Abstract. Velocity measurements were performed in the draft tube cone of a 1:5.1 scaled model of the Tokke hydropower plant, Norway; also known as the Francis-99 model. Results from the laser Doppler anemometry measurements undertaken at three operating points will be used as validation data for an upcoming workshop on the state of the art of Francis turbine numerical simulation. With the turbine operating at the best efficiency point, a sensitivity analysis of the flow parameters head, flow rate and runner rotational speed shows that the effects on the dimensionless velocity profiles are small as long as $n_{ED}$ and $Q_{ED}$ are held constant. The results indicate a well-functioning turbine at the best efficiency point and high load. At the part load operating point, a vortex breakdown occurs which distorts the velocity profiles and significantly lowers the turbine’s hydraulic efficiency. Frequency spectrums of each LDA signal at part load reveals a peak which is asynchronous to that of the runner angular speed. The peaks might be related to the precession of a rotating vortex rope but the characteristics of the LDA signals are different compared to previous studies involving rotating vortex ropes.

1. Introduction
Francis-99 is a set of three upcoming workshops which aims during the next years to determine the state of the art of high head Francis turbine simulations under steady state and transient operating conditions. A high head Francis turbine model known as Tokke, designed and manufactured at the Norwegian University of Science and Technology (NTNU), is the focus of the workshops. Trivedi [1] performed an experimental and numerical investigation of the pressure distribution at different locations of the model; in the spiral casing distributor, on the runner blades and in the draft tube cone. Analyses were carried out during steady state conditions at several operating points covering part load (PL), best efficiency point (BEP) and high load (HL). The agreement between experimental and numerical results was fair with largest discrepancies at part load. The study did however not include any velocity measurements which are necessary data to the first workshop.

Velocity measurements in hydraulic turbine models have been performed by a number of research groups including for example École Polytechnique Fédérale de Lausanne (EPFL), NTNU and Luleå University of Technology. Non-intrusive measuring techniques such as laser Doppler anemometry (LDA) and particle image velocimetry (PIV) have been used to study the flow in Francis and Kaplan turbine models.

At EPFL, Ciocan et. al. [2] used LDA and PIV to investigate the rotor-stator interaction at design and off-design operation at the runner inlet of a pump-turbine model and LDA at the runner outlet of a Francis model. Iliescu et. al. [3], used PIV to analyze the rotating vortex rope (RVR) in a Francis turbine model at different cavitation numbers $\sigma$. It was shown that the RVR diameter varies with $\sigma$ but not with the phase of the RVR. The opposite was shown to be true for the RVR center position, i.e., it varies with the RVR phase but not with $\sigma$.

Vekve [4], presented a study of draft tube flow in a Francis model with different runner cone configurations when the turbine was operating at PL. The study comprised wall pressure and LDA...
measurements. With the original cone configuration, an RVR of significant strength was observed. When different semi-tapered cones were installed and tested, the strength of the RVR was suppressed. The largest semi-tapered cone almost completely diminished the RVR.

Mulu and Cervantes [5] presented LDA measurement results acquired in the spiral casing of a Kaplan model known as Porjus U9 during steady state operation at BEP, PL and HL. The work showed that the mean values of non-dimensional circumferential and radial velocity profiles were similar independent of the operating points. LDA and pressure measurements in the draft tube cone of the model were presented by Mulu et al. [6] and Jonsson et al. [7]. At BEP and HL, an axisymmetric flow was observed and the pressure recovery in the draft tube was close to the ideal value. At PL, the presence of an RVR revolving around a recirculating region distorted the velocity profiles in the draft tube cone and reduced the efficiency of the conical diffuser significantly.

These measurements were followed by inter-blade LDA measurements at steady state operation by Amiri et al. [8]. The velocity measurements inside the blade channels showed good performance of the runner at BEP but revealed some sources of losses, mainly due to hub and tip clearance leakages.

This paper presents the results of LDA measurements performed in the draft tube cone of the Tokke model. Time- and phase-averaged results of the axial and tangential velocity components and Reynolds normal stresses are presented at three steady state operating conditions of the turbine; PL, BEP and HL. The results will be used during the Francis-99 workshop for validation of the numerical simulations of the model at the three operating points. Geometry, mesh, boundary conditions and experimental results are available at www.francis-99.org.

2. Experimental set up

The experimental study was undertaken in a 1:5.1 scaled model of the Norwegian hydropower plant Tokke. The full scale unit comprises a 1.78 m diameter Francis runner operating under a nominal head of \( H = 377 \) m with a power of 110 MW. The distributor of the model and the corresponding prototype are equipped with 14 stay vanes, 28 guide vanes and a runner with 15 splitters and 15 full length blades. The model was mounted in a closed-loop system in which the head was controlled by adjusting the pressure in the upstream and downstream pressure tanks. The flow rate, controlled by the head and the guide vanes position, was monitored by an electromagnetic flow meter installed between the upstream pressure tank and the spiral casing inlet.

Tests were carried out at three steady state operating conditions covering PL, BEP and HL. The head, flow rate and runner angular speed proposed for the Francis-99 workshop corresponding to these operating points are presented in table 1. These operating conditions are in accordance with those investigated by Trivedi et al. [1]. In the present study however, at BEP and HL, vibrations were induced in the test rig which interfered measurements at these conditions. The absolute values of head, flow rate and runner speed were therefore changed according to table 2 while the non-dimensional quantities \( n_{	ext{ED}} \) and \( Q_{	ext{ED}} \) were kept constant. A sensitivity analysis of the velocity profiles dependence on the absolute head, flow rate and runner speed, while keeping \( n_{	ext{ED}} \) and \( Q_{	ext{ED}} \) constant, was carried out.

2.1. Measurement method

A two-component LDA system from Dantec Dynamics was used to measure the axial and tangential velocity components. The measurement system consisted of an 85 mm fiber probe operating in backscattering mode. The probe front lens had a focal length of 310 mm, the measuring volume sizes were \( 0.15 \times 0.15 \times 2.34 \) mm and \( 0.14 \times 0.14 \times 2.16 \) mm, respectively. The radial movement of the probe was controlled by a traverse. An encoder installed on the main shaft allowed the measured velocity components to be phase-resolved with respect to the runner frequency.
Table 1. Test conditions corresponding to the three operating points proposed for the Francis-99 workshop to be held at NTNU in December 2014. The difference in hydraulic efficiency at PL compared to that presented in Table 2 is within the experimental uncertainty.

| Operating point | Head (m) | Flow rate (m³/s) | Runner speed (Hz) | $n_{ED}$ | $Q_{ED}$ | Hydraulic efficiency (%) |
|-----------------|----------|------------------|-------------------|---------|---------|-------------------------|
| PL              | 12.29    | 0.07             | 6.77              | 0.22    | 0.05    | 71.7                    |
| BEP             | 11.91    | 0.20             | 5.59              | 0.18    | 0.15    | 92.6                    |
| HL              | 11.84    | 0.22             | 6.16              | 0.20    | 0.17    | 90.6                    |

Table 2. Test conditions corresponding to the operating points of the current measurements. The difference in hydraulic efficiency at PL compared to that presented in Table 1 is within the experimental uncertainty.

| Operating point | Head (m) | Flow rate (m³/s) | Runner speed (Hz) | $n_{ED}$ | $Q_{ED}$ | Hydraulic efficiency (%) |
|-----------------|----------|------------------|-------------------|---------|---------|-------------------------|
| PL              | 12.29    | 0.07             | 6.77              | 0.22    | 0.05    | 72.5                    |
| BEP             | 12.77    | 0.21             | 5.74              | 0.18    | 0.15    | 92.4                    |
| HL              | 12.61    | 0.23             | 6.34              | 0.20    | 0.17    | 91.0                    |

2.2. Measurement positions

The measurements were performed at two axial locations along the draft tube cone. As shown in figure 1 the measurement sections were located 64 and 382 mm below the draft tube inlet, respectively. The draft tube cone had been manufactured in Plexiglas to allow for optical access. An index matching box made of glass was installed around the cone and filled with water in order to reduce optical distortion from the curved surface. The data acquisition time at each measurement point was 720 s. Depending on the measuring position and operating point this resulted in 75,000-2,800,000 samples. At BEP and HL, the velocity components were measured at 16-17 radial points. The corresponding number at PL was 25-26. The higher number of measuring points at PL was chosen in order to better resolve the larger gradients expected at this operating point.

Figure 1. Cross sectional view of the Tokke runner and draft tube cone with the measuring sections marked. Section I is located 64 mm below the draft tube inlet, the radius is 177.5 mm. The corresponding values at section II are 382 and 196.2 mm, respectively.
3. Data reduction

Due to the periodicity of the flow leaving the runner, a Reynolds triple decomposition as proposed by Telionis [9] was utilized to analyze the flow. The instantaneous velocity field $u(r, \theta, t)$ at radius $r$, phase $\theta$ and time $t$ was decomposed into its mean value, periodic component and random fluctuation as

$$u(r, \theta, t) = \bar{u}(r) + \bar{u}(r, \theta) + u'(r, \theta, t) = \langle u(r, \theta) \rangle + u'(r, \theta, t).$$

(1)

Where $\bar{u}(r)$, $\bar{u}(r, \theta)$, $u'(r, \theta, t)$ and $\langle u(r, \theta) \rangle$ are the time-average, periodic component, random fluctuation and phase-average, respectively. The acquired velocity data was divided into phase bins of equal size $\Delta \phi = 1^\circ$ centered at $\phi_0$. The bin size should be chosen to optimize phase resolution while still keeping up enough statistics in each bin. Amiri et. al. [8] argued that the bins should be selected as small as possible to take into account most systematic fluctuations for phase-average calculations and determine RMS values as accurately as possible. This is of special importance when the flow exhibits large temporal gradients (Zhang et. al. [10]). The mean velocity and RMS in each bin was calculated by a gradient compensation method (linear regression) proposed by Glas et.al [11]. Gradient compensation was performed in order to reduce the influence of possible variations in the mean velocity in the bins and the effect of unevenly spaced data.

4. Results

The velocity components are made dimensionless using the mean velocity at the draft tube inlet. All spatial coordinates are normalized with the draft tube inlet radius ($R=0.175$ m). The results section is divided into two parts; time-averaged and phase-averaged results. Positive axial velocity is defined in the stream-wise direction and the tangential velocity is positive in the runner rotational direction.

4.1. Time-averaged quantities

The effects on the axial and tangential velocity profiles at BEP by varying the head, flow rate and runner rotational speed while keeping $n_{\text{ED}}$ and $Q_{\text{ED}}$ constant is shown in figure 2. There is a small effect on the dimensionless amplitude of the velocity profiles. The shapes of the profiles along the radius however, are similar. The simulations performed at the operational conditions given prior to the Francis-99 workshop should therefore be compatible with the measurements presented in here.

![Figure 2](image-url)
The mean axial and tangential velocity profiles along the radius at the two measuring positions and three operating points are shown in figures 3-5. The axial velocity profiles at the BEP and HL are similar. The axial component reaches a maximum slightly out from the center and this is accompanied by a decrease over most part of the radius. Close to the wall, the axial velocity exhibits a small increase. This might be related to a design criteria, i.e., to energize the boundary layer to prevent separation. Another possibility is that the increase is related to a tip clearance jet as observed by Amiri et. al. [8]. The velocity magnitude decreases from position I to II due to the cone divergence.

At the BEP, the tangential velocity is mainly negative, i.e., it counter-rotates with the runner. The remaining swirl leaving the runner is suitable for flow control purposes by making centrifugal forces in the draft tube cone; see Amiri et. al. [8]. A boundary layer is observed close to the cone wall and a high shear flow at the center. The velocity gradient is small outside the boundary layer and central shear layer. At HL, the tangential velocity profile is similar to that at the BEP but the velocity increases more linearly between $r^* = 0.2$ and 0.8.

![Figure 3](image-url)

**Figure 3.** Mean axial (left) and tangential (right) velocity profiles at measuring positions I and II when the turbine operates at the BEP. Note that the vertical scale differs between the figures.

![Figure 4](image-url)

**Figure 4.** Mean axial (left) and tangential (right) velocity profiles at measuring positions I and II when the turbine operates at HL. Note that the vertical scale differs between the figures.
At PL operation, the performance of the turbine is different from the two previously presented operating points. The runner’s inability to extract the swirl generated by the guide vanes together with the low flow rate results in a vortex breakdown in the draft tube. This gives rise to a recirculation/dead zone formation in the draft tube center. The recirculation/dead zone covers more than half of the cone radius. In this region, the axial velocity is negative which consequently forces very large velocities close to the wall. The performance of the draft tube is poor at PL and the turbine’s efficiency is about 20 % lower than that at the BEP. At measuring position II, the tangential velocity exhibits solid body rotation with an almost linear increase in magnitude over most part of the radius. The tangential velocity is positive at this operating point contrary to the previous cases due to the high level of swirl generated by the guide vanes.

![Figure 5. Mean axial (left) and tangential (right) velocity profiles at measuring positions I and II when the turbine operates at PL. Note that the vertical scale differs between the figures.](image)

The Reynolds stresses, presented in figures 6-8, were calculated by subtracting the phase-averaged velocity (with respect to the runner frequency) from the acquired signals as presented in (1). As for the mean velocity profiles, the stress profiles at the BEP and HL are similar in both magnitude and shape. The axial and tangential components follow similar trends along the radius. The Reynolds stresses are nearly constant along the radius at the draft tube inlet except close to the blades ending region. This is due to the boundary layer effect close to the draft tube walls and the runner cone. The high Reynolds stresses are attenuated along the draft tube cone at the BEP. At HL however, the regions with high Reynolds stresses are present at both measurement sections.

At PL, the Reynolds stresses are one order of magnitude larger than those at the BEP and HL. In contrast to the profiles at the BEP and HL, the maximum stresses are not attained at the draft tube center but close to \( r^* = 0.8 \), i.e., close to the end of the dead zone. This is due to the high shear layer between the central dead flow region and the high velocity flow at the outer part of the draft tube cone.
Figure 6. Reynolds normal stresses $u'^2$ (left) and $v'^2$ (right) at measuring sections I and II when the turbine operates at the BEP. Note that the vertical scale differs between the figures.

Figure 7. Reynolds normal stresses $u'^2$ (left) and $v'^2$ (right) at measuring sections I and II when the turbine operates at HL. Note that the vertical scale differs between the figures.

Figure 8. Reynolds normal stresses $u'^2$ (left) and $v'^2$ (right) at measuring sections I and II when the turbine operates at PL.
4.2. Phase-averaged quantities

Contour plots of phase-averaged velocity profiles at the BEP and PL measured at position I are shown in figures 9-10. In three of the sub figures, the encoder installed on the runner shaft was used to phase-resolve the data. The flow is periodic at the BEP and the 15 blade passages are clearly visible in both the axial and tangential components. The contours at HL (not presented in here) also show similar effects of the blades, less pronounced though. At PL, the velocity is presented with an exponential scale in order to highlight the effects of the blades close to the wall. The blade passages are clearly visible close to the wall but the effect diminishes as the dead zone is approached.

Frequency spectrums of the LDA signals from all measurements at PL (not shown in here), reveal small peaks around 1.8 Hz. The source of these peaks has not yet been determined but they can be related to an RVR, or oscillations of the vortex breakdown. The PL data were also phase-resolved with respect to the 1.8 Hz oscillation using the method introduced by Jonsson et. al [7]. The LDA signals were band-pass filtered around 1.8 Hz and the time difference between two consecutive peaks was used as the triggering signal to phase-resolve the data. The passage of an RVR results in a maximum or minimum value of the tangential velocity and the radial profiles were matched based on this criterion. The phase-averaged tangential velocity component measured at position I is presented in figure 10. The profile does not display a periodic behavior and there is no sign of an RVR. A similar behavior, although not shown here, is exhibited at position II. This is in contrast to the results presented by Jonsson et. al [7] and Vekve [4]. Their works showed strong effects on the tangential and axial velocities at the passage of the RVR. Regions of almost constant velocities at the center of the RVR surrounded by significant peaks were observed. The pressure measurements performed in the Tokke model by Trivedi et. al. [1] neither showed any clear sign of an RVR at the present operating point. These results differ from the PL study of a Kaplan model performed by Amiri et. al. [12] where strong effects of an RVR was observed in the pressure measurements at the draft tube cone, runner blades and inlet. Since neither LDA nor pressure measurements have successfully explained the behavior of the turbine at PL, flow visualization should be used for further investigations.

![Figure 9. Phase-averaged axial (left) and tangential velocity (right) measured at position I during BEP operation.](image-url)
Figure 10. Tangential velocity component phase-averaged with respect to the runner frequency (left) and with respect to the 1.8 Hz oscillation (right) measured at position I during PL operation. Note that the velocity in the left figure is presented with an exponential scale in order to more clearly visualize the effects of the blades.

5. Conclusions
Velocity fields in a Francis turbine model was investigated by LDA measurements at two axial sections in the draft tube cone when the turbine was operating at part load, best efficiency point and high load.

By varying the head, flow rate and runner angular speed while keeping the dimensionless numbers $n_{E/D}$ and $Q_{E/D}$ constant, it is shown that these parameters only have a small effect on the dimensionless velocity profiles at the best efficiency point. Hence, numerical simulations performed at the values of $n_{E/D}$ and $Q_{E/D}$ investigated within this work should be compatible with the measurements presented in here independent of the absolute values of head, flow rate and runner frequency.

At the best efficiency point and high load, the velocity profiles and Reynolds stresses are qualitatively similar and the turbine is working properly. The low level of swirl leaving the runner is mainly negative, i.e., counter-rotates with the runner but close to the wall it is positive for flow control purposes by making centrifugal forces in the draft tube cone to prevent separation. At part load operation, the velocity profiles are distorted and a vortex breakdown occurs which creates a recirculation region covering more than half of the cone radius. Frequency spectrums of the LDA signals at this operating point reveal small peaks, asynchronous to the runner frequency, at 1.8 Hz. The source of these peaks is not completely determined but they might be related to a rotating vortex rope. However, the characteristics of the LDA data do not resemble that of previous studies involving rotating vortex ropes. The peak might therefore as well be related to oscillations of the vortex breakdown. Flow visualization should be used for further investigations of the source of this peak.

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