Discharge measurements at SLAPY HPP – Comparison between acoustic scintillation and pressure-time methods

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1. Introduction

Slapy hydroelectric plant (HPP) is a typical mid-head HPP hosting three 50 MW Kaplan turbines on the Vltava river, 50 km south of Prague, Czech Republic. The gross head is 47 ÷ 53 m in normal operation regime. Pressure-time (PT) flow measurement method was specified for the acceptance tests of the upgraded Unit #3 in autumn 2011 and OSC had the contract for those tests. ASL AQFlow proposed to both OSC and EDF to use the Slapy HPP efficiency measurements on the Unit #3 for an on-site comparison test between the PT and Acoustic Scintillation (AS) methods. Both OSC. and EDF agreed and the comparison testing proceeded thanks to the kind permission of ČEZ Hydro Power Plants management. OSC supported the design and manufacture of the movable frame for the AS method, while EDF provided its own AS system as well as the necessary workforce.

2. Description of Slapy HPP

The longitudinal section through the unit #3, with the sensor positions marked in red, is displayed in Fig. 1. Slapy units are not equipped with valves in front of the spiral cases. The intakes can be closed by the emergency gates and also by the temporarily installed stoplogs. An aeration pipe allows the air entry into the penstock downstream of the emergency gate. The total length of the penstock is approx. 45 m. Pressure taps are installed in the spiral case for the Winter – Kennedy flow measurement in accordance with the requirements of Standard IEC 60041.

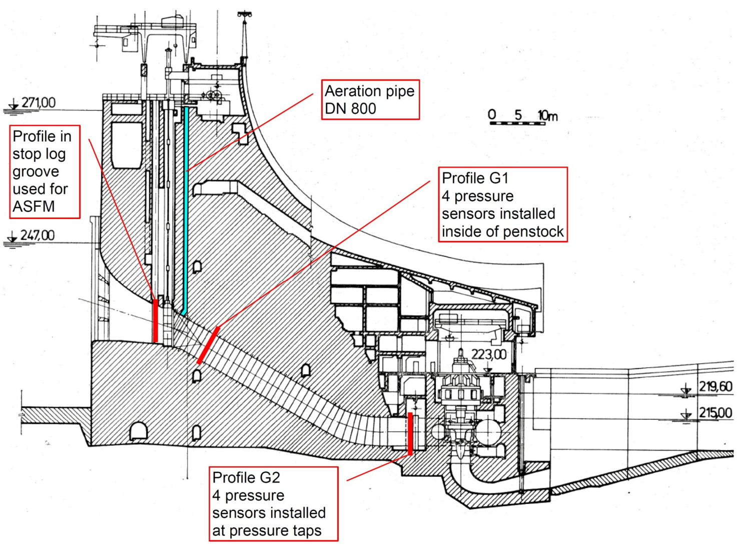


Fig. 1 – Longitudinal section of HPP Slapy

3. Description of the measurement methods

3.1. Pressure-time

The method of separate pressure diagrams in accordance with the requirements of IEC 60041 and IEC 62006 was chosen. Four pressure sensors with protection IP68 were installed in the upper part of the penstock (profile G1) – see Fig. 2. Cables from these sensors were led trough the cable ducts and the aeration pipe up to the dam crest. Four additional sensors were installed in front of the spiral case on the pressure taps from the outside of the penstock. All pressures were recorded individually. All deviations of particular pressure values from the mean pressure value in both profiles G1 and G2 were evaluated. The deviations in the profile G1 were negligible, while the max./min. value in the profile G2 was ±0.5 kPa at full discharge (standard IEC 60041 requires max. 20% of the dynamic pressure). This means that the pressure distribution in both profiles fulfilled the requirement of the standard.

The inner penstock dimensions were measured using a laser distance gauge with a magnetic jig, telescopic geodesic lath and tape measure when the unit was drained. The mean value of the inner diameter of the measuring section is 4.995 ± 0.01 m, and the center line length is 38.651 m, with an estimated absolute uncertainty of ± 0.05 m.

Leakage through the closed guide vane was determined from the water level decrease in the aeration pipe after the emergency shutdown with the stoplogs. The pressure difference on the stoplogs was low and the leakage became negligible shortly after the shutdown. Two tests were carried out with the results of 0.106 and 0.105 m^3/s.

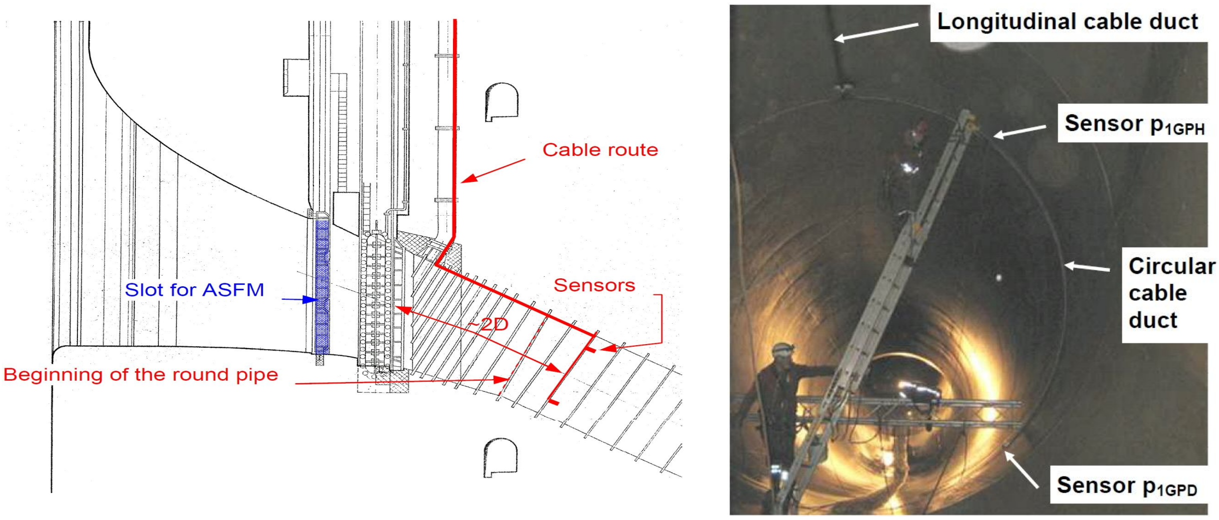
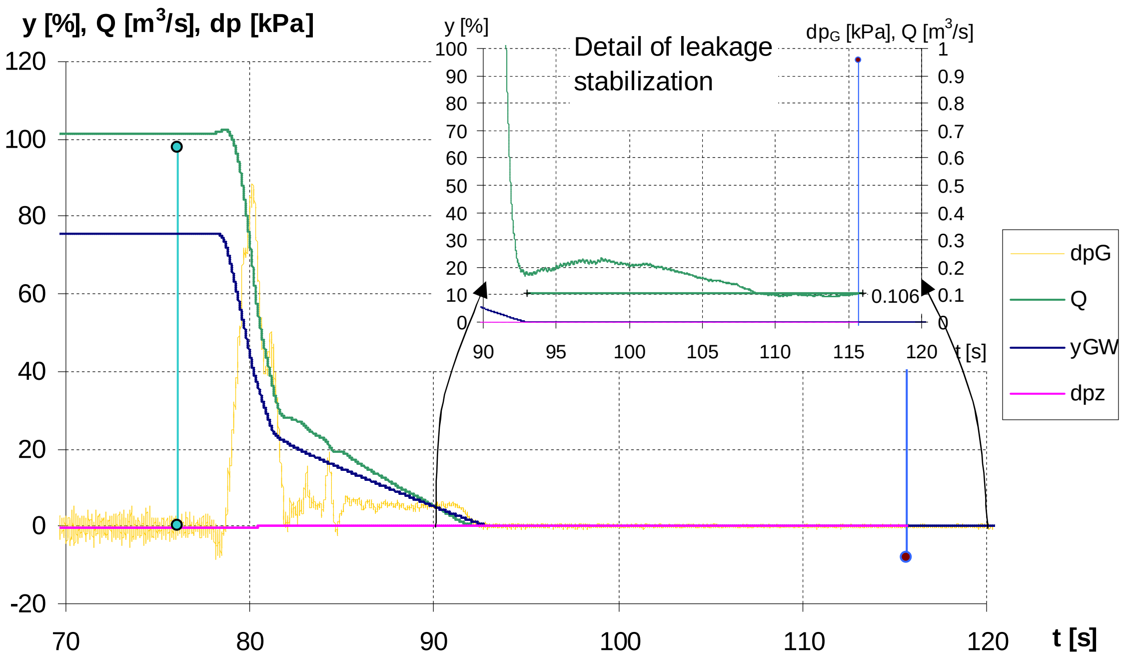


Fig. 2 - Upper part of the penstock with pressure sensors in profile G1

Four pressure-time tests were performed as part of the comparative measurements. An example of the pressure-time diagram is presented in Fig. 3. Post-processing was not used for the flow calculation except for a very exactly determined zero of the dynamic differential pressure. This procedure was important for minimizing the integration error as described in [3] – see the detail of the leakage stabilization after the guide vanes closing in Fig. 3. The pressure oscillations after the guide vane closing were negligible, therefore no additional procedure for integration termination was used.

HPP Slapy is part of the cascade on the Vltava River. The upper lake is large, but the bottom lake is small and very narrow. Therefore, a fast unit shutdown causes waves in the bottom lake and also changes in the mean values of the tailwater level. Because the record of stable operation in pressure-time diagrams before the unit shutdown takes approx. 1 minute, but the one for the AFSM measurement takes about 20 minutes, the direct comparison of the two methods was impossible. Instead, Winter – Kennedy taps were calibrated by the pressure-time method and the mean values of discharge from the Winter-Kennedy and ASFM were compared for the entire measurement period.



Legend:

dp_G	Differential pressure at measuring section between profiles G2 and G1
Q	Discharge
y_{WG}	Wicket gate (guide vanes) opening
dp_Z	Friction losses at measurement section

Fig. 3 – Example of pressure-time diagram

3.2. Acoustic scintillation (ASFM)

3.2.a Description of the ASFM

The ASFM utilizes the effects of natural turbulence embedded in the flow on acoustic signals (Fig. 4). In its simplest form, two transmitters are placed on one side of the intake, two receivers on the other. The acoustic signal amplitude at the receivers varies randomly as the turbulence along the path changes with time and the flow. If the two paths are sufficiently close (Δx), the turbulence remains embedded in the flow, and the pattern of these variations at the downstream receiver will be nearly identical to that at the upstream receiver, except for a time delay (Δt). This time delay corresponds to the position of the peak in the time-lagged cross-correlation function calculated for Signal 1 and Signal 2. The mean velocity perpendicular to the acoustic path is then $\Delta x/\Delta t$. Because three transmitters and three receivers are used, the average inclination of the velocity is also obtained. The flow is calculated by integrating the average horizontal component of the velocity at pre-selected levels over the total cross-sectional area of the intake.

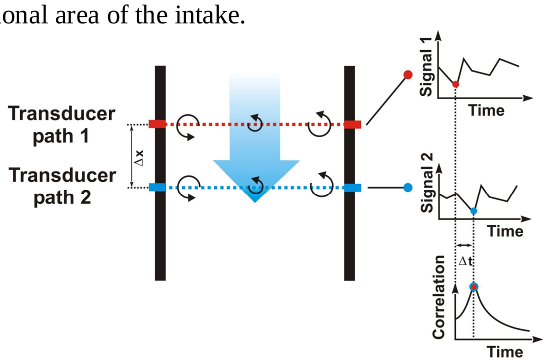


Fig. 4- Representation of the acoustic scintillation principle

3.2.b The ASFM frame

The ASFM movable frame was designed by OSC and built in the Czech Republic by a sub-contractor of OSC The design was reviewed by both ASL AQFlow and EDF-DTG before the construction began. It was decided to build a small, rigid frame with three main round transversal beams, connected by a series of smaller beams to improve the mechanical structure. The drawback of such frames is that they create a fairly large obstruction which impacts the velocity profile at the measurement location.

As can be seen in Figures 5-7, the frame was equipped with one-pair of ASFM transducers. The frame travelled smoothly up and down in the stoplog slot during all the tests, and no flow-induced vibrations could be detected.

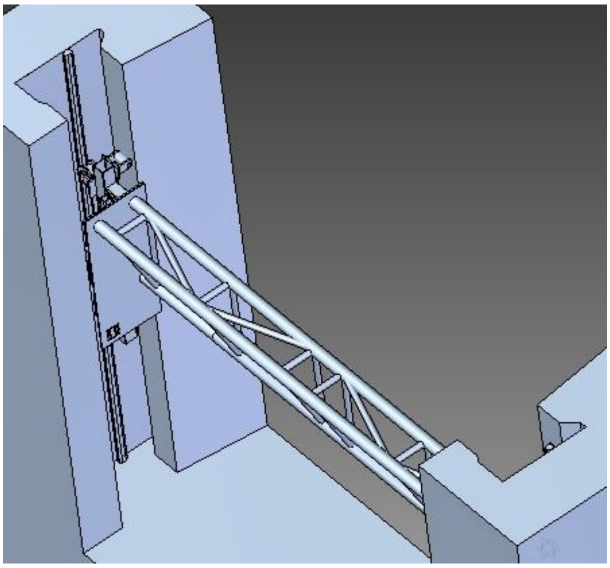


Fig. 5 - 3D view of the frame in the slot

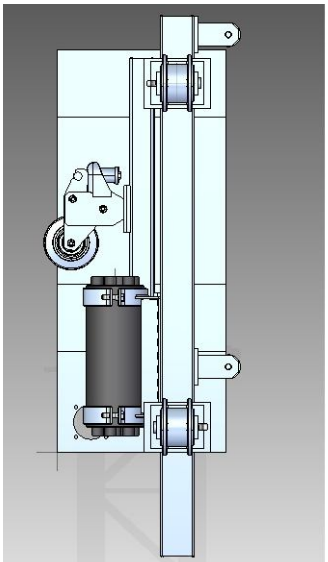


Fig. 6 - side view of the frame (the canister in black)

Fig. 7 - picture of the frame being deployed

4. Results

4.1. CFD computations

A CFD model was built for the frame in the slot, essentially to check the impact of the closest transversal beam on the velocity profile along the ASFM acoustic path. Such impact was present whatever the frame location, adding a potential systematic uncertainty to all ASFM measurements. The CFD computations were performed with the ANSYS CFX-Flo package, first in 2D, then in 3D, using a symmetric condition on the axis.

The computational domain comprised:

- A section upstream of the trashrack, upstream to the free surface
- The trashrack section (only the main vertical supports)
- The intake, downstream to the transition from rectangular to circular
- A small part of the ASFM stoplog groove

The boundaries of the computational domain can be seen in Fig. 8, an example of the meshing in Fig. 9:

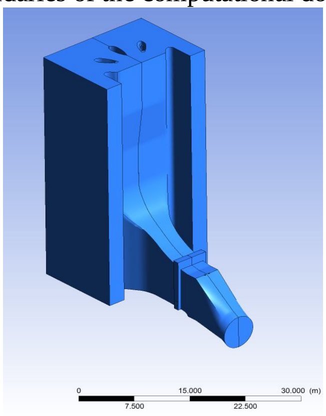


Fig. 8 - Full computational domain

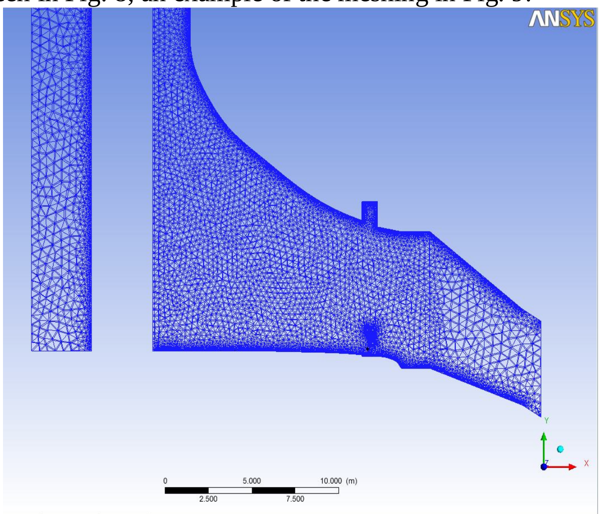


Fig. 9 - Cross-section of the mesh

4.2. Correction factor k

The correction factor k has been proposed to take into account the blockage effect. The CFD k-factors have been compared to those computed using formulas from the international code ISO 3354.

In the case of the Slapy measurements, the blockage ratio is estimated at s = 2,4 %; thus the ISO 3354 Appendix B blockage effect by current meters can be applied and yields k_{ISO} = 0,12 s = 0,3 %.

Using the CFD, the mean flow velocity was computed for several discharge values with and without the frame, and for various locations of the frame in the measurement section. Then the bias between the values obtained with or without the frame was calculated for various locations of the ASFM transducers.

Table 1 shows this bias for various combinations of the discharge values and locations of the ASFM transducers.

Discharge value	location of ASFM transducer in the slot	difference on the horizontal velocity with and without frame (kCFD values) (%)
107 m3/s	floor	0,6%
	middle	0,4%
	top	-1,9%
77 m3/s	floor	0,7%
	middle	0,4%
	top	-1,9%
36 m3/s	floor	0,7%
	middle	0,4%
	top	-1,7%

Table 1: correction factors computed using CFD

The values for the ASFM transducers located at the top of the section can be sensitive to the secondary flow in the gate slot, therefore they should be considered with caution.

If we focus on the k_{CFD} values for the floor and middle locations only:

- k_{CFD} values are larger near the floor region (0.6 % with CFD vs. 0.3 % with ISO 3354), as the ASFM transducers are "stuck" between the floor and a large structural beam which is close and causes large flow disturbances
- k_{CFD} values are somewhat lower for the middle locations, where the influence of the beams is diminished as the flow has more space below to recombine around the beams. Here, the k_{CFD} values are very close to the k_{ISO} values (0.4 % vs. 0.3%)

While a correction factor value of 0.4% has been retained for the following ASFM discharge calculations, the CFD computations tend to show that a higher correction value might be appropriate to better account for the systematic error due to the beam effect of the frame. If the correction factor of 0.6% is used, the average difference between the two measurement methods in Table 2 reduces from 1.8% to 1.6%.

4.3. Comparison of discharge values obtained from both methods

As mentioned above, the pressure-time method was used to calibrate the index measurement method (Winter-Kennedy taps), as the ASFM and the pressure-time methods could not be run simultaneously: acoustic scintillation explorations of the whole intake took about ½ hour, in steady operation mode, whereas the pressure-time method required rapid shut-downs of the unit.

The calibrated index method was therefore used as a sort-of-transfer standard to compare the two methods. The agreement between the pressure-time and index methods (Q_G and Q_i columns in Table 2) is excellent, particularly for the higher discharge values.

Table 2 shows all computed discharge values. The differences between the corrected ASFM discharge values and the index method values (ΔQ column) are presented for all the measurement points which were recorded.

4.4. Uncertainties of both methods

The expanded total uncertainty of the pressure-time measurements is estimated at 1.4 % (with a coverage factor k = 2).

The expanded total uncertainty of the acoustic scintillation measurements is somewhat harder to determine; whereas the internal experience within EDF indicates values ranging from 2 to 3.5 % (see [9]), recent international measurement comparisons show that an uncertainty as low as 1 % (or even better) can be achieved with the hydraulic conditions at the intake as good as was the case at Slapy. So, to be conservative yet reasonable, a value of 2 % is considered for the total uncertainty of the ASFM measurement.

To estimate the quality of the bias between the two methods, the normalized error E_n has been computed (see [10]), using the following formula:

$$E_n = \frac{|Q_1 - Q_2|}{\sqrt{U_1^2 + U_2^2}}$$

where: Q_1 and Q_2 are the flow rates measured by the two methods (ASFM providing Q_1 and pressure-time acting as reference method and providing Q_2);

U_i is the expanded uncertainty associated with the value of the flow rate Q_i with a coverage factor of 2, giving a 95% confidence level.

With this definition, the critical E_n value is unity and values below unity indicate insignificant bias between the measurements, i.e. the difference between the measurements is well within the combined total uncertainties of the two methods.

meas. Point #	Power output	raw Q_{AFSM}	Q_{AFSM} with correction kCFD	Qpt	Q_i	ΔQ (corrected Q ASFM / Qi)	En
	MW	m^3/s	m^3/s	m^3/s	m^3/s	%	-
1	15	38,67	38,5		38,193	0,8%	0,34
2				37,768	38,212		
3	25	59,23	59,0		58,009	1,7%	0,68
4				58,158	58,136		
5	30	71	70,7		69,055	2,3%	0,96
	35	80,7	80,4		79,100	1,6%	0,65
6	35			79,185	79,195		
7	40	92,55	92,2		90,450	1,9%	0,77
		104,6	104,2		101,510	2,6%	1,05
8				101,16	101,618		
					average =	**1,8%**	**0,74**

Table 2: comparison of discharge values from the two measurement methods

5. Conclusions

The hydraulically smooth intake shape and the steel lining of the penstock at Slapy HPP provide good conditions for the pressure-time method despite the bend in front of the spiral case. This has been confirmed by the minimal deviations of the individual pressure measurements from the mean values in each measuring profile. Experience from both previous and subsequent pressure-time tests, and comparisons with the efficiencies determined from various current meter flow measurements, justify the selection of 1.4% as the total uncertainty of index flow measurements calibrated by the pressure-time method.

The hydraulic conditions at the Slapy HPP intake were considered also very good for the acoustic scintillation method. The frame operated just fine and did not generate any vibrations, though it probably introduced a bias in the ASFM measurements through flow acceleration around the large round transverse beams which were used for its construction.

The corrected ASFM discharge values are in good agreement with the values obtained with an index measurement method calibrated with the pressure-time method. With the correction factor of 0.4%, the average agreement between the two measurement methods is within 1.8 % over the whole range of operation. This corresponds to a normalized error of 0.74 and shows that the measured bias is not significant with respect to the combined total uncertainties of the two methods. If a correction factor value of 0.6% is used, the value of the average agreement between the two methods drops further, from 1.8% to 1.6%.

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