial velocity, are subject to a large gradient in the radial direction. Furthermore, the magnitude of the radial velocity is significantly larger than for the two other operating points. The discrepancies appear in the region of high axial velocity coinciding with region of large swirl. At this operation condition, the ratio of the tangential to the axial velocity is above 1.5, see Sundström et al. [2].

The difference in measured velocities can stem from either a difference in operating conditions, errors in the PIV calibration, or a physical phenomenon. The experimental conditions are controlled by the flow rate \( Q \), the guide van opening angle \( \alpha \), the turbine rotational speed, and the turbine head \( H \). Dimensionless parameters \( n_{ED} \) and \( Q_{ED} \) are used to characterize the turbine operation. The maximum deviation of these parameters is shown in Table 3. The deviations are considered to be too small to cause the observed differences in the velocity profiles. The complete results from the comparison given in Table 3 can be found in tabular form in appendix A.

An index matching box filled with water was used to decrease the light aberration during the PIV measurements. A 2D calibration target was used to compensate for the light aberration.
Figure 5. Mean axial (left) and radial (right) velocity profiles at section III for HL operation. The red lines are data from the lower measurement window and the blue lines are data from the upper measurement window.

Figure 6. Mean axial (left) and radial (right) velocity profiles at section III for PL operation. The red lines are data from the lower measurement window, the blue lines are data from the upper measurement window, and the black lines are data from the full window measurement.

which still exists close to the areas of high curvature, i.e., close to the draft tube wall. Figure 7 presents a picture of the calibration target in the Plexiglas draft tube cone. Seen in the figure, there is a distance between the draft tube wall and the first calibration point. Hence, the calibration results are extrapolated close to the wall. Moreover, the picture is warped
Table 3. Maximum deviations in operating conditions. The deviations are given as maximum percentage variation from the mean value over the different measurements of the given condition.

|       | PL | BEP | HL |
|-------|----|-----|----|
| $Q_{ed}$ | 0.37 % | 0.14 % | 0.14 % |
| $n_{ed}$  | 0.03 % | 0.01 % | 0.03 % |
| $H$       | 0.05 % | 0.05 % | 0.05 % |
| $Q$       | 0.36 % | 0.12 % | 0.12 % |
| $\alpha$ | 0.00 % | 0.00 % | 0.00 % |

significantly close to the wall but unaffected along the draft tube cone centerline. Thus, the calibration matrix calculated may be subject to some uncertainties close to the wall, i.e., in the region $r^* > 0.85$. Consequently, the axial velocity profiles cannot be affected by the calibration process all along the radius. The calibration uncertainty in the radial direction may result in variation in the radial velocity magnitude and not its direction. However, the results showed that the uncertainty in the radial direction is too small to cause the observed differences in the velocity profiles. If calibration has some effects on the velocity profiles, it should be restricted near the wall region and just in the radial velocity profile, while, as shown in Figure 4, the discrepancies can be seen in the high velocity region close to the draft tube center in this case.

Figure 7. 2D calibration target inside the draft tube cone.

The discrepancies appear only between profiles obtained after restarting the test rig. The discrepancies in the measured profiles are mostly significant in region of high swirl and axial velocities. It may be argued that the swirl encountered in the draft tube cone is sensitive to initial conditions. As a matter of fact, the swirl living the runner creates an asymmetrical flow
in the draft tube after the elbow through gyroscopic effects. The flow is divided into a low and high velocity region which extend may be sensible to initial condition. The question needs to be further addressed and the following measurements are considered as preliminary as long as the matter is not completely addressed.

5. Results and discussion

The axial and radial velocity profiles obtained at section I and II with the PIV system are presented in this section. The axial velocity is compared with the LDV measurements of Sundström et al. [2]. Velocity contours at each operating point are also included.

5.1. BEP results

Figure 8 shows the dimensionless axial and radial velocity profiles at section I for BEP operation. The trend captured by the LDV and PIV measurements is similar. There are some differences between the results especially in the wake region of the runner hub. A probable asymmetry at the runner outlet may be the reason, since the PIV and LDV measurements were not performed at the same azimuthal position as presented in Figure 3. Such an asymmetry may stem from the asymmetric flow distribution at the spiral casing distributor as reported by some researchers, see Amiri [6], but also from the gyroscopic effect as previously mentioned. The PIV measurements show slightly lower axial velocities in the middle part of the graph (0.2 < \( r^* \) < 0.8) and higher velocities in the region affected by the runner hub wake. An integration of the velocity profiles results in comparable flow rate for the two measurements assuming a symmetrical flow at the runner outlet, in agreement with the flow rate measurements. The axial velocity shows a linear decrease with the radius in the middle part of the graph (0.2 < \( r^* \) < 0.8). The axial velocity decreases again towards the centerline of the draft tube due to the runner hub wake. The axial velocity slightly increases close to the wall. This may be due to the design criteria to energize the boundary layer on the draft tube cone or may be related to the tip clearance. Illustrated in Figure 8, the radial velocity is increasing with the radius at the draft tube inlet. The results show that the radial velocity is positive close to the draft tube wall as expected for a diffuser. The flow at the draft tube cone centerline is expected to be purely axial for symmetric flow at the runner outlet. However, the negative radial velocity indicates an asymmetrical flow that may also be the source of the discrepancies between the PIV and LDV measurement results, as discussed before.

Figure 9 presents the velocity distribution at section II. The agreement between the LDV and the PIV results is much better. The axial velocity profile is similar to the velocity profile captured at section I. Surprisingly, the radial velocity is somewhat lower close to the centerline. The negative radial velocity at the draft tube center will move water into the other side of the draft tube, causing a higher velocity in that window, than in the one presented here. This is due to the gyroscopic effect induced by the draft tube bend. The LDV measurement results presented by Sundström et al. [2] showed that the flow at the runner outlet counter-rotates with respect to the runner rotation at the BEP. The rotating flow leaving the runner together with the draft tube bend produces a gyroscopic force resulting in an asymmetric flow in the draft tube cone. The asymmetry effect may propagate upstream resulting in some asymmetry at section I as presented in Figure 8.

Figure 10 presents the contour plot of the meridional velocity inside the draft tube cone. The results indicate a well-distributed flow in the draft tube cone. The figure shows the flow development along the draft tube cone. The velocity smoothly decreases in the stream wise direction without separation. The presence of the hub is seen in the upper center of the draft tube cone, where the velocities are lower. The hub effect can also be seen in Figure 9, where the radial velocity shows a sharp change at \( r^* = 0.19 \), the radial position of the runner hub cone. A visible boundary layer can also be seen in the axial velocity component in Figure 9, where the
Figure 8. Axial (left) and radial (right) velocities at section I for BEP operation. The red line shows the LDV result obtained by Sundström et al. [2] and the blue line shows the mean PIV results. The error bars indicate a 95% confidence interval. The dashed lines at $r^* = 0.19$ and $r^* = 1.00$ indicate the radial position of the runner hub corner and the draft tube entrance, respectively. Note the difference in scale on the ordinate axis.

Figure 9. Axial (left) and radial (right) velocities at section II for BEP operation. The red line shows the LDV result obtained by Sundström et al. [2] and the blue line shows the mean PIV results. The error bars indicate a 95% confidence interval. The dashed lines at $r^* = 0.19$ and $r^* = 1.00$ indicate the radial position of the runner hub corner and the draft tube entrance, respectively. Note the difference in scale on the ordinate axis.
velocity shows a visible reduction at $r^* = 1$. This is only visible in the LDV measurements, since one of the lower pressure bolts prevents optical access.

![Contour plot of the meridional velocity within the PIV plane at BEP.](image)

**Figure 10.** Contour plot of the meridional velocity within the PIV plane at BEP. Pressure bolts in the draft tube cone are seen in both the upper and lower part of the cone. The maximum velocity is obtained at $r^* = 0.15$

### 5.2. HL results

Axial and radial velocity profiles at section I are presented in Figure 11 while the turbine operates at HL. The low velocity region in the wake of the runner hub, presented in the BEP case, does not exist anymore and the axial velocity decreases with the radius all along the draft tube. The radial velocity shows the same profile as the one at the BEP: monotonically increasing with the radius. The flow direction is towards the draft tube wall at $r^* > 0.5$ and towards the draft tube centerline at $r^* < 0.5$. The radial velocity shows a sharp decrease in the middle of the draft tube, at the radial position of the runner hub corner. Sundström et al. [2] showed that the swirl exiting the runner at the HL is higher than the one at the BEP. Hence, the gyroscopic effect is expected to be higher for HL, resulting in a larger decrease in the radial velocity in the middle of the draft tube cone. The radial velocity at section II (Figure 12) is three times larger close to the draft tube bend compared with section I, supporting the hypothesis of an asymmetry imparted by the gyroscopic effect induced by the draft tube bend. The axial velocity profile at section II is similar to the profile captured at section I, but with a lower magnitude, as expected. The draft tube cone decreases the axial velocity, allowing for the recovery of pressure.

Figure 13 shows the contour plot of the meridional velocity at the HL operating point. The contour plot is altered along two horizontal lines of $y^* = -0.09$ and $y^* = -0.34$. It may be due to the change in draft tube angle at those positions resulting in different light aberration at the position that the angle is changed.
Figure 11. Axial (left) and radial (right) velocities at section I for HL operation. The red line shows the LDV result obtained by Sundström et al. [2] and the blue line shows the mean PIV results. The error bars indicate a 95% confidence interval. The dashed lines at $r^* = 0.19$ and $r^* = 1.00$ indicate the radial position of the runner hub corner and the draft tube entrance, respectively. Note the difference in scale on the ordinate axis.

Figure 12. Axial (left) and radial (right) velocities at section II for HL operation. The red line shows the LDV result obtained by Sundström et al. [2] and the blue line shows the mean PIV results. The error bars indicate a 95% confidence interval. The dashed lines at $r^* = 0.19$ and $r^* = 1.00$ indicate the radial position of the runner hub corner and the draft tube entrance, respectively. Note the difference in scale on the ordinate axis.
Figure 13. Contour plot of the meridional velocity within the PIV plane at HL. Pressure bolts in the draft tube cone are seen in both the upper and lower part of the cone.
5.3. PL results

Figure 14 shows the velocity profiles captured at section I while the turbine operates at the PL. The larger error-bars compared to the other operating points is attributed to the presence of the rotating vortex rope (RVR) formed in the draft tube at this operating point. The axial velocity profile at section I shows backward flow for \( r^* < 0.7 \). This is due to the recirculation bubble formed in the middle of the draft tube cone at this operating point. The low guide vane angle and the runner inability to extract the swirl generated by the guide vanes result in high swirl flow exiting the runner, see Sundström et al. [2]. The swirl results in a centrifugal force exerted on the flow. Hence, the axial velocity is significantly increased in the outer part of the draft tube cone for \( r^* > 0.7 \). The radial velocity at section I decreases with the radius. The positive radial velocity for \( r^* < 0.5 \) can be explained by the shape of the recirculation bubble region formed in the draft tube cone. The fact that the radial velocity is negative at \( r^* > 0.5 \) indicates that the flow does not follow the draft tube wall. The large pressure gradient in the radial direction close to the wall cause a negative radial velocity at this position, but it should be symmetric, i.e., the negative radial velocity should be seen close to the wall on the other side of the draft tube. This is not the case, as seen in Figure 17. This asymmetry could be caused by a local flow separation, which will propagate due to the high tangential velocity, see Sundström et al. [2]. Such a localized flow separation was not measured, but it could be the cause of the asymmetry in the radial velocity.

![Figure 14](image-url)

**Figure 14.** Axial (left) and radial (right) velocities at section I for PL operation. The red line shows the LDV result obtained by Sundström et al. [2] and the blue line shows the mean PIV results. The error bars indicate a 95% confidence interval. The dashed lines at \( r^* = 0.19 \) and \( r^* = 1.00 \) indicate the radial position of the runner hub corner and the draft tube entrance, respectively. Note the difference in scale on the ordinate axis.

The axial and radial velocity profiles at section II are presented in Figure 15. The main features of the velocity profiles are similar to the ones captured at section I. The axial velocity is monotonically increasing with the radius while the flow direction is downward for \( r^* > 0.7 \) and is upward for \( r^* < 0.7 \). The radial velocity decreases with the radius. Although the radial velocity is not measured close to the draft tube walls, the curve shows that the velocity should...
be negative close to the wall, i.e., the flow does not follow the draft tube wall. It is expected that this will vary in the azimuthal position, as seen in Figure 17.

Figure 15. Axial (left) and radial (right) velocities at section II for PL operation. The red line shows the LDV result obtained by Sundström et al. [2] and the blue line shows the mean PIV results. The error bars indicate a 95% confidence interval. The dashed lines at \( r^* = 0.19 \) and \( r^* = 1.00 \) indicate the radial position of the runner hub corner and the draft tube entrance, respectively. Note the difference in scale on the ordinate axis.

Figure 16 presents the meridional velocity in the draft tube cone. Note the distinct dark blue lines of zero velocity at \( r^* = 0.6 \). Since the meridional velocity in this figure is a scalar value, the velocity will not be negative, but the zero-lines give an indication of the recirculation bubble in the draft tube cone.

Figure 17 presents contour of the axial velocity at PL. The figure shows the large recirculation region formed inside the draft tube cone. This recirculation region decreases the effective area of the draft tube cone affecting the turbines overall efficiency. Presented in Table 2, the turbine efficiency is decreased by about 20% at this operating point compared with the one at the BEP. The flow rate is about 1/3 of the one at BEP.

Figure 18 presents the contour plot of the radial velocity in the draft tube cone. The figure shows the asymmetry in the radial velocity distribution inside the draft tube cone. Moreover, the flow does not follow the right wall of the draft tube all along the draft tube cone as discussed before. The clear vertical line visualizes the asymmetry of the flow.
Figure 16. Contour plot of the meridional velocity within the PIV plane at PL operation. Pressure bolts in the draft tube cone are seen in both the upper part of the cone.

Figure 17. Contour plot of the axial velocity within the PIV plane at PL operation. Pressure bolts in the draft tube cone are seen in both the upper part of the cone.
Figure 18. Contour plot of the radial velocity within the PIV plane at PL operation. Pressure bolts in the draft tube cone are seen in both the upper part of the cone.
6. Conclusions
PIV measurements have been performed on the francis-99 model turbine at the Waterpower Laboratory at the Norwegian University of Science and Technology. The results show good agreement with previously performed LDV measurements.

The measurements show discrepancies in the overlapping region between the measurement windows. Further measurements in the draft tube are needed in order to fully understand the reason. The non-zero radial velocity at the centerline of the draft tube cone indicate an asymmetry in the flow certainly due to a gyroscopic effect induced by the draft tube elbow on the swirl leaving the runner.
Appendix A. Operating point repeatability

Table A1. Maximum deviations in operating parameters for all operating points investigated.

| Parameter                          | PL  | BEP | HL  |
|------------------------------------|-----|-----|-----|
| Axial Force                        | 1.15%| 0.82%| 1.80%|
| Axial force prototype              | 1.16%| 0.82%| 1.79%|
| Differential Pressure              | 0.04%| 0.05%| 0.05%|
| Dimensionless Axial force          | 1.16%| 0.80%| 1.77%|
| Dissolved Oxygen                   | 0.00%| 0.03%| 0.00%|
| Flow                               | 0.36%| 0.12%| 0.12%|
| Flow prototype                     | 0.37%| 0.14%| 0.13%|
| Friction Torque                    | 35.87%| 27.63%| 28.14%|
| Generator Speed                    | 0.01%| 0.02%| 0.01%|
| Generator Torque                   | 1.27%| 0.22%| 0.43%|
| Guide Vane Opening Degree          | 0.00%| 0.00%| 0.00%|
| Hydraulic Efficiency               | 0.25%| 0.14%| 0.17%|
| Hydraulic efficiency prototype     | 0.24%| 0.14%| 0.17%|
| Hydraulic Energy                   | 0.38%| 0.08%| 0.10%|
| Kinematic Viscosity                | 0.00%| 0.00%| 0.00%|
| Mechanical Energy                  | 0.13%| 0.12%| 0.21%|
| Mechanical Effect prototype        | 0.12%| 0.12%| 0.20%|
| \( n_{11} \)                        | 0.03%| 0.01%| 0.03%|
| \( n_{ED} \)                       | 0.03%| 0.01%| 0.03%|
| Nominal hydraulic efficiency model | 0.25%| 0.14%| 0.17%|
| NPSE                               | 2.37%| 3.31%| 1.72%|
| \( P_{11} \)                       | 0.12%| 0.08%| 0.18%|
| \( P_{ED} \)                       | 0.13%| 0.08%| 0.18%|
| Pressure Inlet                     | 0.69%| 0.93%| 0.46%|
| Pressure Inlet Sensor              | 0.63%| 0.79%| 0.52%|
| Pressure inlet sensor abs          | 0.62%| 0.84%| 0.41%|
| Pressure Outlet                    | 1.95%| 2.75%| 1.38%|
| Prototype Head                     | 0.05%| 0.02%| 0.05%|
| \( Q_{11} \)                       | 0.37%| 0.15%| 0.14%|
| \( Q_{ED} \)                       | 0.37%| 0.14%| 0.14%|
| Reynolds Number Model              | 0.63%| 0.63%| 0.65%|
| Scalable loss                      | 0.00%| 0.00%| 0.00%|
| \( T_{11} \)                       | 0.12%| 0.09%| 0.17%|
| \( T_{ED} \)                       | 0.13%| 0.10%| 0.18%|
| Thomas number                      | 2.38%| 3.30%| 1.75%|
| Vapor Pressure                     | 1.60%| 1.58%| 1.64%|
| Water Density Inlet                | 0.01%| 0.01%| 0.01%|
| Water Density Mean                 | 0.01%| 0.01%| 0.01%|
| Water Density Outlet               | 0.01%| 0.01%| 0.01%|
| Water Head Model                   | 0.05%| 0.05%| 0.05%|
| Water Temperature                  | 1.34%| 1.34%| 1.38%|
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