Whole Field Flow Measurements of Attraction Channel as Entrance to Fishways

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Migrating fish that swim upstream rivers for reproduction need to overcome obstructions like hydropower plants in their path to the spawning grounds. To guide the fish pass the obstruction fishways are often used. Since most of the water in regulated rivers flow through the power plant fish are often attracted to the turbine tailrace instead of the fishways. The efficiency of the fishways is often low due to inefficient attraction water.

In this report an attraction channel which uses a small fraction of the tailwater, or any free stream, to create the attraction water is studied. The channel is open and U-shaped. A local acceleration of the water is created by changing the cross sectional area in the downstream end of the channel. The flow through the channel is subcritical and the bump which accelerates the water also blocks the water flowing into the channel. To study how the water flows are affected of the blockage as the geometry is altered, a model of the channel is studied in lab scale using Particle Image Velocimetry (PIV). With PIV instant flow field can be studied in a plane of the flow.

The results show the water flow in and around the channel and how the flow pattern in the channel changes with water depth. Increased depth over the bump increases the downstream traceability of the acceleration. It is also shown that it is possible to obtain accelerations up to 50% downstream the attraction channel compared to the pure flow upstream.
This project has been carried out at the Division of Fluid Mechanics, Luleå University of Technology, Sweden, August 2006 - May 2007. The supervisors for this project have been Professor T. Staffan Lundström and PhD student Elianne Wassvik. It is carried out as a Master thesis for the Master of Science Program in Mechanical Engineering with focus towards Applied Mechanics. This thesis has also been a part of the Research Trainee program 2006/2007 at Luleå University of Technology.

I would like to thank my supervisor’s professor Staffan Lundström and Ph.D. student Elianne Wassvik for their encouragement in my work. I would also like to thank professor Håkan Gustavsson for his never ending ideas and the technician Allan Holmgren without whom the division would come to a stop.

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CHAPTER 1

Introduction

Migrating fish who swim upstream rivers for reproduction need to overcome obstructions of different kinds, for example hydropower plants. To help the fish on their way upstream fishways and fishlooks are commonly used. There are problems with the modern fishway. Firstly the fishway uses water directly from the reservoir above the hydropower plant. This water does not pass through the turbines and does not generate any electricity, and is therefore a financial loss for the hydropower companies. Secondly, the fish does not find the entrance to the fishway [13] because they have a hard time to find the fishway access, also known as attraction water, in the dominating flow from the turbine tailrace [1].

To create effective attraction water the objective is to receive as high velocity of the water as possible since the salmon like fish is attracted by the higher velocity [16]. When designing the attraction water one has to account for what type of fish that is supposed to pass and adapt the water velocity to their maximum swimming capability. The recommended speed of the attraction water is 1.2 to 2.4 m/s [3].

The division of Fluid mechanics, at Luleå University of Technology, has since 2004 had an ongoing project on how to create more effective attraction water. The idea is to use an open U-shaped channel, further on referred to as attraction channel, with a contraction in the downstream end; see figure 3.1(a) and 3.1(b). The attraction channel uses only a fraction of a free stream, like the tailrace from a hydropower plant [14], to locally accelerate the water and guide the fish.

Earlier work on the attraction channel includes lab scale model tests with Laser Doppler Velocimetry, LDV [14], and field studies [15]. This thesis continues the work previously conducted by PhD student Elianne Wassvik [14, 15]. The objective for this work is to see how the depth over the contraction in the attraction channel affects the flow through and behind the attraction channel using Particle Image Velocimetry, PIV, as the method. Also a comparison of the flow rate measured with the PIV-system and the mass flowmeter to estimate the exactitude of the PIV was performed.
The fundamentals of PIV has been known since 1904 when Ludwig Prandtl first started doing flow visualization experiments with a simple water tunnel and added particles. These neat experiments gave Prandtl qualitative description of the flow [12]. But it was not until the eighties that PIV, as we know it today, began to develop thanks to technical progress in lasers, electronics and digital graphics processing. It is therefore in our time possible to receive quantitative information out of a technique first developed for qualitative flow visualization.

As illustrated in figure 2.1 a simple PIV setup consists of a light source that illuminates the fluid of interest with a thin light sheet. The idea is to light up tracer particles in the fluid, at least two times in a short time period. The tracer particles motion is recorded. From the recordings the particles displacement can be calculated statistically with cross-correlation. From the cross-correlation the velocity vector field can be achieved.

The advantage of PIV is that it is a non intrusive measuring method, compared to other methods that use probes of various kinds, like hotwire or pressure tubes. The disadvantage of PIV is that it is an indirect method since the tracer particles distributed in the fluid are the object for the measurement and the particles might move in a different pattern as compared to the fluid.

### 2.1 Light Sources

Today the most PIV investigations are performed with laser as light source. However it is possible to use white light, for example Xenon lamps which are well suited for CCD cameras. The disadvantage of a white light is the finite extension and that it can not be collimated as well as monochromatic light. On the other hand they are cheaper and not restricted with safety rules compared to lasers.

As mentioned above, lasers are widely used in PIV. The advantage is their ability to emit monochromatic light with known wavelength. The emitted laser beam can be altered
Figure 2.1: The figure shows a simple PIV system containing a laser, dispersion optics, recording device and a seeded fluid. The laser beam is spread by the optics to a light sheet which illuminates the tracer particles in the fluid. The illuminated particles are recorded with a camera.

Figure 2.2: The light sheet optics as seen from the side, where $T_1$ is the diameter of the laser beam and $T_2$ is the illuminating light sheets thickness.

into thin light sheet through a positive cylindrical lens, $L_1$, and a negative spherical lens, $L_2$; see figure 2.2. The light sheet thickness, $T_2$, should be adjusted so that the tracer particles out of plane motion is reduced from each recording but broad enough to illuminate enough particles.

2.2 Tracer Particles

In PIV measurements the tracer particles in a fluid has a significant role. It is assumed that the particles are homogeneous distributed in the fluid and that the particles follow the fluids motion well. To oblige the assumption that the particles follow the fluids motion it is important to choose the tracer particles wisely. If the particles have a density, $\rho_p$, significantly separated from the fluid, $\rho_f$, the gravitational force affects the particles path. The induced gravitational velocity $U_g$ that affects a spherical particle in a viscous flow at
low Reynolds number, can be derived from the Stokes drag law according to equation 2.1.

\[
U_g = \frac{d_p \rho_p - \rho_f}{18 \mu} g
\]

where \(d_p\) is the particles diameter, \(g\) the acceleration vector due to gravity and \(\mu\) the dynamic viscosity of the fluid.

The tracer particles should also be chosen by their light scattering behaviour. The more light scattered from the particle the greater contrast in the PIV recordings, which assists the cross-correlation.

Another important aspect is the particle image density. The image density can be categorised in three different modes; low, medium and high image density. In the case of low image density a single particle can be traced from different illuminations, hence this situation is referred to as particle tracking velocimetry. In the case of medium image density the images of individual particles can be detected, although it is challenging to distinguish image pairs by ocular examination. For the high image density case it is impossible to detect pattern since the particles form speckles.

To receive high quality PIV recordings it is desired to get medium density images, i.e. each interrogation window (see section 2.3) should contain 10-14 tracer particles.

### 2.3 Cross-Correlation

In signal processing, the cross-correlation is a measure of similarity between two signals, commonly used to find characteristics in an unknown signal by comparing it to a known one. In PIV the cross-correlation evaluation is done by dividing an image in to sub-pictures, \(I\), and comparing each sub-picture with a connected sub-picture from a time-displaced image, \(I'\). The tracer particles in each sub-picture have a higher intensity then the rest of the sub-pictures. When the particle pattern in the two samples corresponds, the displacement between the two sub-pictures can be decided. If the time-displacement is known the resulting velocity vector can be decided.

A rule of thumb when choosing the size of the sub-pictures, also known as interrogation window, is that the particles should move not more than \(\frac{1}{4}\) of the interrogation windows size in X- or Y-direction.

The mathematics of the cross-correlation scheme is well described by Raffel et al [12], therefore is only the function and a short description presented bellow.

\[
R(x, y) = \sum_{i=-K}^{K} \sum_{j=-L}^{L} I(i, j) I'(i + x, j + y)
\]

The variables \(I\) and \(I'\) are the sub-pictures as extracted from the images, where \(I'\) is larger then the reference \(I\). \(I\) are linearly transferred over \(I'\), resulting in that for each shift \((x,y)\) the sum of the products for all overlapping pixel intensities produces one cross-correlation value \(R(x,y)\). This results in a correlation plane of size \((2M + 1) \times (2N + 1)\). In the correlation plane there exists one value of \(R(x,y)\) that is larger then elsewhere.
A faster way to calculate the cross-correlation is to do it in the frequency domain by taking advantage of the correlation theorem which states that the cross-correlation of two functions is equivalent to a complex conjugate multiplication of the Fourier transforms:

$$R \Leftrightarrow \hat{I} \cdot \hat{I}'^*$$

(2.3)

where $\hat{I}$ and $\hat{I}'^*$ are the Fourier transforms of the functions $I$ and $I'$. The Fourier transform is effectively implemented for discrete data using the fast Fourier transform [2, 10, 11, 12].
CHAPTER 3

Experimental setup

The experimental equipment consisted of a scale model of the attraction channel, a commercially available PIV-system, a water flume and a Coriolis mass flowmeter. A more specific description of the equipment is found in section 3.1.

The PIV measurements was carried out in two steps; firstly a flow mapping study of the pure flume was performed. Secondly measurements of the attraction channel were performed.

3.1 Experimental Equipment

3.1.1 PIV-System

The PIV-system from LaVision GmbH consists of a Litron Nano L-PIV laser, i.e. a double pulsed Nd:YAG laser. The generated laser beam has a wavelength of 532 nm. The laser was mounted on a traverse that allows the light sheet to be moved freely 500 mm in the X-, Y- and Z-direction. This simplifies scanning procedure of a volume.

To the PIV-system followed a light sheet optic. All the lenses are mounted in a house, allowing the user to easily change the dimensions of the light sheet, like sheet height, focus length, etc. The height of the light sheet is determined by an extra divergence lens at the end of the sheet house. With the optic house came two divergence lenses with different focal length, $f = -20$ mm and $f = -10$ mm. For this experiment the $f = -10$ mm were found suitable since it spread the light sheet sufficiently. For more detailed description about the light sheet optics see chapter 4 of the DaVis hardware manual [9].

Since the fluid direction of interest is the U-component $V_x$ going in the X-direction, see figure 3.1(c), and the bottom of the flume is made out of metal, the light sheet had to come vertically from above, i.e. the Z-direction. This was managed by attaching the light sheet optics on a Linos FLS rail. Another benefit with this setup was that both flume walls could easily be reached in the flow mapping experiment.
With the system came two LaVision ImagerProPlusHS cameras, allowing stereo-PIV. Here only one camera was used. The ImagerProPlusHS has a Peltier cooled CCD with $1280 \times 1024$ pixel resolution, the pixel size is $12.0 \times 12.0 \mu m$. The maximum recording speed is 636 frames per second when using full frame. The sensor is optimized for light with the wavelength of 520 nm.

The lasers and the camera are triggered by a programmable timing unit, PTU, which is managed from LaVisions computer software *DaVis FlowMaster 7.1*. The software also controls the translation stages and computes the vector fields.

### 3.1.2 Water Flume

The water flume used is a 7.5 m *S5 tilting flume* from Armfield Ltd, with a inner cross-section of $295 \times 310 \text{ mm} W \times d_0$; see figure 3.1(b) and 3.1(c). The S5 is a rigid construction with glass walls and metal bottom. At the inlet of the flume a honeycomb and steel net was placed to create a uniform velocity distribution. The honeycomb is 75 mm thick and the holes has a diameter of 7.6 mm. The net is made out of 0.8 mm thick steel wire, woven with a thread spacing of $2.5 \times 2.5 \text{ mm}$.

Water level is controlled by a wire at the downstream end of the flume; see figure 3.1(c). Under the flume outlet is a water reservoir, with a volume of 1 m$^3$, and a pump. The pump supplies the flume with water at variable flow speed.

The flume can be tilted in positive and negative angle to study different flow phenomena.

### 3.1.3 The Attraction Channel

The model of the attraction channel is the same as Wassvik used[14]. It is an 500 mm long open channel made of 1.7 mm window glass; see figure 3.1(a). The inner cross-section of the attraction channel is $200 \times 96 \text{ mm}$. At the downstream end of the channel is a contraction in the shape of a quadratic polynomial, given by

$$h(x') = B - \frac{x'^2}{12B} \quad (x' \geq 0, h \geq 0)$$

where $B$ is the highest point of the bump and $x'$ originates at the highest part of the bump and run in the negative $x$ direction. The bump have a vertical downstream end. The upstream inlet of the attraction channel is placed 4015 mm downstream from the steel net; see figure 3.1(c).

According to Wassvik [14] the 80 mm high bump gave the highest acceleration, therefore only the 80 mm bump was used.

### 3.1.4 Coriolis-Acceleration Flowmeter

A Coriolis-acceleration flowmeter measures two things, the fluids density and flow rate [5].
A mass flowmeter uses the Coriolis acceleration [8] to measure the fluid density. The density is measured by letxing the fluid flow through a U-shaped tube. The tubes two ends are stiffly mounted. The bend is vibrated with the tubes natural frequency. Since the amplitude of the vibration is inversely proportional to the square root of the tubes mass the fluids density can be decided by measuring the pipes change in natural frequency, compared to the frequency of an empty pipe or filled with a fluid of known density.

The fluid flow produces a torquing motion about the axis of symmetry of the U. This torsional motion is directly proportional to the mass flow, due to the Coriolis effect.

The used mass flowmeter is a DanfossMassFlo Coriolis flowmeter with an error of 0.5%. The mass flowmeter was connected to the system in the middle between the pump and the flume inlet. It was used to monitor the flow rate and temperature of the water.

### 3.2 Measuring Procedure

Common for the flow mapping and the measurements of the attraction channel is that the surface was kept at a height of $118 \pm 1$ mm ($d_0$ in figure 3.1(c)) above the flume bottom, and that the flow rate was $5.3 \times 10^{-3}$ m$^3$/s ($\pm 1\%$). These settings where chosen to imitate the original experiment made by Wassvik.
The sampling frequency, i.e. the recording frame rate, was 50 Hz.

### 3.2.1 Mapping of the flume

To control the flume's flow distribution, a mapping study was performed by scanning the flume horizontally from wall to wall. This was repeated three times with a stop of the whole system for more than an hour between the scans, to control the repeatability of the experiment. By closing down the whole system and letting it rest, the stability of the experiment is tested. Each scan consisted of 25 measuring points (further referred to as a *set*). The sets were randomized with Matlab according to statistical experimental design [7] for all three scans.

First, each set contained 10 pictures, i.e. 1/5 of a second sampling time. This was discovered to be too short; see section 4.1. Hence, each set was changed to contain 250 pictures.

The pictures were calculated with an interrogation window size of $64 \times 64$ pixels and no overlapping.

### 3.2.2 Measuring the attraction channel

The objective of this work is to study the depths ($d$, over the bump) influence of the attraction water. As mentioned earlier, the depth between the surface and flume bottom is kept constant, i.e. $d_0$ in figure 3.1(c). Hence, the only way to change $d$ is to vary the attraction channel's vertical position in the flume. To manage this, the attraction channel was mounted in a manually operated traverse system.

Three different depths were investigated. The shallowest depth was 7 mm over the highest point of the bump, see $d$ in figure 3.1(b), the second depth was 13 mm and the third depth was 20 mm, further referred to as the small, medium, and large depth.

Due to lack of time, the attraction channel was measured at three places along the symmetric axis; see figure 3.2. To cover the hole area between the surface and the bottom of the flume, two sets were needed, hence resulting in six measuring points for each depth.

The pictures were calculated with an interrogation window size of $64 \times 64$ at first and then decrease to $32 \times 32$ with three passings, 75% overlap and post-processing of the vector fields.
Figure 3.2: A schematic figure of the six sets along the symmetry axis in the middle of the attraction channel.
CHAPTER 4

Results and discussion

4.1 Mapping

The repeatability of the experiment was poor when the sample size was only 10 pictures, i.e. a sampling time of 0.2 seconds, see figure 4.1. By plotting the results of 700 samples it is obvious that the scatter in results is large between individual samples, see figure 4.2. To find out the minimum sampling time required a small study was performed; sampling three sets with 700, 350 and 175 pictures.

The results shows that for a set of 700 pictures, see figure 4.3(a), i.e. sampling time of 14 seconds, one receives a smooth velocity profile. For 350 pictures, i.e. 7 seconds sampling time, the profile is still smooth but the relative error is larger than for 700 pictures. For 175 pictures, i.e. 3.5 seconds sampling time, the profile becomes crocked. The standard deviation also varies a lot more when approaching the bottom of the flume then for the other profiles; see figure 4.3(c). This implies the need for a longer sampling time to get a more accurate measurement and using statistical evaluation methods to analyze the results. Although a longer sampling time would enhance the results, however 700 pictures end up in about 1.8 gigabyte of data. The DaVis im7-file is about 2 Mb and the post-processed vc7-file can become up to 1 Mb, depending on the post-processing settings. That amount of data is time expensive to process and the total amount of data for one measuring point becomes near 2 Gb after post processing.

As mentioned above, 175 pictures are to small sample and 350 is a bit to large. Hence a sampling time of 5 seconds, i.e. 250 pictures, were assumed to give a fair description of the flow course and still give a manageable amount of measuring data.

With the new sampling time a satisfying result was achieved. Although there are some differences between the three velocity profiles in figure 4.4(a), the relative error is largest near the flume wall and bottom, see 4.4(b).
14 Results and Discussion

MeanU

![Graph showing MeanU](image)

Figure 4.1: In the figure the mean value of three sets, each consists of ten pictures, are plotted. Obviously there is a low repeatability in the measurements.

700 vectors in one set

![Graph showing 700 vectors in one set](image)

Figure 4.2: Plotting 700 vectors of the mean value of U make it obvious that PIV is a statistical method.
4.1. Mapping

Figure 4.3: is a comparison between a sampling size of 700, 350 and 175 pictures in the middle of the pure flume.
An estimate calculation of the flow was made using figure 4.3(a), which shows the mean value velocity profile in the middle of the flume from the bottom and up, and the numeric integration method forward difference.

\[
q = \sum_{i=1}^{n} \left( \frac{v(n) + v(n + 1)}{2} \right) \cdot \delta y \cdot W
\]  

(4.1)

where \( q \) is the flow, \( v \) the velocity at data point \( n \), \( \delta y \) is the distance between two data points and \( W \) is the width of the flume.

\( q \) is calculated to be approximately 0.0088 m\(^3\)/s, the flow measured with the mass flowmeter were 0.0053 m\(^3\)/s. In this estimated calculation the flow profile has been assumed to be ‘endless’ sideways. If one had taken in the flume walls influence on the flow profile, see figure 4.4(a), \( q \) would decrease. The reason for approximating the flow profile to an endless profile were that the bottom near the flume walls could not be photographed cause the optic bench holding the light sheet house would have crashed in to the flume wall. Based on the results found from the estimated calculation and the measured flow from mass flowmeter it is assumed that a fairly high accuracy of the total flow could be calculated with the PIV-system, depending on what integration scheme and number of sets across a volume.

Figure 4.4: Mapping study of the water across the pure flume, 90 mm above the bottom.
4.2 Attraction Channel

In table 1 one can find the results from the attraction channel experiments. The notation follows Wassviks [14]. To compare the influence of the height above the bump a dimensionless relationship between the depth at the upstream inlet of the attraction channel and the bumps height, \( H = h/d_1 \). \( F_r \) is the Froude number [4] given by

\[
F_r = \frac{V}{\sqrt{g \ast L}}
\]  

where \( V \) is the velocity, \( g \) the gravitational force and \( L \) a typical length scale which for an open channel usually is the depth.

At the upstream inlet of the attraction channel a recirculation pattern was observed about 35 mm in the channel for the small depth; see figure 4.5(a). It was also observed for the medium depth. The recirculation hinders the water to freely enter the channel, thus it creates a blockage effect. The effects of the blockage effect on the outside of the attraction channel is described by Wassvik [15]. Inside the attraction channel the blockage rendered a jet along the bottom of the channel; see figure 4.6(a). For the large depth the flow was not blocked, that is probably the reason for the highest velocity being reached near the surface and that there is almost no motion along the bottom.

Looking at the vector plots over the bump and downstream, see appendix A, one can see that the depth over the bump affects the appearance of the jet. For the small depth the jet is very flimsy and irregular. For the medium depth there are still some irregularities, but the jet appears to be more stable. The large depth created a steady jet out from the bump. According to a presentation during the 6th International Symposium on Ecohydraulics by Katy Haralampides [6] the salmon like fishes are more attracted to ordered flow.

In figure 4.7 has the dimensionless velocity, \( V_x/V_0 \), been plotted as a function of the distance from the vertical downstream end of the bump. This clearly shows that a small depth over the bump is not a good idea. Just after the bump the water has a 40% higher velocity for the small depth, but already at the end of the attraction channel (75 mm after the vertical end of the bump) the velocity has stagnated to \( V_0 \). After that it keeps
stagnating to a 60% velocity decrease 200 mm downstream the attraction channel. For the medium depth the velocity increase is up to 50% and more traceable downstream. The large depth gave a maximum velocity increase of 40%.

Worth noticing is that it has previously been found that the jet is traceable about $18 \times d$ [15] which would be approximately 105 mm downstream from the bump for the small depth, 234 mm for the medium depth and 360 mm for the large. For the small depth the jet is traceable 90 mm downstream, and the medium depth to 190 mm, this is shown in figure 4.7. This corresponds to $13 \times d$ for the small depth, and $15 \times d$ for the medium depth. Due to the length of reach for the traverse system, the jets reach could not be decided for the large depth without moving the whole PIV-system. This was not done since it would most certainly introduce several alignment errors in the measures.

Figure 4.6: Three vertical velocity profiles at different positions in, and downstream the attraction channel. ◇ = small depth. ○ = medium depth. □ = large depth
4.2. Attraction Channel

Table 1: Results from the channel

<table>
<thead>
<tr>
<th>$d_0$ [mm]</th>
<th>$d_1$ [mm]</th>
<th>$F_r$</th>
<th>$q_1$ [$m^3/s$]</th>
<th>$H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>98</td>
<td>0.64</td>
<td>$1.3 \times 10^{-4}$</td>
<td>0.82</td>
</tr>
<tr>
<td>13</td>
<td>102</td>
<td>0.70</td>
<td>$3.6 \times 10^{-4}$</td>
<td>0.78</td>
</tr>
<tr>
<td>20</td>
<td>110</td>
<td>0.40</td>
<td>$5.3 \times 10^{-4}$</td>
<td>0.73</td>
</tr>
</tbody>
</table>

Figure 4.7: The dimensionless relationship $V/V_0$ as a function of the distance from the vertical end of the bump. $0$ is the vertical end of the bump. The attraction channel ends at 75 mm.
A model test of an attraction channel as entrance to a fishway was tested with the whole field method PIV. The attraction channel uses a fraction of any free stream to entice fish to swim through it by creating a local acceleration of the water. The channel is U-shaped and has a cross-sectional contraction at the downstream end. The contraction renders a local acceleration of the water, which attracts fish [16].

It is possible to achieve an acceleration up to 50%.

The results show that the depth over the contraction has a significant role in the downstream traceability of the acceleration. Increasing the depth give an acceleration that is perceptible further downstream of the attraction channel. This is important since it is assumed that it is the higher velocity that attracts salmon like fish.

It is also shown that a larger depth gives a more ordered jet stream, which can help to attract fish [6].
Bibliography


A.1 Small depth

Figure A.1 and A.2 shows the vector plots taken at the surface at the bump and downstream. The unit on the x-axis and y-axis are the position in [mm].
Figure A.1: Vector plot taken at the bump.
A.1. Small depth

Figure A.2: Vector plot at the surface, downstream the attraction channel
A.2 Medium depth

Figure A.3 and A.4 shows the vector plots taken at the surface at the bump and downstream. The unit on the x-axis and y-axis are the position in [mm].
Figure A.3: Vector plot taken at the bump.
Figure A.4: Vector plot at the surface, downstream the attraction channel.
A.3 Large depth

Figure A.5 and A.6 shows the vector plots taken at the surface at the bump and downstream. The unit on the x-axis and y-axis are the position in [mm].
Figure A.5: Vector plot taken at the bump.
Figure A.6: Vector plot at the surface, downstream the attraction channel.