Application of an ultrasonic velocity profile monitor in a hydraulic laboratory

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Abstract

Velocity profile measurement using the ultrasound-pulse-Doppler method was successfully conducted on a physical model of an inverted siphon with three Plexiglas pipes ranging from 62 mm to 246 mm in diameter. Turbulent flow within the pipes was studied under non-intrusive conditions by installing the ultrasonic transducer on the pipe wall. The velocity profiles were obtained by moving the transducer around the pipe to four angles .

Measurements in a flume included simultaneous measurement of velocity profiles and fluid surface profiles for both smooth and wavy flows. We did not only obtain velocity profiles, but also interfacial profiles of wavy flows. These experiments were performed in a horizontal glass channel. The transducer was inserted from above the test section into the medium facing the direction of flow.

In the same horizontal channel, water level measurement for wavy flow was performed successfully. The transducer was inserted from beneath the test section through an outlet hole at a right angle to the direction of flow. The up and down movement of the water surface caused by an upstream weir became clearly visible in each case. The water level was also measured by use of a potentiometric method, simultaneously with the UVP, using a pair of parallel wire electrodes. The results showed good agreement.

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Ultrasonic Velocity Profile Measurements

The ultrasound-pulse-Doppler technique for velocity profile measurements represents a modern measurement method that exemplifies a non-intrusive technique to measure complete velocity profiles of fluid flow. It uses the Doppler effect in which a sound wave, scattered by a moving particle, is subjected to a frequency shift, which is proportional to the velocity of the particle. If the echoes are received continuously within definite time windows, a complete velocity profile can be obtained, as shown in figure 1.

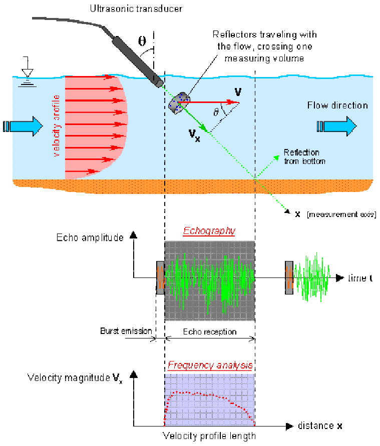

Figure 1: Ultrasonic velocity profile measurements of open channel flow [MET FLOW]

The measurement equipment that was used for this investigation came from Met-Flow, Lausanne, Europe. The actual measurement process was controlled by the supplied software.

Tests on Pipe Flow

The investigation of pipe flow was performed on the test model of an inverted siphon. The model included the inlet and outlet structures, three pressure conduits of various diameters, and adjacent headwater and tailwater areas, as shown in figure 2.

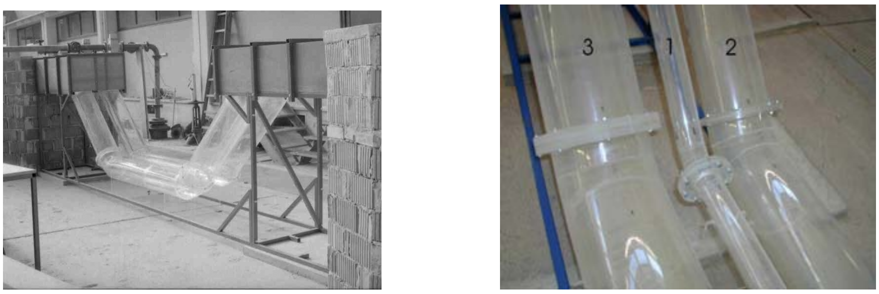

Figure 2: Test pipes, numbered 1 to 3. Overview (left) and close-up of elbows (right).

The pipes were manufactured from Plexiglas with internal diameters of d_1=62, d_2=172 and d_3=246 mm.

The flow conditions were investigated at various discharges to measure velocity profiles at different flows. Table 1 lists the expected flow rates and average velocities for the discharges that were tested. The numbers in the table below are based on the assumed flow distribution among the three pipes.

Pipe 1		Pipe 2		Pipe 3	
Flow [l/s]	**Velocity** [m/s]	**Flow** [l/s]	**Velocity** [m/s]	**Flow** [l/s]	**Velocity** [m/s]
1.0 - 1.5	0.35 - 0.51	3.0 - 15.0	0.13 - 0.66	5.0 - 34.0	0.11 - 0.75

Table 1: Expected flow rates and average velocities in the inverted siphon pipes

Due to the special design of the intake structure of the inverted siphon (sideweir with a converging U-shaped geometry and two lateral outlets), the river discharge is separated according to the headwater level.

Measurement Planes

The flow inside the pipes was investigated by placing the ultrasonic transducer on the pipe wall at an incident angle of 10° from the normal, as shown in figure 3a. Each of the test sections was then divided into four measurement planes, which were evenly distributed over the circumference of the pipe wall, as displayed in Figure 3b.

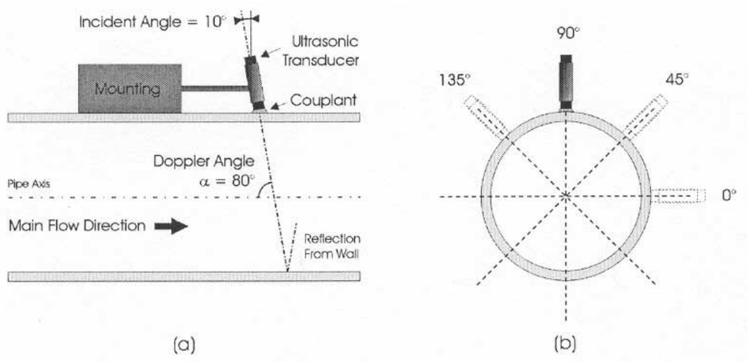

Figure 3: (a) Positioning of the transducer and (b) measurement planes as viewed in the direction of flow

Four measurement planes were used so that the true direction of the velocity vector at one spatial point could be reconstructed. To obtain a suitable amount of profile data, seven test sections on each pipe were investigated. The positions of the test sections along the pipes are shown in Figure 4. Normally the transducer was attached to the pipes facing in the direction of the flow. An exception had to be made downstream from the two elbows (**de**$_i$), where the transducer faced toward the flow because of lack space for the support.

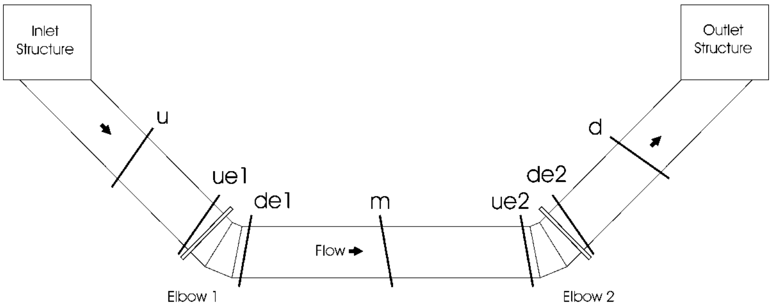

Figure 4: Position of test sections along the pressure pipes of the inverted siphon.

Particle Seeding: One constraint of the ultrasound-pulse-Doppler method is that it completely relies on echo signals from reflecting particles suspended in the test medium. The test phase of our experiments revealed that water from the circulating system of the laboratory was not sufficiently filled with particles. Therefore, we decided to improve the measurement situation by seeding with heterogeneous sediment (0.006 mm to 1.0 mm).

Software Parameter: The instrumentation that was used for the pipe flow experiments was supplied by Met-Flow. The main unit UVP-Monitor XW-3-PSi was operated with a 4-MHz transducer. The water temperature was measured several times a day, and was found to remain almost constant at 20° C (c = 1480 m/s).

The software parameters determined the spatial and temporal resolution of the attained profile data as well as the velocity resolution. These important parameters are summarized in table 2.

Test Pipe	Measurable Velocity v_{max} [m/s]	Resolution			
		Velocity Δv [mm/s]	Spatial w [mm]	Temporal Δt_{theor} [ms]	Temporal Δt_{meas} [ms]
1	3.81	30	0.74	18	55
2	1.97	16	0.74	35	36
3	1.33	10	0.74	50	52

Table 2: Measurable velocity and resolution (temporal, spatial, velocity) for the pipe flow experiments.

Another important parameter displayed in Table 2 is the measurable flow velocity v_{max} in axial direction. At first glance, the measurable velocity is far above the expected velocity maximum of 0.75 m/s, but one must consider that the expected velocity is only an averaged value based on the equation of continuity. Peak velocities in pipe 3 were expected to be much faster, and so the velocity range was almost doubled to 1.33 m/s by selecting the corresponding angle of incidence. An incident angle of 10° was used on all three pipes because we decided not to modify the transducer mounting during measurement.

Results pipe flow

Each of the three test pipes was investigated at seven measurement sections (figure 4), which were again divided into four measurement planes (figure 3). Considering the fact that the flow inside the pipes was examined for a number of load cases, more than 500 were conducted. To give a representation of the obtained results, two measurement sections will be analyzed in more detail. While the first sample deals with measurement at a straight pipe, the second sample in this paper covers the measurement that was conducted downstream from a pipe elbow.

Results straight pipe

The first section to be examined is section **m** on pipe 1 (figure 4), which is right in the **m**iddle of the two elbows. Although the pipe diameter is quite small (d_1=62 mm), decent velocity profiles were obtained because of the excellent spatial resolution of the 4-MHz transducer. Figure 5 displays a typical velocity profile measured at this section. The mean time velocities (dots) and the standard deviation (vertical lines) are shown. This plot displays the velocity component along the line of measurement.

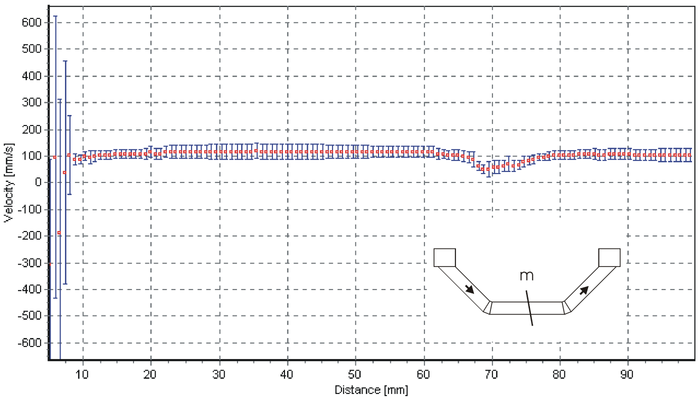

Figure 5: Sample velocity profile obtained at section m on pipe 1 showing undistorted turbulent flow.

The profile in figure 5 indicates the characteristic velocity distribution for turbulent flow. Outside the near wall boundary layer the fluid moves with the full velocity and may be considered to be practically unaffected by the reduction of velocity close to the pipe walls. The velocity gradient is highest at the pipe wall and becomes progressively smaller with increasing distance from the wall.

The decrease of flow velocity in the range of about 70 mm indicates the position of the back wall of the pipe. Beyond this distance, a mirror image of the velocity profile appears. This imaginary profile is caused by ultrasound reflection at the back wall. Since the reflected waves still propagate within the test medium, the flow velocity is detected a second time.

Results bent pipe

This case is expected to happen **d**ownstream from the **e**lbows, because the flow becomes separated from the inward bend of the pipe. Hence the second test section to be analyzed is section **de2** on pipe 3 (d_3=246 mm). Figure 6 shows a sample profile that was obtained in the vertical measurement plane of this section. Again, the mean time velocities and the standard deviation are shown. In contrast to the previous sample, the flow can neither be considered axially symmetric with respect to the pipe centerline, nor is the highest velocity found in the middle of the stream. Even the standard deviation bears little resemblance to the previous profile: the vertical lines have lengthened and indicate that the intensity of turbulence has increased.

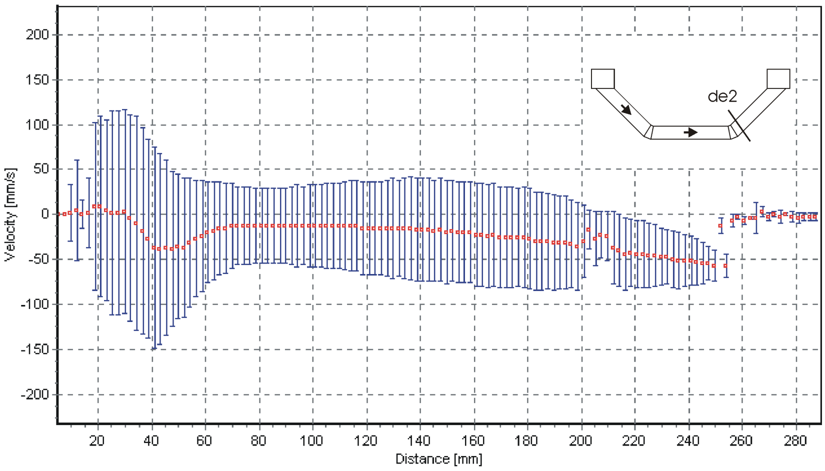

Figure 6: Sample velocity profile obtained at section de2 on pipe 3 showing distorted turbulent flow.

As flow moves through the elbow, it accelerates around the outside of the bend and slows down near the inside of the bend. The profile is distorted with a high velocity zone occurring near the outside of the bend, as shown in figure 7. The Doppler angle α varies along the line of measurement due to the converging geometry of the streamlines. In the middle of the stream, flow particles typically travel perpendicular to the measurement line and fail to generate significant frequency shifts. During measurement, however, the flow direction varied so as to generate either a positive or a negative frequency shift, as indicated by the standard deviation in figure 6.

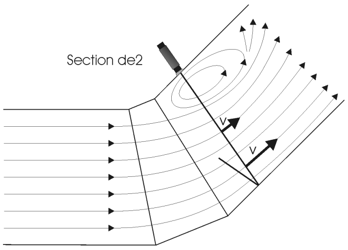

Figure 7: Flow pattern at the elbow showing strong eddies at the inward bend

Synthesis

The velocity is found to be affected by the elbow located upstream from the test section. Flow leaving the elbow is distorted and returns to an undistorted velocity profile after a certain pipe length (6 to 10 times the pipe diameter *d*). If the test section is located within that zone, the computation of the flow rate is likely to be incorrect. The velocity profiles shown in figure 8 (left) were measured on pipe 1 (d_1=63 mm) where the flow rate was established correctly. In contrast, the profiles displayed in figure 8 (right) caused the highest error in the computation of the flow rate. The profiles were measured on pipe 3 (d_3=246 mm) where, considering the larger diameter of the pipe, the test section was located too close to the pipe elbow.

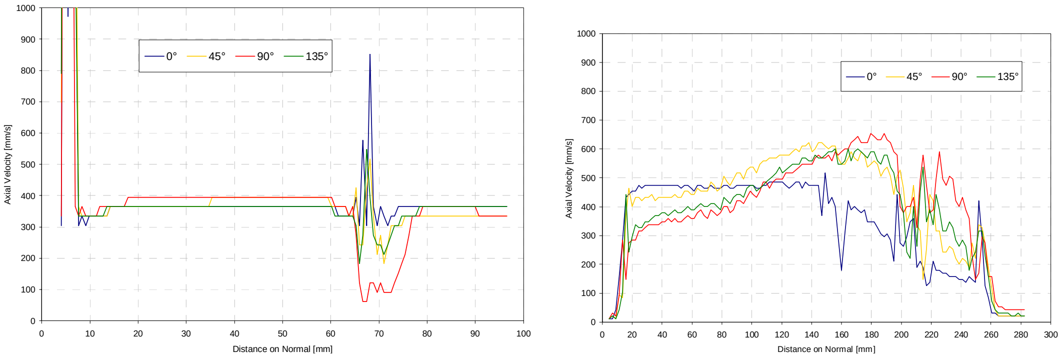

*Figure 8: Velocity profiles obtained at section **m** on pipe 1 (left) and **de2** on pipe 3 (right).*

Study of Open Channel Flow

The experiments were performed in a horizontal channel about 10 m long, 30 cm wide, and 80 cm high. The bottom of the channel was made from steel, while the sides were manufactured from glass. Water from the overhead reservoir of the laboratory entered the channel through the pipe system. The inflow was adjusted by a control valve, while the depth of the water was varied using a slide gate at the downstream end of the channel. Because of its short length, non-uniform flow was expected in the channel.

Figure 9: Test facilities for employing the UVP-Monitor in the study of open channel flow.

Measurement of Velocity Profiles

The movement of the free surface may affect the experimental study of open channel flow by means of ultrasonic velocity profile measurement. The experiments described in this section were conducted to investigate the reported influence of surface movement [Nakamura]. For the generation of wavy flow, an overflow structure was built across the upstream end of the channel. The structure produced waves with a small amplitude at the downstream end of the channel where the test section was positioned. The transducer was inserted from above the surface of the water facing the direction of flow, as shown in figure 10. The axis of the transducer was placed at two different angles to the surface to test the effect of angle variation. In order to validate the obtained velocity profiles, a Höntzsch current meter with a four-vane propeller of 18-mm diameter was used as well. The UVP-Monitor model XW-3-PSi was operated with the same 4-MHz transducer as in the pipe flow experiments. The water temperature was found to remain constant at 15°C, thus the speed of sound was set to c = 1466 m/s.

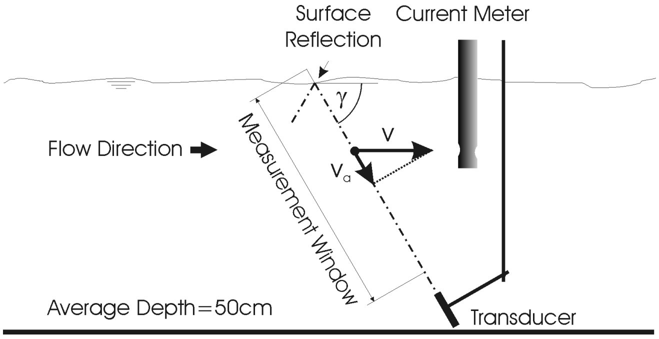

Figure 10: Experimental setup for velocity profile measurements in wavy flow.

The diagram in figure 11 compares the velocity profiles obtained by the UVP-Monitor with the measurements made by the current meter. The time-averaged velocity profiles were smoothed using a floating average computation. For the most part, the velocity profiles are found to be in good agreement with the samples from the current meter. However, the closer the measurements are to the bottom of the channel, the less the data corresponds, which is caused by disturbances in flow near the ultrasonic transducer. The reported influence of ultrasound reflection from the free surface shows in a number of significant velocity drops.

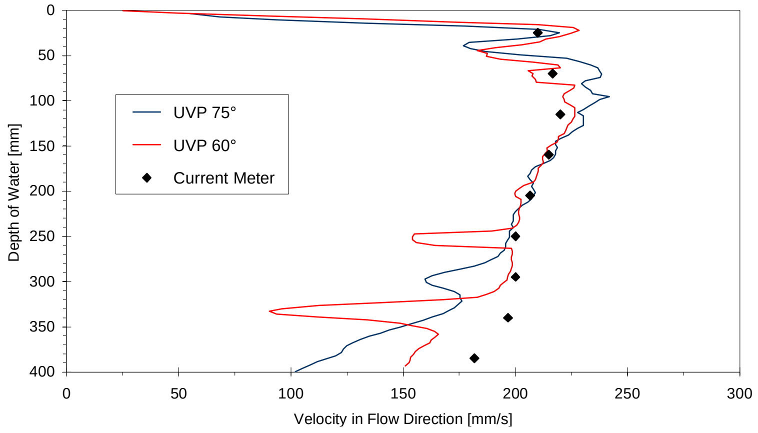

Figure 11: Velocity profiles obtained by UVP-Monitor and current meter.

Surface Level Measurement

Consideration was given to ways of measuring surface levels with the instrumentation originally designed for velocity profile measurement. For this purpose, separate test runs were conducted to find the most favorable setup for the measurement of surface levels. The largest part of the measurements were made with the 4-MHz transducer, but a 2-MHz transducer was used as well. The axis of the transducer was placed at three different angles to the surface of the water. The surface level was simultaneously measured by an electrical conductivity method using a pair of parallel wire electrodes (Fafnir probe). The results for an angle of 90° to the surface (4 MHz) are displayed in figure 12.

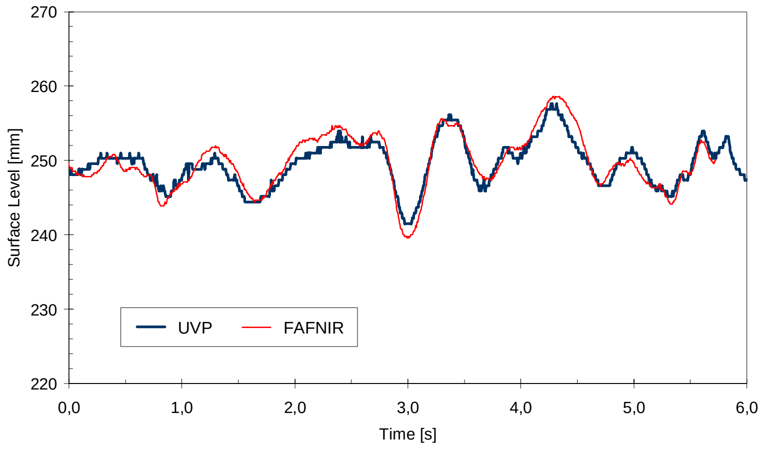

Figure 12: Comparative diagram showing the UVP plot and the output of the Fafnir probe.

For measurements with a transducer axis placed at an angle of 75° and 60° to the flow direction, the results are found to be less precise, as indicated in Figure 12.

Summary

Pipe flow was investigated non-intrusively using the UVP-Monitor model XW-3-PSi.The investigations were conducted on a hydraulic model of an inverted siphon. The model included three Plexiglas pipes from 62 mm to 246 mm in diameter on which the measurements were performed. Velocity profiles were measured in each measurement plane over a sufficient time interval (20 to 50 seconds) to obtain characteristic information about the turbulent flow studied. Two representative measurement sections were analyzed in more detail: the first located within a straight pipe, the second situated downstream from an elbow. The time-averaged velocity profiles and the respective standard deviations are shown.

Additionally free-surface flow in a glass-walled channel was investigated. The instrument performed measurements of both flow velocity and surface level. In each case, the ultrasonic transducer was inserted from above the surface of the water and faced the direction of flow, with the axis of the transducer placed at different angles to the free surface. The data from the identification process was compared to an electrical conductivity method for the measurement of surface level, showing good agreement if the transducer axis is placed perpendicular to the flow direction. Other measurement angles were tested as well, but the identification of the surface level was found to be less precise.

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