FLOW ANGLE MEASUREMENT with CURRENT METERS at the LA GRANDE–1 POWER PLANT

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1. Introduction

Hydro–Québec's La Grande–1 power plant was put into operation last year and includes 12 units, of 114 MW each under a 27.5 meter head with 460 m^3/s of nominal discharge. The turbines are of the propeller type, eight supplied by GE Canada and four by GEC Alsthom. The bid called for efficiency tests on four of the units, two of each design.

The efficiency tests were made last year, the first one at the end of June and the three others in September. Figure 1 is a cross section of the power station showing the water intake, where the current meter frames were installed for the measurement of the discharge. Only the current meter method was applied due to the difficulties that would be encountered with the other code proven methods.

The main goal of this article is to describe how the water velocities and especially the flow angle were measured and the importance of this last parameter for a variable geometry entrance which usually is typical of low head power plants.

2. Description of the entrance and current meter frames

Each turbine has a triple conduit entrance made of concrete. Each conduit is 5.56 meters wide and 17.88 meters high at the current meter metering section. The walls are vertical while the floor and the ceiling are at angles of 13.5 and 31 degrees respectively from the horizontal. The metering section is located near the dam face in a variable geometry section. It was expected that the flow angle would be difficult to predict and the flow velocities could vary a lot because of their smallness.

In the present case, it was recognized that the flow angle knowledge was as important as the velocity magnitude because of the following relation :

$$Q_i = |A_i| \cdot |V_i| \cdot \sin \beta \qquad (1)$$

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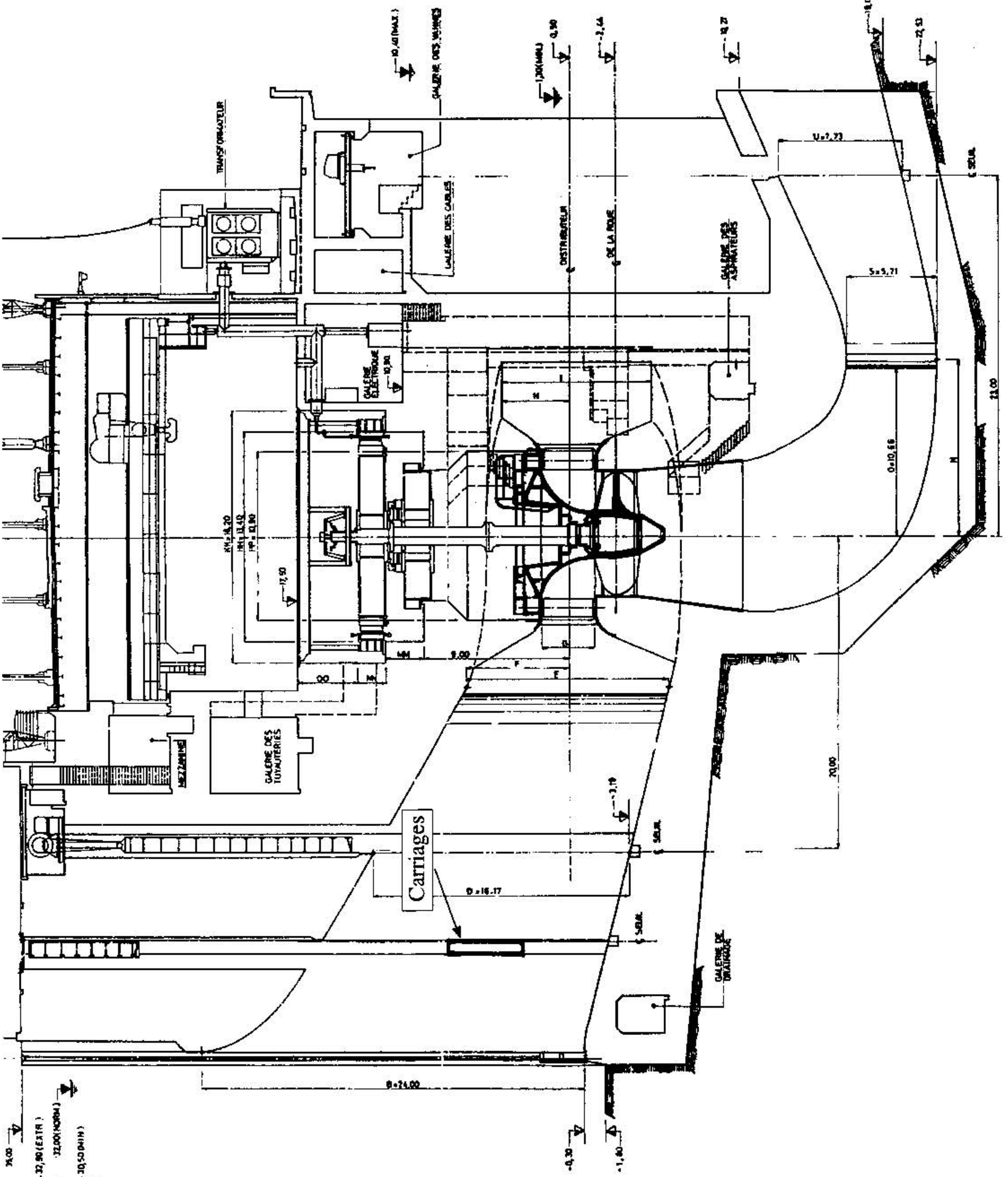

Figure 1. La Grande–1 Power Station

where

Q_i is the partial discharge through partial area Ai at a velocity Vi
and with an angle of β, between the section and the velocity.

Since all the partial areas Ai are vertical, it is better to use the following equation, with the angle φ from the horizontal:

$$Q_i = |A_i| \cdot |V_i| \cdot \cos\phi \qquad (2)$$

The angle of the flow φ can vary in theory, from 13.5 to 31 degrees. The cosine of these angles will then change accordingly from 0.972 to 0.857. That also means that an uncertainty of one degree on the angle will correspond to 0.7 % uncertainty on this partial discharge.

Since the total flow will be composed of many partial discharges, then comes the need to measure the flow angle at many places. It was also expected that the velocities might vary a lot. In each conduit, 33 current meters were placed on 3 horizontal ovoid shaped bars, with 11 current meters on each level. These bars were then attached to the carriages to be moved up and down, to any desired level. The spacing of the bars was approximately 1 meter and since the conduit hydraulic section is almost 18 meters, it took 6 different levels of the whole frame to cover the section by a total of 187 velocities per conduit, for a total of 561 for the three conduits composing the entrance of one turbine only.

At the design stage of the power station, four units were equipped with special gate slot grooves which include provision to hold in place carriages while permitting the sliding of these. Two carriages, one on each side, were necessary to hold bars for the application of the current meter method. To avoid blockage effect, no heavy rods, pipes, or other devices were used to reinforce the current meter bars in order to maintain their position in the water flow.

Figure 2 is a picture showing the three frames and figure 3 shows a closer view of part of the angle orientation mechanism. The aluminum round bars were used as spacers only during the transportation of the frames and they were removed when the frames were put into place. The orientation mechanism allowed to adjust the angle of the ovoid bars from 10 to 34 degrees from the horizontal, by pumping a small quantity of oil, from the upper deck of the water intake, into the two double effect hydraulic cylinders. Each cylinder was independent and the displacement of the connected lever was measured by a submersible transducer.

As it appears in figure 2, a special holder was used for the current meters. This special holder permits to reduce by half the interference effect of the supporting ovoid bar. The area of the three ovoid bars is only 0.6 % of the area of the hydraulic passage but the real obstruction

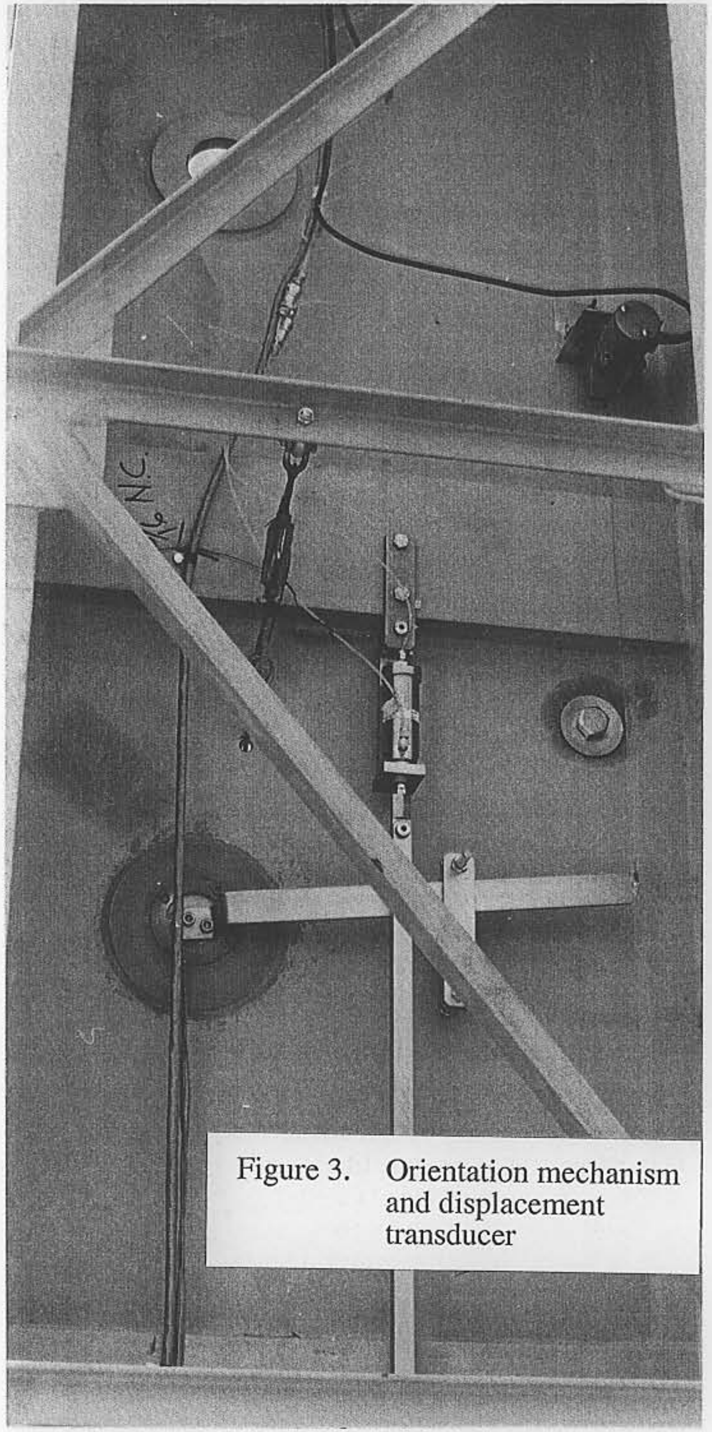

Figure 3. Orientation mechanism and displacement transducer

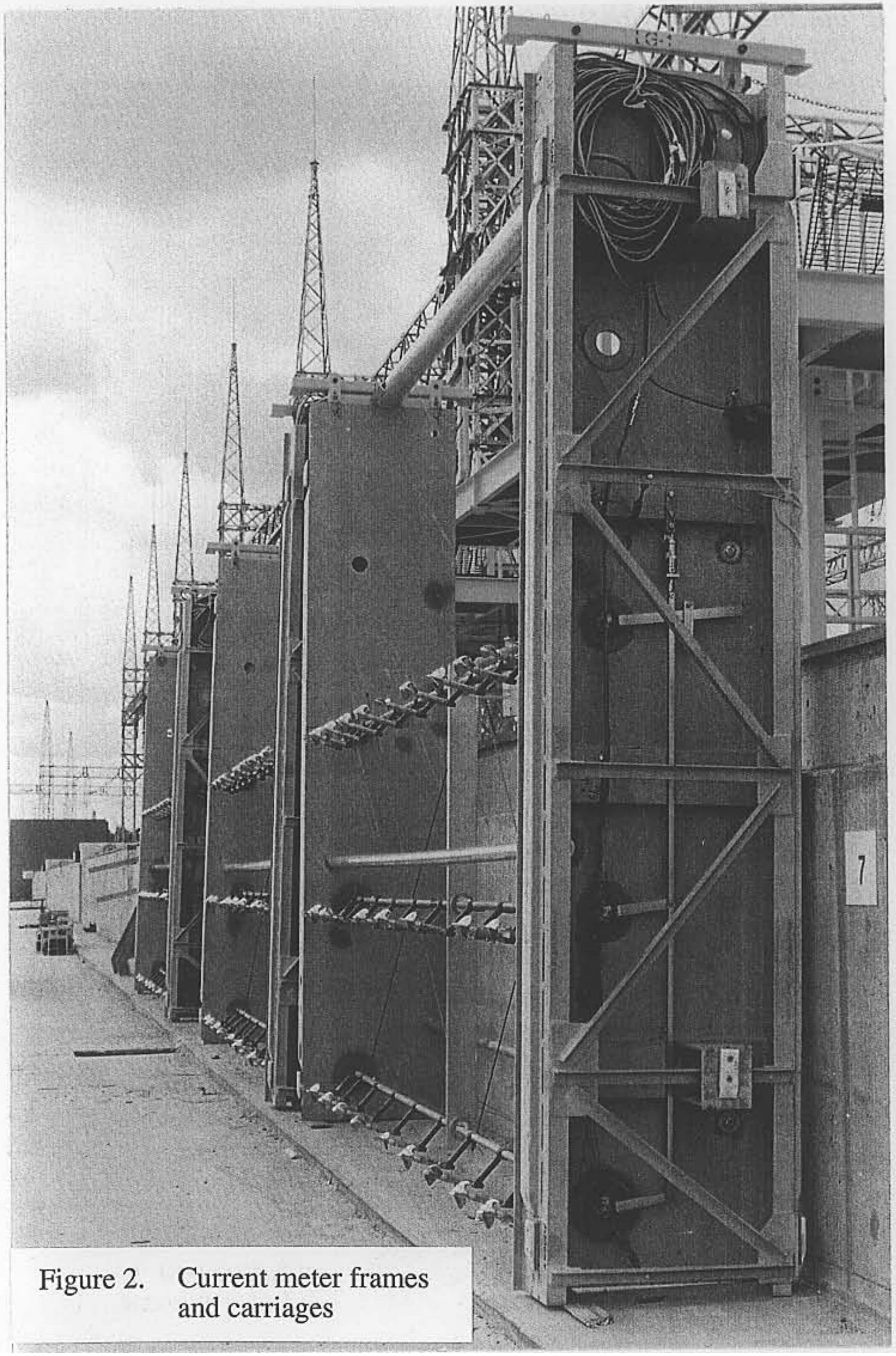

Figure 2. Current meter frames and carriages

factor is certainly more important, especially if we calculated this factor using the proximity area rather than the total area. Nevertheless, it is believed to be one of the slimmest frames used for such an application.

The width between the face of the two carriages was maintained by the ovoid bars even if they can rotate in bushings. Before and after each test, the frame was placed vertically with plumb bulbs and the angle of the three bars, of the levers and of the current meters were measured with an inclinometer. The readings of the displacement transducers were also taken. That control was done on the three frames for 3 angular positions of the ovoid bars, namely 10, 22 and 34 degrees from the horizontal.

The frames were placed in position by crane and after that, three temporary special cranes were used to hold the frame in the desired position, which was measured by tapes attached to each end of the carriages.

3. The test procedure and the computation

With the frames adjusted at a given level, the current meter angles were changed from minimum to maximum then back to minimum, at a steady rate and in a 10 minute time lap, during which, the measuring system recorded rotation signals from each current meter. The six height positions were done the same way for a particular turbine. Two turbine tests were carried out with trash racks in place and two others, without.

The mean velocity and the mean angle are calculated for each 20 second time lapse and examples are given at figure 4. A smoothed curve of parabolic form is calculated from the average points of velocities and angles. The coefficients of the following equation are determined by the least square method.

$$V(\phi) = a_0 + a_1 \cdot \phi + a_2 \cdot \phi^2 \qquad (3)$$

The peak velocity corresponds to an angle equal to $-a_1/(2 \cdot a_2)$, which is the angle of the local flow relative to the horizontal. This is done for each measuring point.

Figure 4 shows different cases of flow angle determination. Case (a) is a good one because the points are well grouped and present both sides of the peak. The difficulty of case (b) comes from the peak that lies outside of the measuring points. In case (c), the dispersion of the points is great with the peak falling outside of the measuring points.

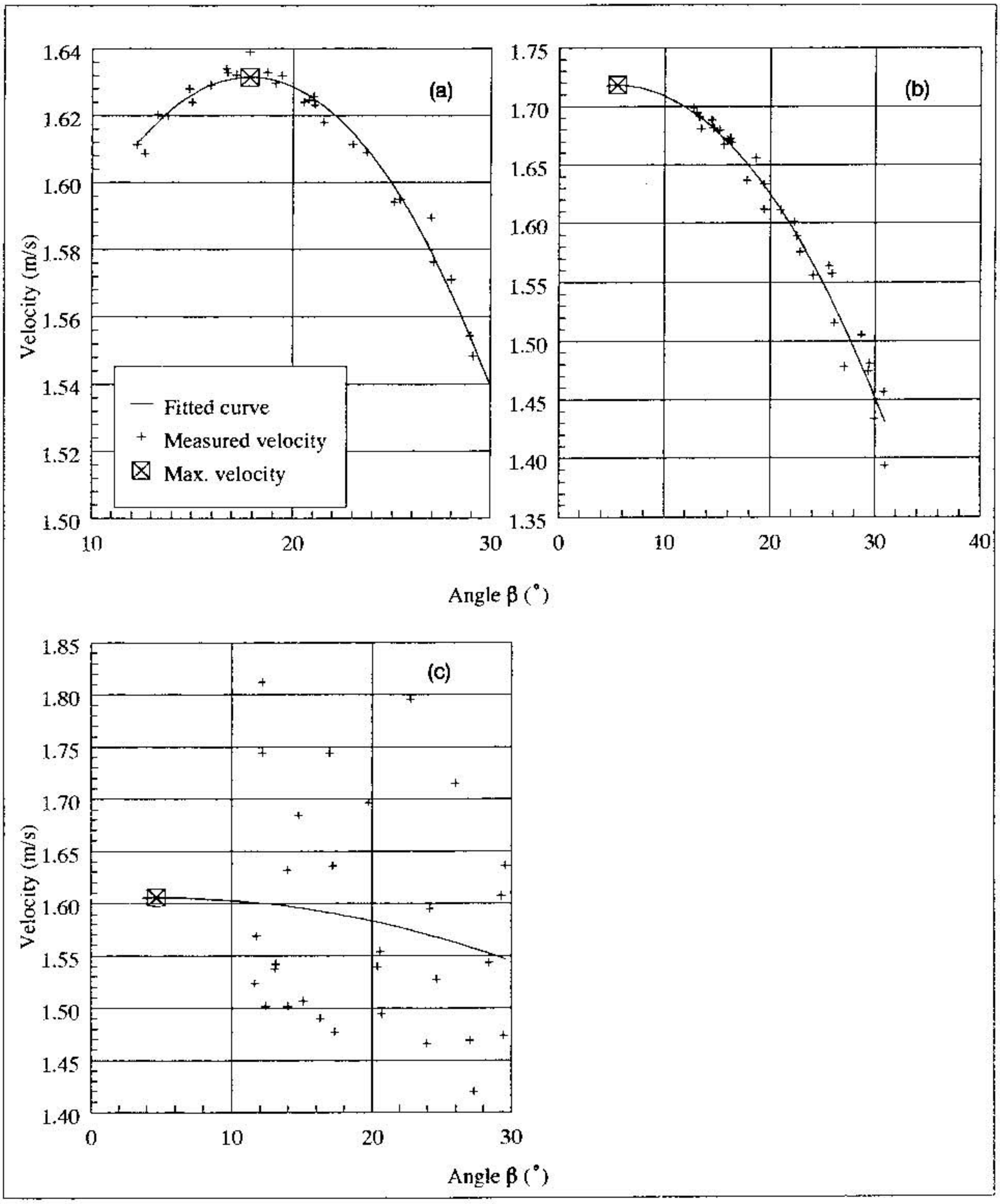

Figure 4. Example of velocity variation as a function of current meter angle

Case (b) generally occurred at the bottom of the conduit where the angle of the flow was outside of the possible measuring angle range of the exploration mechanism. In few cases, the difference between the flow angle and the possible current meter angle exceeded 20 °. Case (c) was mostly present near the walls and the floor where the turbulence is important. The variations in local temporal flow velocities, were more important than the changes due to angle changes of the current meter. It did occur that the fitted curve had an inverted shape and was considered as an aberrant result.

Following the calculations of the flow angles, it did come clear that some had to be eliminated. Boundary conditions must be respected, as an example, the flow angle near the floor has to be at 13.5 degrees. For the ceiling, no limit was imposed because the opening due to the vane groove is large and is likely to produce a local disturbance. It was decided to represent the flow angle found for each measuring point, by an equation system which includes the distance from the floor (y) and from the right wall (x). The following equation would be smoothed using the least square method.

$$\phi(x,y) = (A_0 + A_1 \cdot x + A_2 \cdot x^2)(B_0 + B_1 \cdot y + B_2 \cdot y^2 + B_3 \cdot y^3), \tag{4}$$

that might be expressed as follows :

$$\phi(x,y) = a_0 + a_1 \cdot x + a_2 \cdot x^2 + a_3 \cdot y + a_4 \cdot xy + a_5 \cdot x^2y + a_6 \cdot y^2 + a_7 \cdot xy^2 + a_8 \cdot x^2y^2 + a_9 \cdot y^3 + a_{10} \cdot xy^3 + a_{11} \cdot x^2y^3 \,. \tag{5}$$

With the flow angle at the floor of 13.5 degrees, we finally get.

$$\phi(x,0) = a_0 + a_a \cdot x + a_2 \cdot x^2 = 13.5 \tag{6}$$

$$\phi(x,y) = 13.5 + a_3 \cdot y + a_4 \cdot xy + a_5 \cdot x^2y + a_6 \cdot y^2 + a_7 \cdot xy^2 + a_8 \cdot x^2y^2 + a_9 \cdot y^3 + a_{10} \cdot xy^3 + a_{11} \cdot x^2y^3 \,. \tag{7}$$

We observe in equation 7 that all terms independent of "y" were eliminated from equation 5, equivalent to removing B_0 in equation 4 or a degree of freedom in the vertical direction. To determine the coefficients a_3 to a_{11}, some flow angles were discarded because of defective current meters, the closeness of the first current meter row from the floor, an inverted curve of the velocities versus the angle, and finally, a point having a flow angle too far from the actual smoothed surface (outlying results).

This last selection was made according with Appendix B of IEC 41. A first surface was established and subsequently, the difference between this surface and each flow angle was calculated as well as the standard deviation. The flow angles having a magnitude difference greater than 3.44 times the standard deviation were rejected. These calculations were repeated without the rejects until all results were within the limits.

Table 1 gives the number of rejected flow angles for the whole metering section at three generator outputs.

Table 1. Proportion of rejects

Output (MW)	104	110	114	Conduit Total
Right bank conduit				
Number of useful flow angles [(1)]	171	175	171	517
Rejects, from 3rd criterion (%)[(2)]	8.2	12.0	8.8	9.7
Rejects, from 4th criterion (%)[(3)]	7.0	8.0	5.8	7.0
Rejects, total (%)	15.2	20.0	14.6	16.6
Center conduit				
Number of useful flow angles	170	170	170	510
Rejects, from 3rd criterion (%)	4.7	4.1	2.4	3.7
Rejects, from 4th criterion (%)	4.7	1.8	1.2	2.5
Rejects, total (%)	9.4	5.9	3.5	6.3
Right bank conduit				
Number of useful flow angles	154	154	154	462
Rejects, from 3rd criterion (%)	3.9	3.9	2.6	3.5
Rejects, from 4th criterion (%)	6.5	3.9	6.5	5.6
Rejects, total (%)	10.4	7.8	9.1	9.1
Test total				
Number of useful flow angles	495	499	495	1489
Rejects, from 3th criterion (%)	5.7	6.8	4.6	5.7
Rejects, from 4th criterion (%)	6.1	4.6	4.4	5.0
Rejects, total (%)	11.8	11.4	9.1	10.7

(1) Total number of flow angles (187 for each conduit) minus the rejects due to the following reasons already mentioned: defective current meters (1st criterion) and boundary conditions near the floor (2nd criterion).

(2) Rejects from 3rd criterion which is "Inverted curve of the velocities versus the angle"

(3) Rejects from 4th criterion which is "Outlying results"

The mean rejected percentage is 11 %. The rejects are higher in the right bank conduit having the shortest distance between the stay ring and the metering section (figure 5). Both adjacent turbines being stopped for the test, it is likely that the flow at the water intake had an important cross velocity component. This hypothesis is also supported by the fact that more rejects occurred near the right wall of the conduit.

Less rejects are present in the center conduit since the conduits on both sides discharge flow, producing straighter flow lines. The left bank conduit had intermediate flow conditions since it is farther from the turbine entrance but the left turbine was also stopped.

Table 2 shows the standard deviation of the difference of the flow angles from the smoothed surface as well as the uncertainty of the smoothed surface for each conduit at different generator outputs. It also gives the overall uncertainty for all three conduits. The overall standard deviation for the three conduits corresponds closely to the mean of the standard deviations. But the overall uncertainty for the three conduits is decreased appreciably due to the fact that the number of samples for the three conduits is about 3 times the number of each conduit. For the three outputs, the uncertainty correspond to 0.3 degrees or an influence of 0.2 % of the calculated flow.

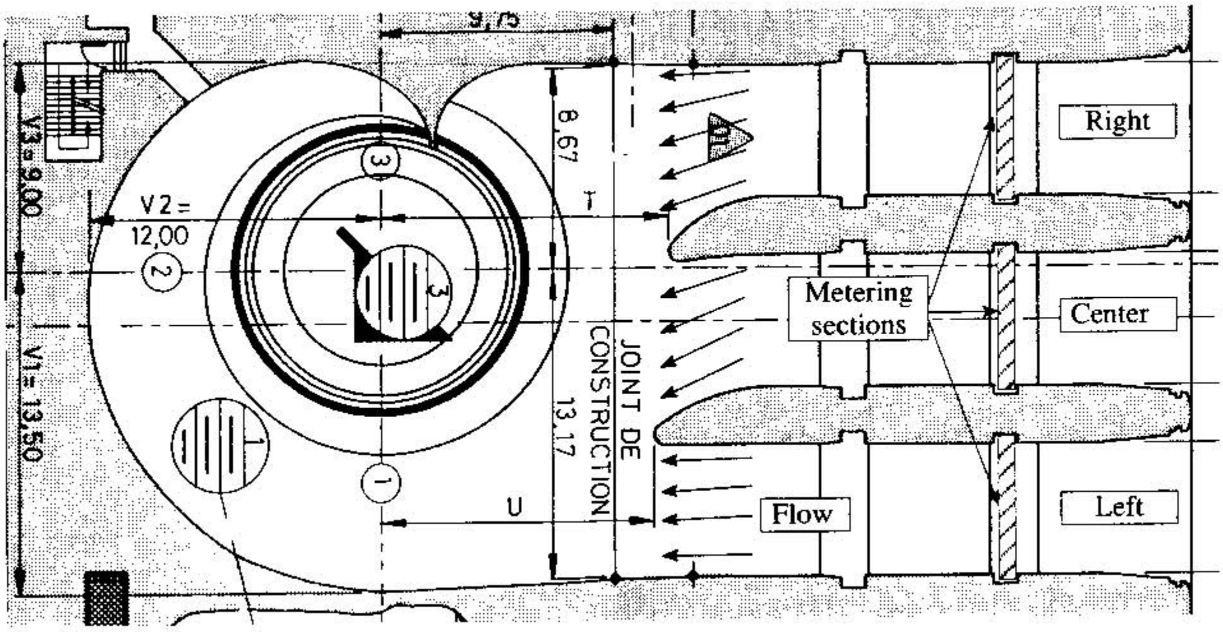

Figure 5. Proximity of metering section to stay ring

Table 2. Standard deviation and uncertainty of related of smoothed surface (°)

Output (MW)	Right bank conduit		Center conduit		Left bank conduit		Overall	
	Std dev.	Uncert.	Std dev.	Uncert.	Std dev.	Uncert.	Std dev.	Uncert.
104	3.3	0.6	2.5	0.4	2.4	0.4	2.7	0.25
110	2.9	0.5	2.5	0.4	2.9	0.5	2.7	0.25
114	3.2	0.5	3.4	0.5	2.8	0.5	3.0	0.3

The procedure to eliminate outlying results was rather loose since a flow angle of 11 degrees satisfies the criteria and corresponds to 3.3 times the standard deviation as it appears in the table.

Although the aim of the article is related to flow angle determination only, in practice, the turbine flow must be calculated to yield the efficiency. A great benefit of the flow angle determination by variations of the current meter angle was the determination on site of the velocity response of the current meter versus the flow angle. This law was known from laboratory calibrations but not from site measurements.

Using the experimental measurements, velocities versus angles, and by adjusting them with a normalization procedure, it was possible to obtain the graph points of figure 6. The normalized velocities were used to determine the exponent of the following equation, which is the model of the current meter response.

$$V_{norm}(\alpha) = [\cos(\alpha)]^b \tag{8}$$

where

V_{norm} is the normalized velocity

α, is the angle between the current meter and the flow, and

b, the experimentally found exponent.

The experimental exponent of 2.3 was determined using the least square method and thousands of points.

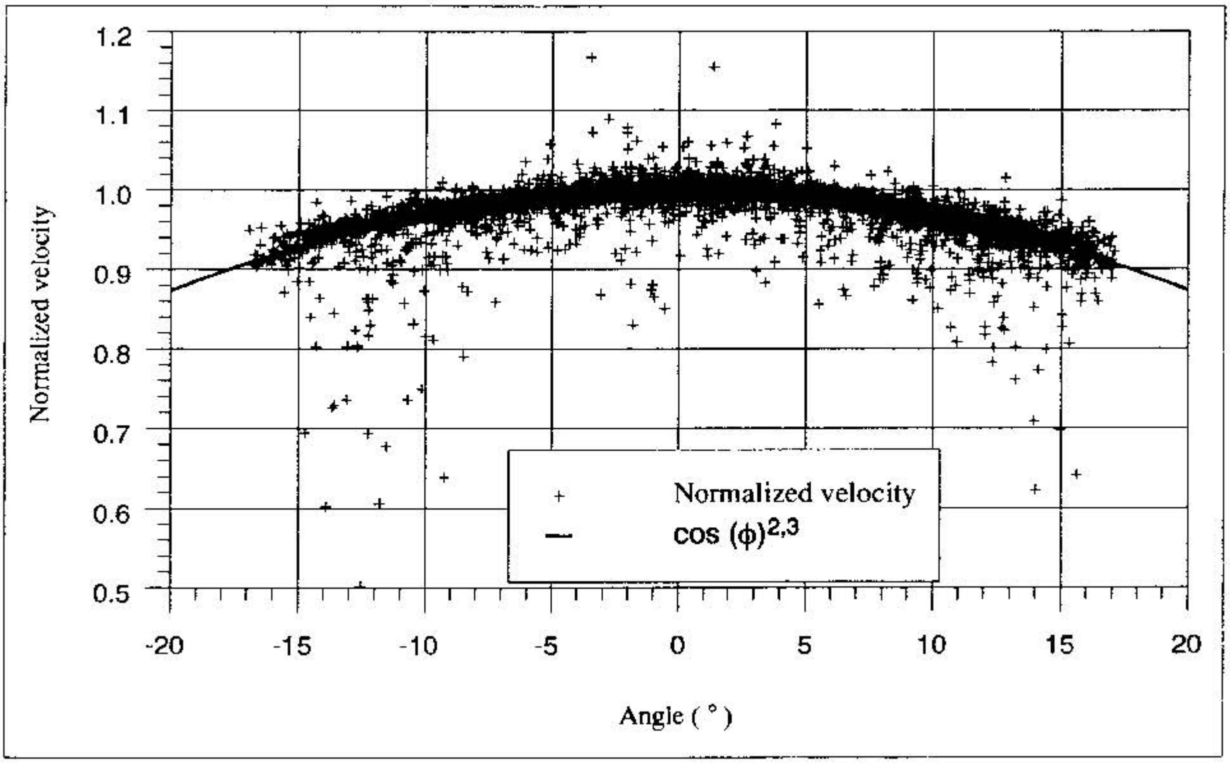

Figure 6. Current meter response versus flow angle.

4. The results

Only typical results are presented at figure 7 for each conduit at a given generator output. The 3D graphs give the flow angle according to color steps of 5 degrees. The distribution of flow angle of the center conduit is less curved than the one of the right bank conduit which is the worst, for the reasons already given. It is therefore normal that more flow angle rejects were present in that right bank conduit. It is also interesting to note that the minimum flow angle, in the right bank conduit, is only of 7 degrees, thus 3 degrees less than the minimum possible current meter angle of the bottom row.

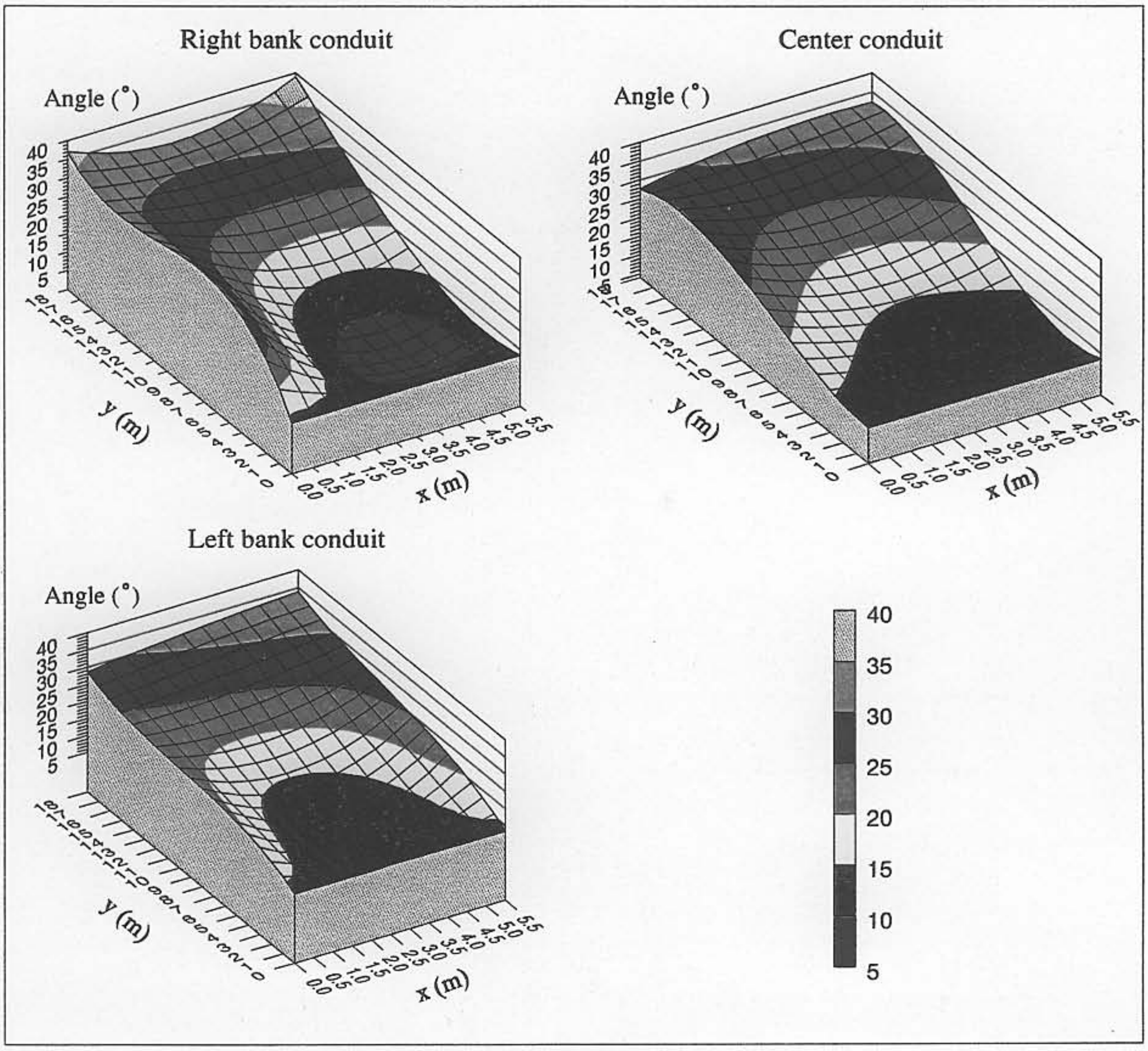

Figure 7. 3D representation of flow angle

The left graph of figure 8 gives the mean flow angle, averaged across the width of the conduit, versus the height of the metering section, for each of the three conduits. The straight line gives the angle from the floor to the ceiling assuming a linear variation. The difference between the hypothetical flow angle and the measured mean one, on a horizontal situated at ordinate of 6 meters of height, attains 5 degrees. The mean difference is about 2.5 ° and represent 1.7 % on the calculated flow or calculated efficiency. It is possible to relate the stay ring with angle flow but modern calculation methods might also show other causes.

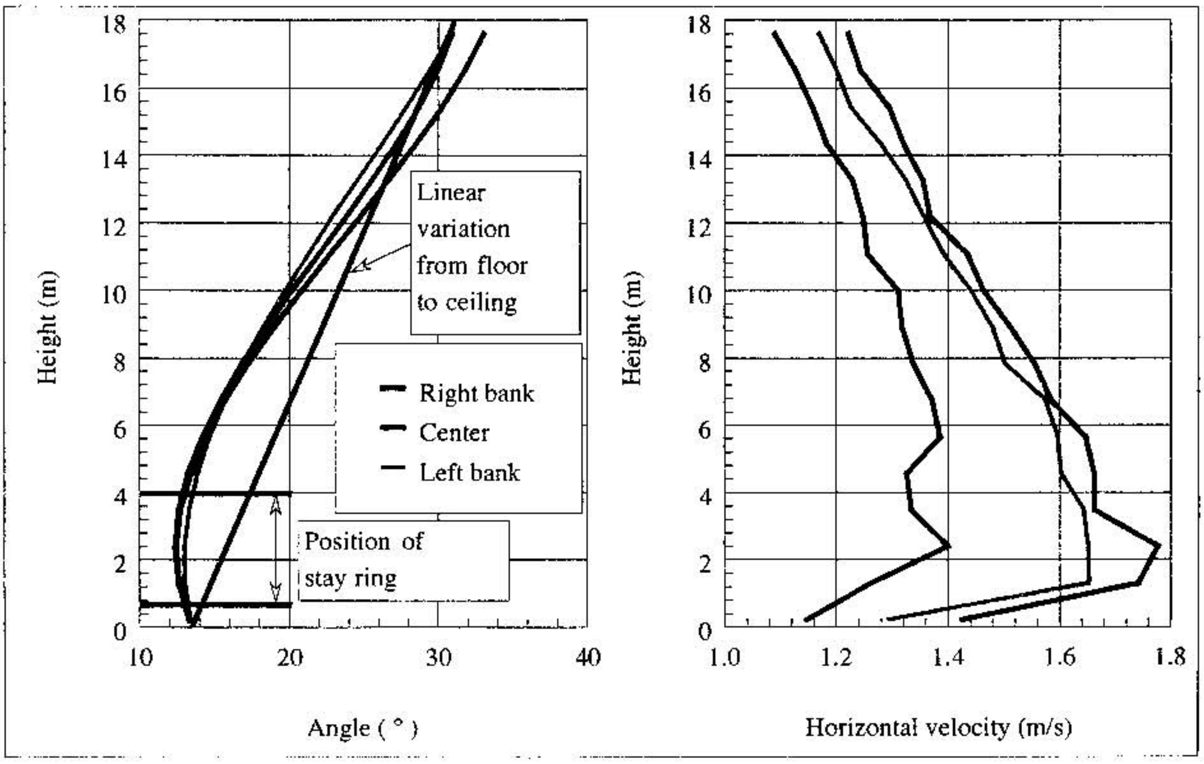

Figure 8. Mean flow angle, across the width of the conduit, and horizontal velocity component.

5. Conclusion

The means taken to measure the flow and particularly the flow angle were presented in this paper for a complex case which is usually encountered in low head power station, due to the shortness and high convergence of the waterways.

The use of swivelling current meters mounted on a movable frame has permitted an adequate exploration of the flow velocity profile including the flow angle, which is mandatory for the determination of turbine discharge and it's efficiency.

To achieve the measurement of flow velocity and angle, an unique current meter light frame was design and constructed. The real flow angle exceeded at many places the foreseen theoretical angle and the maximum adjustment possibility of the orientation mechanism, adding to the difficulty of measuring accurate flow angle also combine with the presence of temporal velocity variations.

Since the measurements were done by modern instrumentation with all the data stored on computer, a complete treatment was possible and prove to be of prime importance. This kind of treatment which would have necessitated so much time few years ago would probably not have been done. Many benefits were obtained from this treatment with the application of modern methods particularly recommended in the international standard IEC 41.

For the test foreseen at Laforge–2 power station in 1997, a low head installation equipped of Kaplan turbines, essentially the same type frame will be used with an equivalent amount of current meters. Nevertheless, the angular possibility of the orientation mechanism will be increased to cover the anticipate flow angle range following the present experience. When possible, it is recommended to keep the adjacent units running at approximately the same flow than the one under test, but this will not be possible at Laforge–2 because the power station contains only two units.