Measuring swirl at a model scale of 1:1 for vertically submersible pumps

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Abstract. Intakes of large pump stations are often designed with the aid of hydraulic modeling. The approach flow to pumps is tested for adverse hydraulic phenomena, such as pre-swirl, velocity variations and vortices. Most commonly, the limits for these phenomena are taken from the ANSI/HI 9.8-2012 standard – Rotodynamic Pumps for Pump Intake Design. The standard, however, does not explain how real pumps respond to swirl, uneven velocity distribution or vortices. The present joined study between Deltares and Xylem aims to bridge this gap. At the Deltares pump sump test facility, two identical pump compartments were built according to the ANSI/HI 9.8-2012 standard. In one of the compartments, a submersible, vertical column pump (Flygt PL7020) was installed, while a 1:1 scale model of that pump was installed in the other compartment. This arrangement allowed measurements of both pump performance (pump head and input power as a function of flow rate) and the model parameters (pre-rotation and vortex occurrence) for nearly identical approach flow conditions. By varying the geometry of the approach channels, the asymmetry of the flow was varied to produce various degrees of pre-swirl including values in excess of the commonly accepted limit of 5 degrees. This paper describes the measurement setup, the results of the measurements with the model pump and the measurement plan for the prototype pump.

1. Introduction

It is commonly known that swirl in approach flows affect the pump performance ([3]). Small hydraulic disturbances in the approach flow towards a pump already induce swirl, while pump curves are normally determined without the presence of swirl. To achieve an optimal pump working, the amount of swirl should be limited.

The performance of a pump is affected by the presence of swirl in the approach flow. If the direction of the swirl is equal to the rotational direction of the impeller, the pump curve will shift downwards, while for a swirl that rotates opposite of the impeller, the pump curve will shift upward ([4]). A shifting pump curve results in a shift in the best efficiency point and therefore in a reduced efficiency. This effect is shown in Figure 1.
The effect of swirl on pumps can be explained theoretically by means of the velocity diagrams. However, to determine the average swirl in the approach flow, physical scale modeling is often used. In these tests, the swirl can be accurately measured by means of a swirl meter in the suction line. The ANSI/HI 9.8-2012 standard for Rotodynamic Pumps for Pump Intake Design (hereinafter referred to as HIS [1]) defines that the amount of swirl in the approach flow should be limited and that the swirl angle should be lower than 5°. This criterion is based on expert judgment ([5]) and is commonly accepted as maximum allowable swirl in pumps.

Although the effect of swirl on a pump is qualitatively known, it is not yet determined quantitatively. In this publication, we present the results of an investigation on the quantitative effect of swirl on the efficiency of a pump. Deltares and Xylem Inc. commonly set up a research plan to quantitatively determine this effect by means of a hydraulic model test. In the Deltares pump sump test facility, two identical pump compartments were built according to HIS ([1]). In one of the compartments, a submersible, vertical column pump (Flygt PL7020) was installed, while a 1:1 scale model of that pump was installed in the other compartment. This arrangement allowed measurements of both pump performance (pump head and input power as a function of flow rate) and the model parameters (pre-rotation and vortex occurrence) for nearly identical approach flow conditions. By modifying the approach flow in the approach flow channels, the asymmetry of the flow was varied in order to produce various degrees of pre-swirl, ranging from 3° to 16°.

This publication presents the whole measurement setup for both the model and the prototype pump and it presents the results of the tests for the model pump. At the moment of writing the results of the prototype pump are not yet available. Therefore only the plan for these measurements is presented. The measurements of the prototype pump and the effect of swirl on the prototype pump will be discussed in the next article in this series.

2. Measurement setup
The setup is built in the Deltares IOS-2 test facility. In this facility, two pump chambers are build adjacent to each other. Figure 2 shows the IOS-2 test facility including the setup in the dashed box. The IOS-2 basin has a length of 15.7m and has a width of 6m. At the location of the pumps a glass wall is present, which allows for visual observation. Table 1 presents the dimensions of the pump compartments. These dimensions are compliant with the HIS ([1]).
The water depth applied in all measurements is 1.4 m. This is the maximum water depth that could be reached in the test facility. Although the submergence criteria as presented in the HIS ([1]) were reached at this water level, free surface vortices were present. The free surface vortices appeared mainly in the test cases with low swirl and little turbulence. At higher flow rates, the turbulence near the pump reduced the stability (and consequently the strength) of the vortex. On average, these vortices were classified as type 4 vortices according to classification as described in the HIS ([1]).

| Symbol | Description                                      | Value             |
|--------|--------------------------------------------------|-------------------|
| $D$    | Bell mouth diameter (model scale)                 | 430 mm            |
| $d$    | Internal diameter suction pipe (model scale)     | 266 mm            |
| $B$    | Distance back wall - centre line bell mouth       | 0.75 $D$          |
| $W$    | Width of the pump compartment                     | 2 $D$             |
| $C$    | Bottom clearance of the bell mouth                | 0.5 $D$           |
| $Z1$   | Distance bell mouth – Flow guiding walls         | 5 $D$             |
| $\beta$| Angle flow guiding walls                          | 30°               |
| $Q_m$  | Flow rate – model pump                            | 150 - 260 l/s     |
| $Q_{p-35Hz}$ | Flow rate – PL7020 at 35 Hz                  | 150 - 260 l/s     |
| $Q_{p-50Hz}$ | Flow rate – PL7020 at 50 Hz                  | 220 – 380 l/s     |

Table 1. Detail of pump compartments including dimensions.

The governing flow patterns are included in Figure 2. The dark blue line represents the flow patterns for the model pump and the light blue line represents the flow patterns for the prototype pump. The return flow from the prototype pump is close to the entrance of the pump chambers. To overcome short cuts in the flow, a separation wall is placed in the test facility to generate a similar approach flow towards the pump compartments as present for the model pump (see Figure 2). At the entrance of the pump compartments, flow guiding walls with a length of approximately 5$D$ are placed under an angle of 30° with the pump compartment walls. These flow guiding walls are applied in order to obtain a more stable and repeatable approach flow condition.

Below the pumps, cones were placed in order to reduce the strength of the submerged bottom vortex. Submerged vortices from the sidewall and the backwall were present in the design. However, by installation of splitters in the pump chamber, not only the vortices would reduce in strength, but the swirl angle would also decrease. For this reason, no anti vortex measures were implemented in the pump chamber other than the cone below the pump.

The model pump and the prototype pump were operated independently. This was mainly done to obtain an equal flow towards the pumps chambers and to avoid large transient flow behaviour in the basin (e.g. water level fluctuations).
Figure 3: Pump compartments seen from the glass wall (back wall). Left: the model pump made of Perspex and right: the prototype pump, which is placed in a green casing. The blue lines represent the flow lines.

2.1. Prototype pump
The prototype pump is the Flygt PL7020 pump. At the best efficiency point, the pump delivers a head of 6.7 m at a flow rate of 235 l/s. This vertical submersible pump is placed in a vertical casing (see Figure 3), which is connected to the return flow pipe. The prototype pump including the measurement equipment is presented in Figure 4. A butterfly valve is located in the return flow line just after the T-junction in order to control the flow and to measure a Q-H curve.

Figure 4: Cross section of prototype pump. The blue lines indicated the flow directions through the system.

2.1.1. Measurement
A pressure sensor is placed on the blind flange at the T-junction above the pump. The pressure sensor that is applied is a PDCR-4030 absolute pressure sensor with accuracy (2σ) of 2 mbar. In the return
flow line, a flow meter is installed at 5 times the pipe diameter downstream of the valve. An electromagnetic Endress and Hauser flow meter is applied with a diameter of DN350. The accuracy (2σ) of this flow meter is 0.5% of the measured flow.

2.2. Model pump
The model pump is made of Perspex and is schematized as a suction line as prescribed in the HIS ([1]). The bellmouth, the internal and external diameters of the pump are exactly reproduced. The swirl meter is located at a distance of 4D above the bellmouth. Swirl is measured by means of 4 magnets on the vanes of a low friction Perspex swirl meter, which are tracked by 3 sensors on the outer tube. This measurement method, including the obtained accuracy is extensively described in De Fockert et al ([2]).

In this setup, a long measurement of 3 hours was performed to investigate the accuracy of the measurement time for a specific measurement window. The average flow rate for this case was 200l/s and the long term swirl angle for this case was 2.9° in clockwise direction. Figure 5 shows the accuracy of the measurement for a specific time window. The selected time window for the measurements is 15 minutes, resulting in an accuracy of 0.3°.

![Swirl accuracy against measurement time](image)

**Figure 5:** Accuracy of measurement against measurement time.

3. Flow patterns and swirl angles

3.1. Approach
Small obstructions in the approach flow lead to swirl. The swirl in our setup was induced by installation of vertical plates perpendicular to the pump compartment walls over the whole depth of the pump compartment. By varying the width of the plate (30cm or 40cm) and by installation of multiple plates at different distances upstream of the pump, repeatable swirl angles were found for 4 steady clockwise swirl angles and for 4 steady counter clockwise swirl angles. For each swirl angle, at least 3 measurements were performed to verify the repeatability of the swirl for a specific approach flow condition.

3.2. Model adaptations to obtain swirl angle
The flow patterns for the different clockwise (CW) rotating swirl angles are presented in the Figure 6 to Figure 9. Clockwise rotating swirl represents co rotating swirl for the prototype pump and vice versa. For counter clockwise rotating swirl, 4 repeatable approach flow conditions are found, representing 3°, 6°, 9° and 16°. Apart from the 3° swirl case the flow is attached to the right sidewall
of the pump compartment. For each implementation, large recirculation zones are present behind the installed plates. For some conditions, this resulted in free surface vortices. However, these vortices were not entering the pump. It was found that larger swirl angle could be created by placing the plates closer to the pump, such that the flow was more defined near the pump, resulting in a stronger circulation around the pump and a larger swirl angle. The free surface vortices that were present at these cases were found at the left side of the pump near the glass wall.

![Figure 6: 3° CW](image)
![Figure 7: 6° CW](image)
![Figure 8: 9° CW](image)
![Figure 9: 16° CW](image)

The Figure 10 to Figure 13 show the depth averaged flow patterns for the cases with a counter clockwise (CCW) rotating swirl. To obtain a counter clockwise swirl at the pump, the geometrical obstructions were placed at the left sidewall instead of the right sidewall, except for the case with a swirl angle of 16° CCW. This is mainly caused by the fixed construction of the guiding walls, which were placed under an angle of 30° with the pump compartment wall. The free surface vortices that appeared in these cases were found at the right side of the pump near the glass wall.

![Figure 10: 3° CCW](image)
![Figure 11: 6° CCW](image)
![Figure 12: 9° CCW](image)
![Figure 13: 16° CCW](image)

It was found that it was difficult to determine the swirl angle for a specific geometrical modification based on anticipated flow patterns and expert judgment. Finding the “stable” and repeatable swirl angles was an iterative procedure, which was done by a dedicated approach.

It has to be noted that for all conditions, submerged vortices were found. At the top of the cone below the pump, submerged vortices were found. The strength of these vortices was found proportional to the discharge rates. Additionally to these vortices, submerged back wall vortices of a type 2 (dye core [1]) were found at the glass wall. The presence of these vortices is inherent to the
setup, because high swirl angles can only be obtained through a strong circulation flow around the pump. For this reason, no obstruction was placed behind the pump. This resulted in vortices coming from the back wall. In most setups, sidewall vortices of type 2 (see ref [1]) were found as well. However, these vortices were relatively weak compared to the back wall vortices.

3.3. Analysis
For the found setups as presented in Figure 6 to Figure 13, a repeatable long term swirl angle was found. However, a significant variation is observed in the short term swirl angle. The results in this section are therefore described as averaged (over 15 minutes) short term swirl angles based on a measurement interval of 30s. This gives the possibility for a statistical analysis on the data.

Figure 14 and Figure 15 illustrate some swirl measurements by means of probability density functions. In Figure 14, a cumulative distribution function is presented for the measured swirl angle of 6° clockwise and 9° clockwise for an average flow rate of 240 l/s and in Figure 15 a cumulative distribution function is presented for 3° clockwise and 3° counter clockwise rotation. From both figures, it becomes clear that there is a large spread in swirl angle of the total measurement period. A long term swirl angle of 9° implicates short term swirl angles ranging from 0° up to 16°. This large range in swirl angles is related to the stability of the flow patterns near the pump. De Fockert et al ([2]) showed that for a pump compartment including splitters the range in swirl angle is much lower than for an empty pump compartment.

![Figure 14: Cumulative density plot for the swirl angles of 6° and 9° clockwise for a flow rate of 240 l/s.](image)

![Figure 15: Cumulative density plot for the swirl angles of 3° CW and 3° CCW for a flow rate of 240 l/s. The error bars in the top of the plot show the mean and standard deviation in case of an absolute summation of the rotation and a total summation of the swirl meter (Section 3.3.2.)(image)

For larger swirl angles, the swirl meter is generally rotating in one direction. However for smaller swirl angles (< 5°), the swirl might change direction during a measurement of 15 minutes. This behavior was also observed for the low swirl angles of 3° (see Figure 15). A clockwise rotation of 3° ranges from 10° clockwise to 7° counter clockwise and a counter clockwise rotation of 3° ranges from 4° clockwise to 9° counter clockwise.

3.3.1. Overlap
In both Figure 14 and Figure 15 it seen that the short term swirl angles overlap. An average short term swirl angle of 6° ranges between 1° and 11°, while an average short term swirl angle of 9° ranges from 0° to 16°. For these measurements the short term swirl angles overlap for 53% of the time.
The range in swirl angles depends both on the turbulent flow and the design of the swirl meter. A swirl meter with a large inertia will catch less turbulent fluctuations and will produce a more continuous signal. In our measurements, we have used a swirl meter that is made out of Perspex and has low friction bearings. Due to the low inertia, all turbulent features in the flow are recorded by the swirl meter. The most referred standard in this field of expertise, the HIS ([1]) prescribes the dimensions of the swirl meter and it prescribes that the swirl meter should have low friction bearings. No requirements related to inertia of the swirl meter are given in this standard.

3.3.2. Defining swirl for low swirl angles
Defining a swirl angle for a measurement with a clockwise and counter clockwise rotation in one measurement is not unambiguous. The main reason for this is the summation of counter clockwise and clockwise swirl. This can be explained best by means of an example:

If a swirl meter in a 10 minute measurement window rotates for 5 minutes in clockwise direction at a swirl angle of 3° and after that in counter clockwise direction at 3° for the remaining 5 minutes, then the swirl angle can be either 0° (viz. the swirl meter has an absolute rotation of 0 degrees in 10 minutes) or 3° when swirl is calculated absolutely.

Both methods of calculating swirl can be augmented. A swirl angle of 0° would be logical, because the head increases and decreases over the measurement period and the average head will be the head of the Q-H curve in (or near) the best efficiency point (see Figure 1). With a constant power, this would result in the efficiency as present in the best efficiency point. However, because the efficiency curve is parabolic, with the highest efficiency at the top of curve, the efficiency has dropped by both clockwise and counter clockwise rotation. This would mean that the average efficiency would be the efficiency at a swirl angle of 3°, which is lower than the efficiency at the best efficiency point.

For small swirl angles (<5°) a clockwise and counter clockwise rotation is normally present, meaning that more swirl angles could be defined. In Figure 15, this behaviour is illustrated in our measurements. At the top of this figure, 2 error bars are presented considering a total rotation of the swirl meter and considering an absolute rotation of the swirl meter. For the low clockwise swirl angle, an absolute long term swirl angle of 2.9° is recorded, while this reduces to 1.9° if the long term swirl angle is considered in total. For counter clockwise rotation, the absolute long term swirl angle is 2.7°, while the total rotation would give a swirl angle of 2.1°. This effect is not observed for larger (>5°) swirl angles, as the rotation is normally fully in one direction.

3.3.3. Summary of results
For each test condition (flow rate / swirl angle), a 15 minutes measurement was performed. Figure 16 presents a statistical analysis on the swirl angles. The average short term swirl angles are presented by means of error bars, showing the standard deviation in the short term swirl angles. In this graph, two lines are presented for the low clockwise and low counter clockwise swirl. These values are based on the definition as presented in Section 3.3.2.

In Figure 16 it is seen that the average short term swirl angles are not fully repeatable for different flow rates. The average of the 9° counter clockwise swirl deviates between 9° and 10°. This figure shows clearly an overlap in data and the average standard deviation in short term swirl ranges between 2° and 3°. The standard deviation in the flow rate is relatively repeatable for all measurements (± 0.5 l/s – 1.0 l/s).
As swirl depends on the turbulent fluctuations in the pump compartments, higher flow rates might result in slightly different approach flows and consequently different swirl angles. The exact relation between these phenomena is not investigated in this research.

4. Prototype pump
At the moment of writing this publication, the results of the prototype pump are not yet available. For the prototype pump, measurements will be carried out 35Hz and at 50Hz. The results of the measurements for 35Hz are directly comparable to the results of the measurements of the model pump, because the range in flow rates is equal. As the normal operation of the PL 7020 pump is at 50 Hz, these results will also be used in the comparison.

5. Discussion
Due to time constraints, the results of the prototype pump are not yet applicable. Therefore this paper only describes the results of the measured swirl angle in the model pump.

Generally, swirl is judged in an absolute sense. This is done, as both clockwise and counter clockwise swirl have an effect on the Q-H curve and thus on the efficiency of the pump. However, defining counter clockwise swirl as positive swirl and clockwise swirl as negative swirl, a summation of clockwise and counter clockwise swirl might result in a reduced swirl angle. In our analysis both methods are presented. For the verification against the prototype measurements, the effect of summation will be analysed and it will be defined which method is better applicable for low swirl angles with both counter clockwise and clockwise rotation.
In the measurements it was observed that the range in short term swirl angle is relatively large for a measurement window of 15 minutes. This large range in swirl angles is related to the stability of the flow patterns near the pump. De Fockert et al. ([2]) showed that for a pump compartment including splitters the range in swirl angle is much lower than for an empty pump compartment. In our investigation, large swirl angles up to 16° were created. This could only be achieved without anti vortex measures in the pump chamber.

In the tests performed, a light swirl meter with low friction bearings was used. Due to the low inertia, all turbulent features in the flow are recorded by the swirl meter. A consequence of this approach is the large variation that was observed in the short term swirl angles. At this moment, no standard or guideline prescribes the detailed requirements of a swirl meter regarding inertia.

Although the higher flow rates might lead to different flow patterns at the pump, the swirl angle appears to be relatively constant for different flow rates. A variation in swirl of about 1° around the average value was found for the different swirl angles.

During the measurements, different types of vortices were observed. At higher flow rates, a type 3 vortex (as specified in HIS ([1]) was observed from the cone. Next to this, for most measurements, submerged vortices from the back wall and the side walls were present. Although it is difficult to quantify the effect of these vortices on the rotation of the swirl meter, the effect on the long term swirl angle is judged negligible.

6. Conclusion
A setup was created to determine the effect of swirl on the pump curve. In two identical pump compartment, a model pump and a prototype pump were placed, which were exactly scaled. Swirl was measured in the model pump and a Q-H curve was measured in the prototype pump.

For the model pump, four clockwise and four counter clockwise swirl angles are determined. A fixed pump compartment design was used with a standardized pump compartment layout (after the guidelines in the HIS ([1]). By means of installation of plates in the pump compartment repeatable swirl angles were defined for 3°, 6°, 9° and 16°.

The relatively wide range in the swirl angles was found, which results in a large overlap of short term swirl angles. An average swirl angle of 6° and an average swirl angle of 9° have an overlap of about 50%. The results are therefore also only judged based on average long term swirl angles.

The modifications in the approach flow by means of installation of vertical plates results in repeatable swirl angles. The modifications form a good basis to determine the effect of swirl on the efficiency of the pump.

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