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Union Fenosa Generación's Field Experience with Acoustic Scintillation Flow Measurement

Jordi Vich Llobet, Ing., Union Fenosa Generación, Spain
David D. Lemon, M. Sc., J. Buermans, P.Eng., D. Billenness, ASL AQFlow Inc., Canada

Abstract

Union Fenosa Generación needed to establish the operational efficiency of their turbines at the Velle, Frieira and Castrelo plants on the Miño River. All three are low head plants with Kaplan units and short intakes. Having considered all presently available flow measurement methods suitable for short intakes, Union Fenosa Generación opted for acoustic scintillation. ASL AQFlow Inc. was contracted to perform flow measurement for one unit at each plant. The contract also included personnel training.

ASL AQFlow's Acoustic Scintillation Flow Meter (ASFM) is frame mountable, which means the instrumentation is completed in the yard, and fully instrumented frames are then moved between intake slots without de-installation and without intake dewatering. As none of the three plants had a slot which could be made available for the measurement, Union Fenosa Generación personnel devised an innovative two-part portable frame, which was fully instrumented in the dry, and then installed in the intakes by divers. It was then moved between plants without de-instrumentation and dewatering.

The ASFM used 15 measurement levels at each of the units' two intake bays. The flows were measured for 21 unit settings at Velle, 25 at Frieira and 12 at Castrelo, with 4 to 6 repeat measurements at each setting. The estimated absolute uncertainty of the measurement was less than ±1% at Frieira and Castrelo, and less than ±1.5% at Velle. After correction for head and power variations at Velle, the repeatability was ±0.3% to ±0.8%, probably influenced by changes in the adjoining unit operation. The repeatability was much better at Frieira (±0.2% to ±0.3%) and Castrelo (±0.1% to ±0.3%). It will be noted that at Castrelo, there is a relatively large reservoir and little variation in the water level during the measurements.

The total duration of the project, including the initial mounting of instrumentation and all the moves from unit to unit, was less than two weeks.

The paper illustrates the frame design, construction, instrumentation and installation in detail. It also describes the actual measurement and the results obtained.

Introduction

Union Fenosa Generación needed to establish the operational efficiency of their turbines at the Velle, Frieira and Castrelo plants on the Miño River in north-western Spain. Each plant has two Kaplan units, with short, converging intakes (Figures 1 – 3). Each unit has a nominal flow of 320 m^3/s at the net head of 13.0 m at Velle, 24.5 m at Frieira and

21.5 m at Castrelo. Having considered all presently available flow measurement methods suitable for short intakes, Union Fenosa Generación opted for acoustic scintillation.

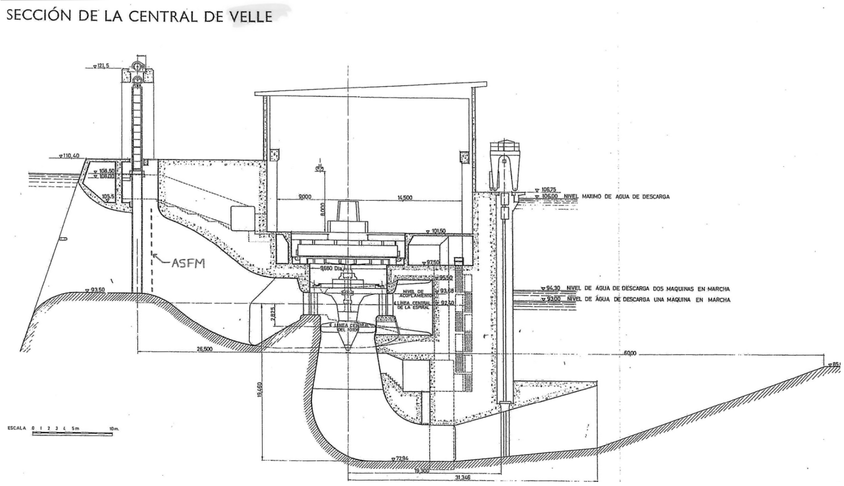

Figure 1: Schematic of the intake bays at the Velle plant

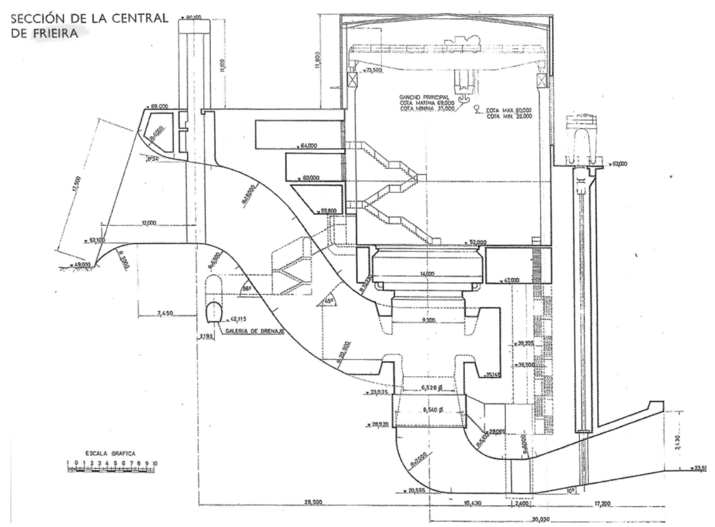

Figure 2: Schematic of the intake bays at the Frieira plant

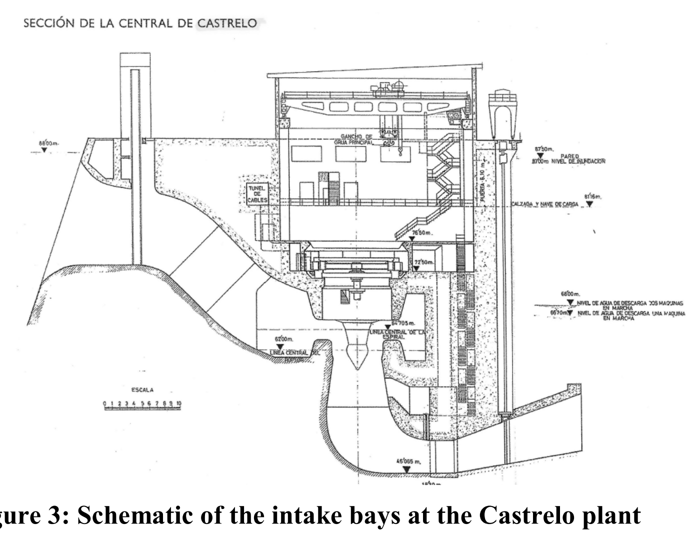

Figure 3: Schematic of the intake bays at the Castrelo plant

The scintillation method was first applied almost 70 years ago to the measurement of winds in the ionosphere and atmosphere, using light or radio waves. It was adapted by Canadian and U.S. Government laboratories to measuring currents and turbulence in ocean channels and rivers using acoustic scintillation signals. In the early 1990's, under a license from the two governments, ASL AQFlow further modified the method specifically for measurements in short, rapidly converging intakes of low-head hydroelectric plants, using its proprietary Acoustic Scintillation Flow Meter (ASFM).

The ASFM measures the flow velocity perpendicular to a number of acoustic paths established across the intake to the turbine *(Ref. 1)*. Fluctuations in the acoustic signals transmitted along the paths result from turbulence in the water carried along by the current. The ASFM measures those fluctuations (known as scintillations) and from them computes the lateral average (i.e. along the acoustic path) of the velocity perpendicular to each path. Both the magnitude and inclination of the velocity are computed, and the discharge is calculated by integrating the horizontal component of the velocity over the cross-sectional area of the intake bay. The discharges through individual intake bays are then summed to compute the total turbine discharge. As the instruments can be mounted on frames inserted into the existing intake slots, no intake dewatering is required, interference with the flow is minimized and the instruments are not exposed to damage from debris. Furthermore, fully instrumented frames can be moved between intakes with relative ease.

Each of the three Union Fenosa Generación plants has units with two-bay intakes. As there are no slots which could be made available for the measurement, the instrumentation had to be mounted on the walls of the intake bays. The following factors were considered in the design of the mounting system:

- minimum interference with the flow from protrusions into the flow area,
- accurate alignment of, and distance between, the transmitting and receiving transducers,
- ease of installation.

Plant personnel devised innovative two-part portable frames: the fixed base plates were bolted to the walls in each intake bay, downstream of the head gates, ahead of the measurement, during a unit outage, while the intake was dewatered. The two sets of portable frames holding the transducers were fully instrumented in the yard, also in the dry. These were then attached to the base plates in the intake bays under water by divers.. The two sets of fully instrumented portable frames were then moved between plants, again without de-instrumentation or dewatering.

Each portable frame contained 15 holes for transducers. The transducers were installed on the frame and the transducer array cables were connected to the receiver and transmitter canisters that were placed above the frames. A receiver surface cable was connected to the receiver canister, a control surface cable to the receiver canister, a transmitter surface cable to the transmitter canister, and interconnect (ICC) cable connected both canisters. The installation of the ASFM components by ASL and Union Fenosa Generación personnel began on the morning of October 1 and was completed the following day. Figure 4 shows the ASFM frames and Union Fenosa Generación personnel installing the components of the ASFM on a frame. The fully instrumented frames were lowered into the slot using an overhead crane (Fig. 5), and bolted onto the base plates. The Group A and B canisters were bolted directly to the intake wall. A view of the top of the frame as installed is shown in Figure 6.


Figure 4: ASFM frames (left) and ASFM components being installed (right - frame upside down)

Figure 5: A fully instrumented frame being moved into the intake bay at Velle

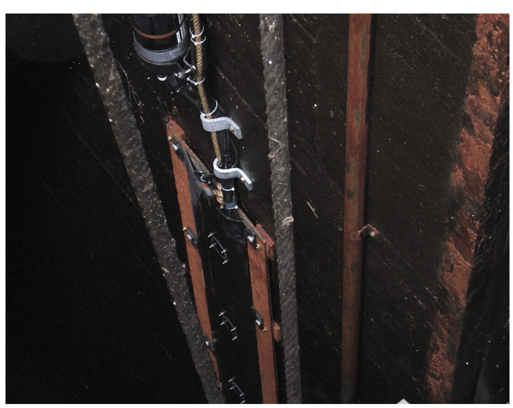

Figure 6: View of the top of a frame as installed in the intake bay

Figure 7 shows a schematic diagram of the components of the 15-path ASFM as installed in the plants. It consists of five major components: transmitting (Tx) and receiving (Rx) transducers and underwater cabling, switching canisters, surface connection cables, a data acquisition surface unit, and a PC computer with the user interface for controlling and operating the ASFM. The ASFM is divided into 3 groups; each group consists of 20 transducer arrays (in pairs of Tx and Rx), two switching canisters and cabling. Group A was located in Bay 1, Group B in Bay 2 and Group C was divided between Bays 1 and 2. The switching canisters for Group C were located in Bay 1. Extension cables were used on the Group C transducers in Bay 2 so that they would reach into Bay 1.

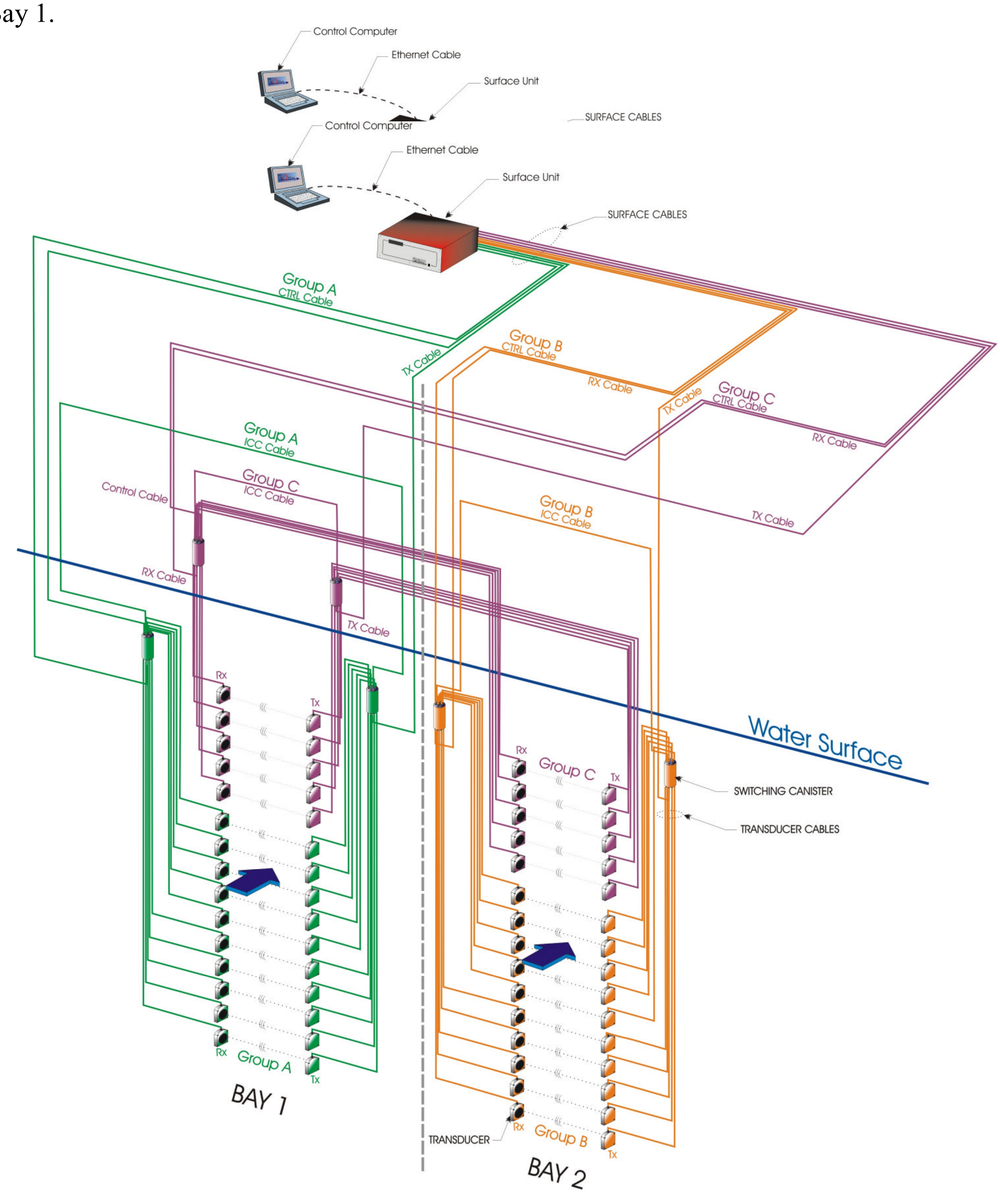

Figure 7: Components of the 2-bay, 15-path ASFM system. The arrows indicate the flow direction

Measurements

Measurements were conducted at the Velle plant on October 3-5. The frames were then removed by divers and moved to Frieira where measurements took place on October 8-9. The frames were moved to Castrelo for measurements on October 11-13.

Measurements were taken at different heads and with the neighbouring unit (Unit 2) at different loads, except at Castrelo where Unit 2 was out of service. ASL personnel were responsible for the flow measurements, while Union Fenosa Generación personnel were responsible for the head, power and differential pressure measurements. Preliminary results were reported as the tests were proceeding.

Each one of the ASFM 15 acoustic paths on the two frames was sampled consecutively (in groups of 3) for 32 seconds and 4 to 6 repeats at each measurement condition were performed. Roughly 30-40 minutes were necessary to obtain an average discharge for each condition. In general, the data collection proceeded smoothly and the quality of the data collected was good. Variations in the plant head and unit power caused changes in the discharge of the individual repeat runs. The head fluctuations at Velle were very large and therefore the individual discharges were scaled to a common head and power before they were averaged.

The acoustic amplitude fluctuations are random variables, and the time delay between them as measured by the position of the peak of the time-lagged cross-correlation is a statistical quantity. A measure of its variability is derived by subdividing the full length of the time series (32 seconds at 250 Hz pinging rate) into segments of 2048 samples (each 8.2 seconds long at 250 Hz pinging rate). The individual blocks are 2048 points long for computational efficiency in the FFT (Fast Fourier Transform) procedure used to compute the cross-correlation. Each of the individual blocks provides a velocity value, and their average is the mean velocity over the full 32-second sampling period. The standard deviation of the individual velocities can be used as a measure of the variability in the velocity. Each of the individual measurements has a relatively high error associated with it, because of the short length of the record. They form a random distribution about the mean; however, there are occasional outliers in the individual velocity measurements. These are rejected using procedures outlined in the IEC 60041 *(Ref. 2).*

Figure 8 show a sample of the velocity vector plots for Castrelo. The base of each vector is located at the position in the intake bay where the measurement was made. The length of the vector gives the magnitude of the velocity, scaled by the legend in the diagram, and its direction shows the inclination. The number at the base of each vector is its magnitude in metres per second. The notations at the top of the figure detail the conditions under which the data were collected.

Between the measured points at the upper and lower extremes and the corresponding boundaries at the roof and floor, it was necessary to impose a form on the horizontal component of the velocity to allow the evaluation of the integral to be completed. The 15 paths at each bay covered most of the height of the intake and thus only a relatively small portion of the total flow needed to be estimated.

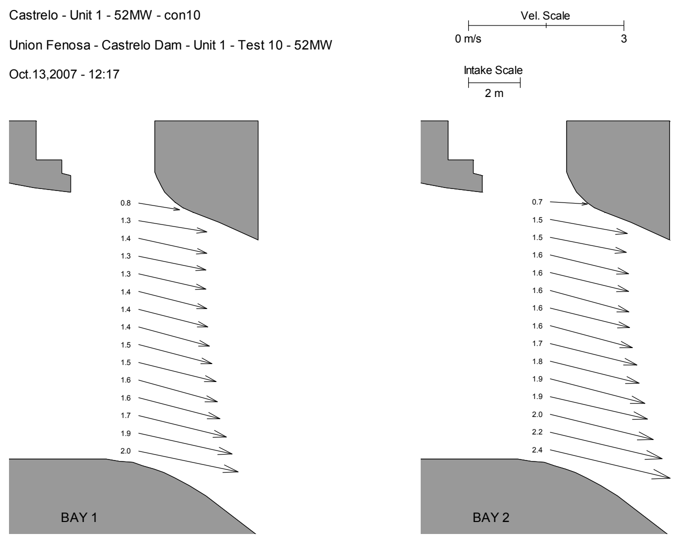

Figure 8: Sample velocity vector plot from Unit 1 at Castrelo

The results collected by current meters in an intake with a similar floor slope *(Columbia River Turbine Discharge Rating Program, Ref. 3)*were used to determine the approximate boundary layer thickness and the flow in the lower zone. A curve of the form:

$$\left[\frac{z}{T}\right]^{\frac{1}{X}} \qquad (1)$$

was fitted for the measured profiles within the boundary layer, where z is the elevation and T the boundary layer width (0.2 m for all three plants). The horizontal velocity at the bottom transducer elevation was extrapolated to the boundary layer thickness (T=0.2) and below this, the curve given in equation 1 was used to estimate the flow. A value of X=7 was used at all three plants, consistent with ISO 3354 *(Ref. 4)* recommendations. The elevation of the bottom transducer varied from 0.465m at Velle to 0.568m at Frieira.

To estimate the flow in the roof region, the horizontal and vertical components of the velocity were examined at the three sites. As an example, Figure 9 shows the horizontal (top) and vertical (bottom) component of the velocity in the upper boundary zone for all measurements and both bays at Castrelo. The dashed blue lines are the measured values, the red line is the average, the green circles mark the transducer elevations and the red cross is the extension of the red line to the upstream roof elevation (10.25 m). The velocity shown is a relative value; the velocity at the second highest path (path 14) was used to normalize the values.

As shown by the Figure 9, the horizontal velocity is close to zero at the roof elevation and thus a closed boundary can be used (zero bypass flow through the slot), with the form:

$$\left[\frac{Zr - z}{T}\right]^{\frac{1}{X}} \qquad (2)$$

where Zr is the roof elevation (10.25 m). X was set to 1 in order to linearly extrapolate the top measured horizontal velocity to the roof elevation. T was set to 1 in order to capture a region large enough to include measurement path 14. This then allowed the discharge in the region between path 14 and the roof to be computed even when the data at the highest path (path 15) was removed due to poor data quality (likely caused by variable flows and by acoustic reflections due to the proximity to the roof). In these cases, the discharge was computed by calculating a value of X in equation 2 so that it matched the discharge computed from the average line (the red line shown in Figure 9).

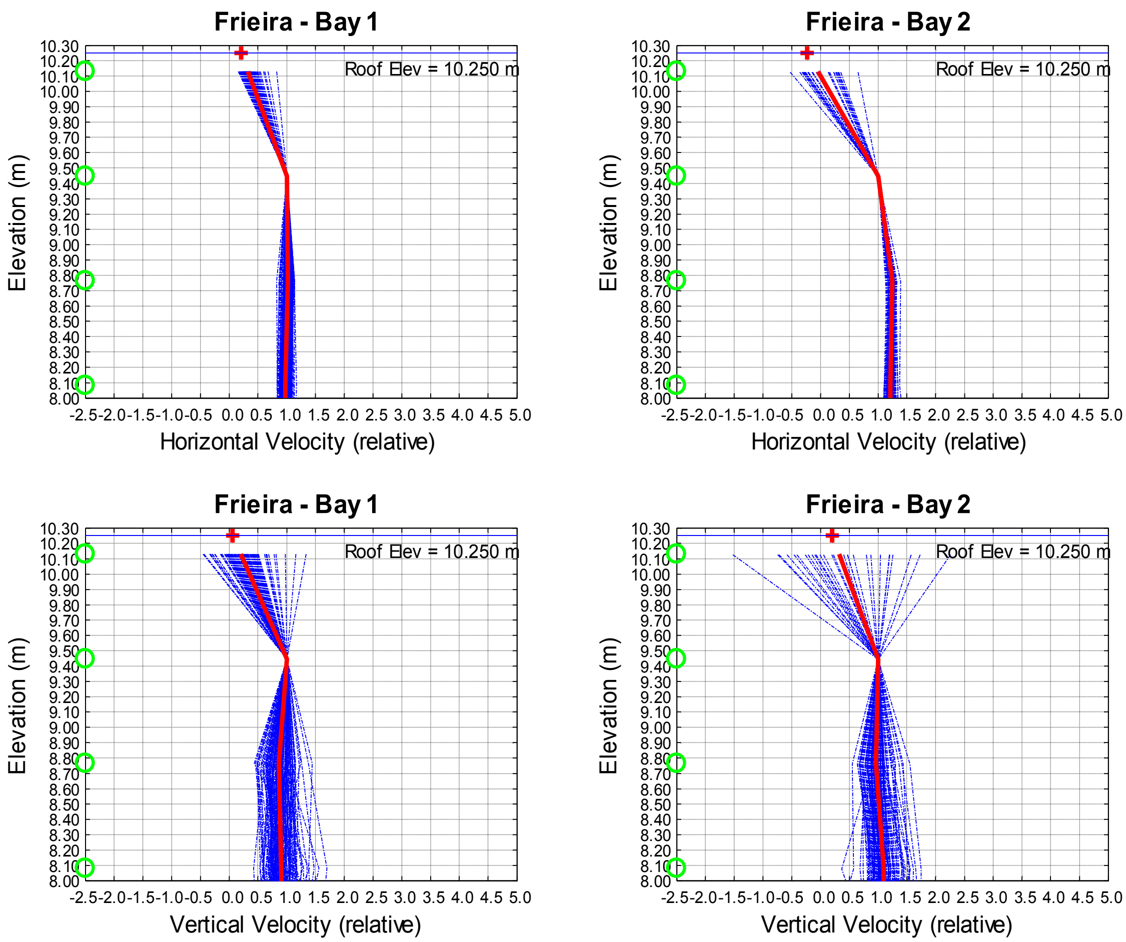

Figure 9: Measured relative horizontal velocity (top) and vertical velocity (bottom) at Frieira

As an example of the measurement results produced by the ASFM, Figure 10 shows the horizontal velocity profiles as a function of intake elevation at Castrelo at 40 MW. The black line is a quadratic interpolation of the measurements; the blue line is the extrapolation from the last measurement point to the floor thickness T; the red line is a simplified curve that represents the same discharge as that calculated from formulas 1 and 2. For simplicity, the plots are shown grouped by the output power in Unit 1 before any head corrections have been made. As illustrated in the Figure 10 and seen at each of the three plants, there is a large change in the velocity between paths 14 and 15. It is recommended that for any future measurements, a mid-level path be moved in between the two top levels to better resolve the velocity distribution in this region.

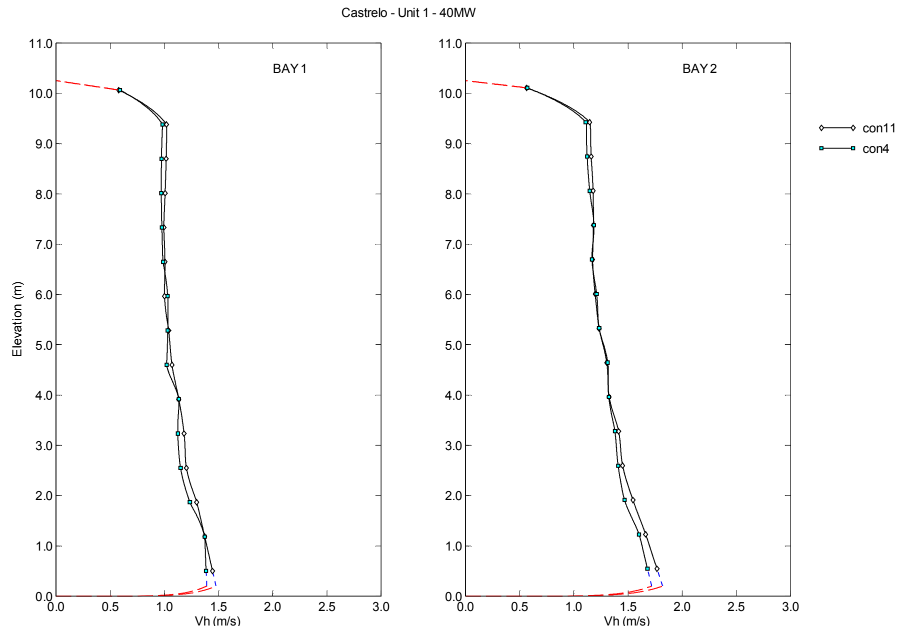

Figure 10: Plots of the horizontal component of velocity at Castrelo (40 MW).

Results

Summary discharge values are listed in Figure 11 for Velle, Frieira and Castrelo. They represent an average discharge from the individual repeat runs. The number of repeat runs used to compute each discharge and the standard deviation of the discharge are also listed. The repeat runs made at each condition allowed the repeatability of the ASFM flow measurements to be calculated at each site.

At Velle, there were large variations in the plant head and unit power during the individual repeat runs. Therefore, conversion of results to an average head was performed for each group of repeat runs. Whenever the head fluctuated by more than 1% during the run, the results were rejected, as per IEC 60041. Following this adjustment, the average standard deviation of the flow results went down slightly from 1.3% to 1.1%. However, there were still significant variations in the head-corrected power. At constant adjusted head, variations in the power must indicate that the flow itself was changing, and therefore the variations in the head-corrected flow are not representative of random error in the measurement, but are at least partly due to changing conditions. To estimate the size of that effect, the flows were scaled by the ratio of the head-corrected power at each repeat to the average power over the series. This assumes that the efficiency of the turbine is constant under small head and flow changes, particularly at or near best cam; IEC60041 specifies that head variations within a test sequence must be within 1% for the sequence to be valid. That condition was met for only 9 of the 21 test conditions at Velle (Figure 11). Outliers of the power corrected discharge were removed from each condition using the Modified Thompson τ Technique (ASME PTC 18-2002: *Ref. 5*). The variability of the flow measurement was then estimated as the average of the standard deviations of the repeat runs for each condition, including only those conditions where the head changed by less than 1% during the measurement and was within ±10% of the

Velle Dam - Unit 1 - October 2007

* Corrected for head and power, except Condition 15

Date (mmm dd, yy)	Time (hh:mm)	Cond	# Repeats	# Repeats Used	U1 MW	U2 MW	Head Range	Qtot* m^3/s	Qtot StdDev (%)
Oct 03, 07	14:49	1	7	6	35	0	1.6%	345.3	0.5%
Oct 03, 07	15:45	2	6	5	32	0	0.8%	310.9	0.5%
Oct 03, 07	16:33	3	4	4	17	0	0.7%	156.6	0.4%
Oct 03, 07	17:07	4	5	5	12	0	0.9%	107.1	0.3%
Oct 04, 07	09:12	5	5	4	12	20	0.8%	97.3	0.6%
Oct 04, 07	09:48	6	6	6	17	20	1.3%	145.0	0.6%
Oct 04, 07	10:32	7	6	4	17	34	1.0%	160.8	1.4%
Oct 04, 07	11:14	8	5	5	22	34	1.4%	210.1	0.6%
Oct 04, 07	11:50	9	5	5	28	30	2.1%	282.2	0.3%
Oct 04, 07	12:27	10	5	4	30	26	2.3%	332.6	0.2%
Oct 04, 07	13:04	11	6	5	26	20	1.1%	294.8	0.5%
Oct 04, 07	13:45	12	6	5	22	20	1.4%	247.2	0.5%
Oct 04, 07	14:42	13	6	5	28	0	0.9%	306.1	0.8%
Oct 04, 07	15:26	14	6	3	22	0	0.3%	229.3	0.5%
Oct 05, 07	09:12	15	6	6	12	0		104.8	
Oct 05, 07	10:00	16	6	5	33	0	0.3%	285.0	0.8%
Oct 05, 07	10:58	17	6	5	33	20	2.2%	340.1	0.6%
Oct 05, 07	11:39	18	6	5	30	20	2.8%	328.5	0.4%
Oct 05, 07	12:27	19	5	4	22	20	6.4%	247.0	1.5%
Oct 05, 07	13:12	20	5	4	12	20	0.6%	137.2	0.1%
Oct 05, 07	13:53	21	6	6	12	24	2.4%	140.2	1.6%
	Head/Power corrections N/A							**Max:**	1.4%
	Not included in Max/Avg >1% head variation							**Avg:**	0.6%

Frieira Dam - Unit 1 - October 2007

* Not corrected for head or power

Date (mmm dd, yy)	Time (hh:mm)	Cond	# Repeats	# Repeats Used	U1 MW	U2 MW	Head Range	Qtot* m^3/s	Qtot StdDev (%)
Oct 08, 07	08:07	1	6	6	25	0		129.6	0.6
Oct 08, 07	08:47	2	6	6	35	0		167.8	0.6
Oct 08, 07	09:56	3	6	6	35	70		190.2	0.7
Oct 08, 07	10:37	4	6	6	40	70		214.0	0.4
Oct 08, 07	11:18	5	6	6	50	70		268.9	0.3
Oct 08, 07	12:05	6	6	6	55	70		296.7	0.4
Oct 08, 07	12:48	7	6	6	65	65		368.3	0.4
Oct 08, 07	13:45	8	6	6	70	0		371.1	0.3
Oct 08, 07	14:34	9	5	5	65	0		336.8	0.2
Oct 08, 07	15:13	10	5	5	60	0		305.8	0.4
Oct 08, 07	15:49	11	5	5	55	0		277.7	0.3
Oct 08, 07	16:24	12	5	5	50	0		254.5	0.5
Oct 08, 07	16:59	13	6	6	45	0		225.4	0.7
Oct 09, 07	08:26	14	5	5	35	35		181.1	0.3
Oct 09, 07	09:03	15	5	5	45	35		226.0	0.4
Oct 09, 07	09:41	16	6	6	50	35		257.5	0.3
Oct 09, 07	10:23	17	6	6	55	35		287.1	0.3
Oct 09, 07	11:04	18	4	4	60	35		317.4	0.2
Oct 09, 07	11:35	19	4	4	65	35		349.7	0.2
Oct 09, 07	12:10	20	5	5	70	35		366.3	0.4
Oct 09, 07	12:53	21	4	4	45	70		252.6	0.4
Oct 09, 07	13:23	22	4	4	40	70		226.3	0.2
Oct 09, 07	13:58	23	4	4	30	70		179.0	0.2
Oct 09, 07	14:37	24	4	4	25	70		149.5	0.5
Oct 09, 07	15:13	25	4	4	25	35		152.4	0.3
								Max:	0.7
								Avg:	0.4

Castrelo Dam - Unit 1 - October 2007

* Not corrected for head or power

Date (mmm dd, yy)	Time (hh:mm)	Cond	# Repeats	# Repeats Used	U1 MW	U2 MW	Head Range	Qtot* m^3/s	Qtot StdDev (%)
Oct 11, 07	08:40	1	4	4	20	0		114.8	0.1
Oct 11, 07	09:17	2	2	2	25	0		140.5	0.1
Oct 11, 07	10:11	3	3	3	35	0		198.8	0.1
Oct 11, 07	10:45	4	1	1	40	0		225.4	
Oct 13, 07	09:27	5	4	4	30	0		162.9	0.5
Oct 13, 07	10:01	6	4	4	44	0		239.2	0.3
Oct 13, 07	10:34	7	4	4	48	0		268.4	0.1
Oct 13, 07	11:09	8	4	4	56	0		316.5	0.1
Oct 13, 07	11:44	9	4	4	58	0		343.3	0.2
Oct 13, 07	12:17	10	4	4	52	0		301.0	0.2
Oct 13, 07	12:51	11	4	4	40	0		230.7	0.2
Oct 13, 07	13:24	12	4	4	25	0		147.9	0.3
								Max:	0.5
								Avg:	0.2

Figure 11: Discharge values for Velle, Frieira and Castrelo

overall average head. The average standard deviation of the flow values then drops to 0.6% (maximum to 1.4%), which is more representative of the repeatability of the ASFM flow measurement under truly constant conditions *(Ref. 6)*. The majority of the larger variation in the raw and head-only-adjusted flows is in fact caused by actual flow fluctuations, and not by measurement error.

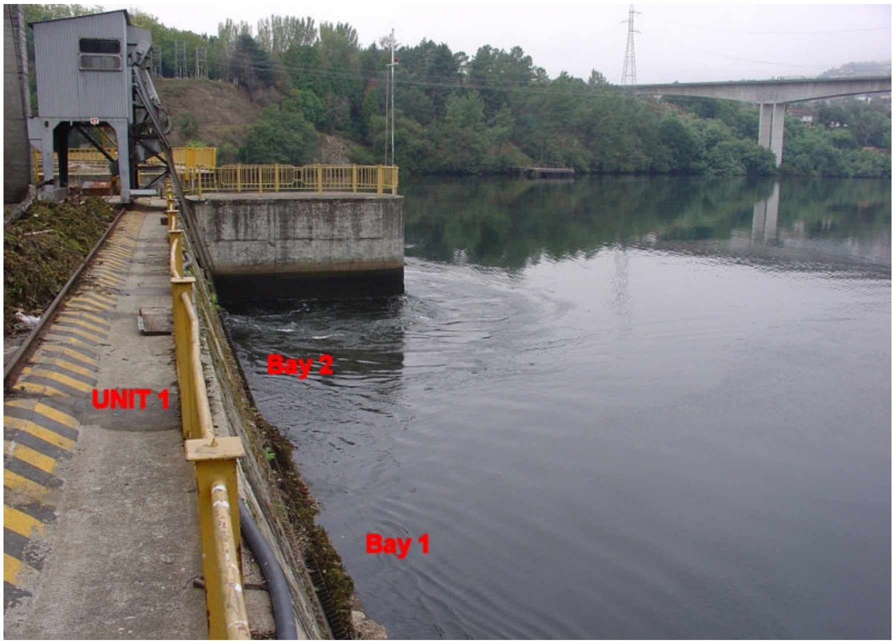

Figure 12: The flow entering at a sharp angle in Bay 2 in Unit 1 at the Velle plant

Interestingly, the maximum standard deviation in Bay 2 was twice as large as in Bay 1, and the average was 20% larger. This may be due to the flow entering Bay 2 at a sharp angle and creating a large eddy in front of the Bay 2 when the spillway was closed, as shown in Figure 12.

At Frieira, the head variations were much lower during the repeat measurements than at the Velle plant, and the average standard deviation of the total discharge from the individual repeat runs made at each condition was 0.4% and the maximum was 0.7%. This is much more typical of what is seen by the ASFM at other plants. Also, the average standard deviation of the discharge in each bay was nearly identical. The Castrelo reservoir is relatively large and a stable head was maintained during the repeat runs. Consequently, the average standard deviation of the total discharge from the individual repeat runs made at each condition was 0.2% and the maximum was 0.5%. The average standard deviation of the discharge in each bay was also nearly identical.

Figure 13 presents the Winter-Kennedy differential pressure across the scroll case plotted against the flow measured by the ASFM at Castrelo. The correlation equation in Fig. 13 is clearly satisfactory and increases one's confidence in the results.

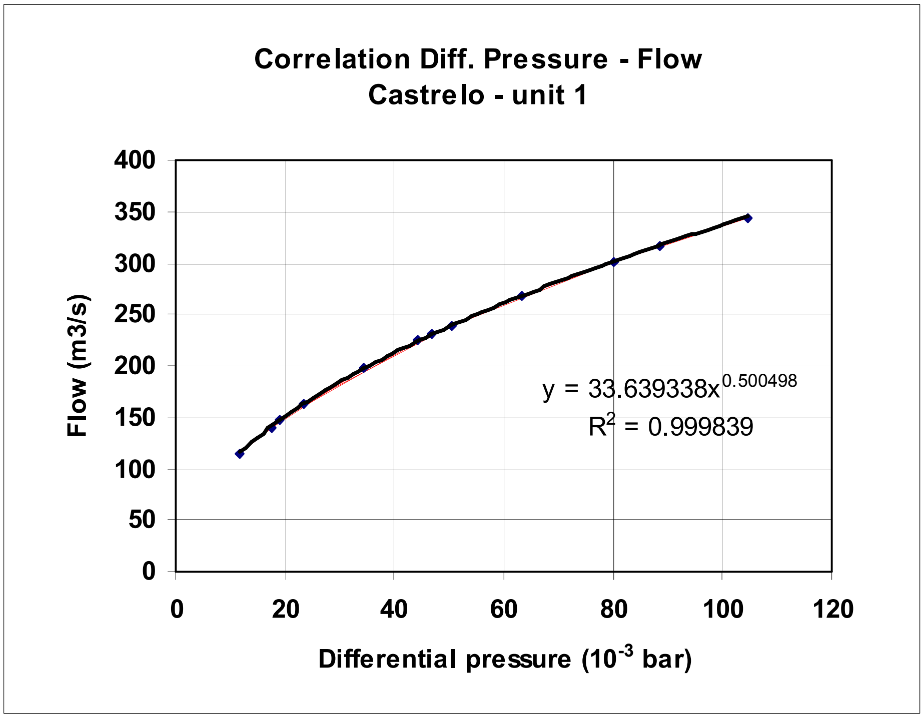

Figure 13: Flow comparison for Unit 1 at the Castrelo plant

Discussion

The installations at the Velle, Frieira and Castrelo are the first to have been done using a two-part ASFM frame fixed to the intake walls, and were a success. Once the base plates were permanently attached to the walls of the intake bays in the dry during a unit outage, the portable frame installation and removal proceeded smoothly. Fully instrumented portable frames were installed in the two intake bays in a day or less at each plant, and removed even faster. Obtaining the necessary dimensional measurements under water is not simple, however, and the care and attention required for divers to obtain accurate results is somewhat time-consuming.

Data collection at all three plants proceeded smoothly, and the data quality at Frieira and Castrelo was very good. At Velle, the data quality was also good, but variations in the plant head and neighbouring unit operation caused large changes in the discharge of the individual repeat runs. However, after head and power corrections, the average standard deviation of the individual repeat runs made at each condition dropped to 0.6%, with the maximum at 1.4%. At Frieira and Castrelo, even without head and power corrections, the average standard deviation was 0.4% and 0.2%, respectively, with the maximum values of 0.7%, and 0.5%, respectively.

None of the intakes at these three plants had major upstream obstructions, such as trashrack supports, which – if large and close to the measurement plane, or under oblique inflow conditions – can be the chief cause of systematic error in ASFM measurements. The only exception was the Bay 2 of Unit 1 at Velle, where an oblique approach flow resulted in somewhat larger measurement variations.

Under these circumstances, experience suggests that the magnitude of any systematic error present would be less than 1% at Castrelo and Frieira, and less than 1.5% at Velle *(Ref. 7)*.

The random error may be estimated from the standard deviations of the repeat runs, as the standard error in the mean, $\sigma/\sqrt{(N-1)}$, where N is the number of repeats: At Velle, 0.6% to 1.9% (before correction for head and power variations) and 0.3% to 0.8% (after correction); at Frieira 0.2% to 0.3%, and at Castrelo 0.1% to 0.3%. Even though head fluctuations at Frieira and Castrelo were much smaller than at Velle, the individual discharges should be adjusted to a common head before they are averaged (§6.1 in *Ref. 2* or §5.2 in *Ref. 5*). Furthermore, flows should be corrected for power fluctuations prior to the standard deviation calculation. As the generation output is measured independently of the flow measurement, and since the efficiency near the best cam position can be expected to remain nearly constant for small blade or vane changes, once adjustments for head are made, the flow may be adjusted by the same fraction as the change in power output recorded between repeat runs.

Acknowledgment

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