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Turbine flow measurements at SLAPY HPP with acoustic scintillation and pressure-time methods

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ANNOTATION

The well established acoustic scintillation drift method has been adapted by ASL AQFlow for measurement of turbine flows in hydroelectric plants. It is currently being incorporated in an updated issue of the international standard IEC 600041. This paper will describe the first implementation of this method in the Czech Republic and Slovakia at HPP Slapy.

KEYWORDS

Accoustic scintilation, pressure-time method, flow measurement, comparative measurement

1. INTRODUCTION

The well established acoustic scintillation drift method has been adapted by ASL AQFlow for measurement of turbine flows in the intakes of hydroelectric plants. It is currently being incorporated in an updated issue of the international standard IEC 600041. This paper describes the first implementation of this method in the Czech Republic at HPP Slapy, when its measurement results were directly compared with the results produced by the pressure-time method.

The pressure-time (Gibson) method was used for the turbine acceptance tests of the Unit #3, and its pressure transducers installed by OSC a.s. inside of the 5m diameter penstock were available for this comparison test. For the acoustic scintillation method, a small movable frame was designed and fabricated by OSC a.s., with input from ASL AQFlow and EDF Division Technique Générale. One pair of the acoustic scintillation transducers was mounted on the frame and the 7.3 m high intake was explored using 15 frame positions, so that the average velocities were computed every 50 cm.

A total of 6 different operating points were investigated with both methods; the agreement between the results was good and thus contributed towards a growing library of examples of flow measurements conducted in the turbine intakes with the acoustic scintillation method accurately and cost-effectively.

2. SLAPY HPP

Pressure-time (PT) flow measurement method was specified for the acceptance tests of the upgraded Slapy Unit #3 in autumn 2011 and OSC a.s. (OSC) had the contract for those tests. ASL AQFlow (ASL) proposed to both OSC and EDF Division Technique Générale (EDF) to use the installed sensors for a comparison test between the PT and acoustic scintillation (AS) methods. Both OSC and EDF agreed and the comparison testing proceeded thanks to the permission of ČEZ Hydro Power Plants management. OSC was responsible for the design and manufacture of the movable frame for the AS method, while EDF brought in its own Acoustic Scintillation Flow Meter (ASFM), as well as the necessary workforce. The longitudinal section through the unit #3, with the sensor positions marked in red, is shown 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 (WK) flow measurement in accordance with the requirements of IEC 60041.

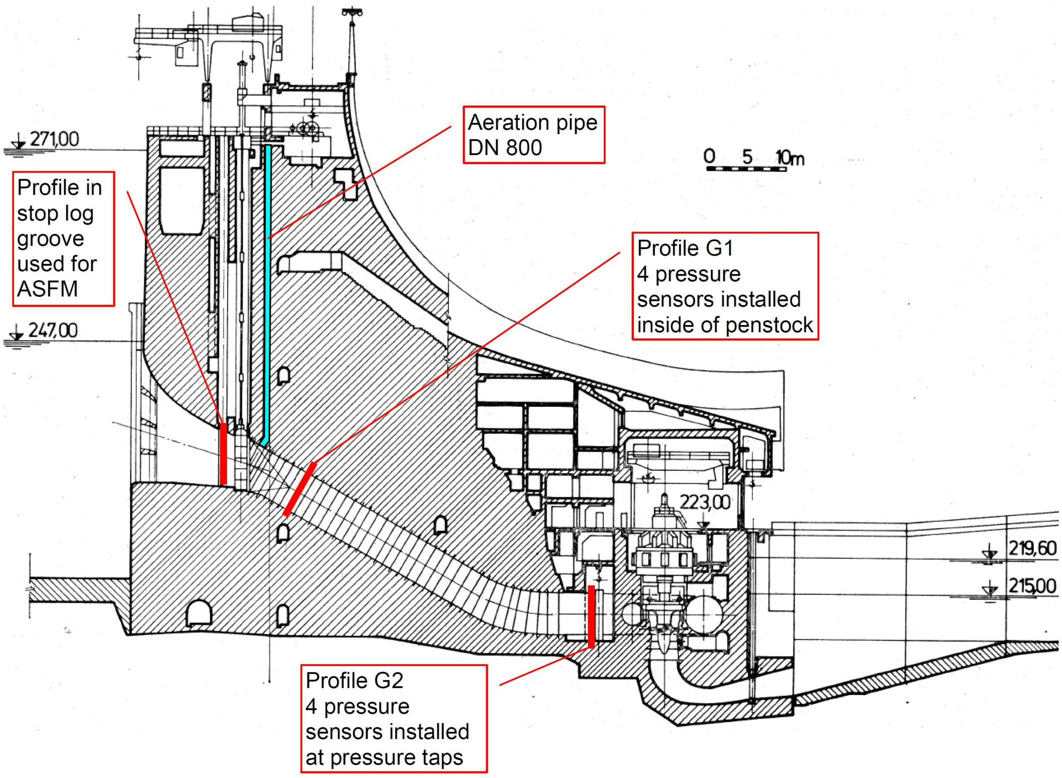


Fig. 1 – Longitudinal section of HPP Slapy

3. PRESSURE-TIME MEASUREMENT METHOD

The method of separate pressure diagrams was chosen in accordance with the requirements of IEC 60041 and IEC 62006. Four pressure sensors with protection IP68 were installed in the upper part of the penstock (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 were evaluated. The deviations in the upstream profile were negligible, while the max./min. value in the downstream profile 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 when the unit was drained using a laser distance gauge with a magnetic jig, telescopic geodesic lath and tape measure. 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 small and the leakage became negligible shortly after the shutdown. Two tests were carried out with the results of 0.106 and 0.105 m3/s.

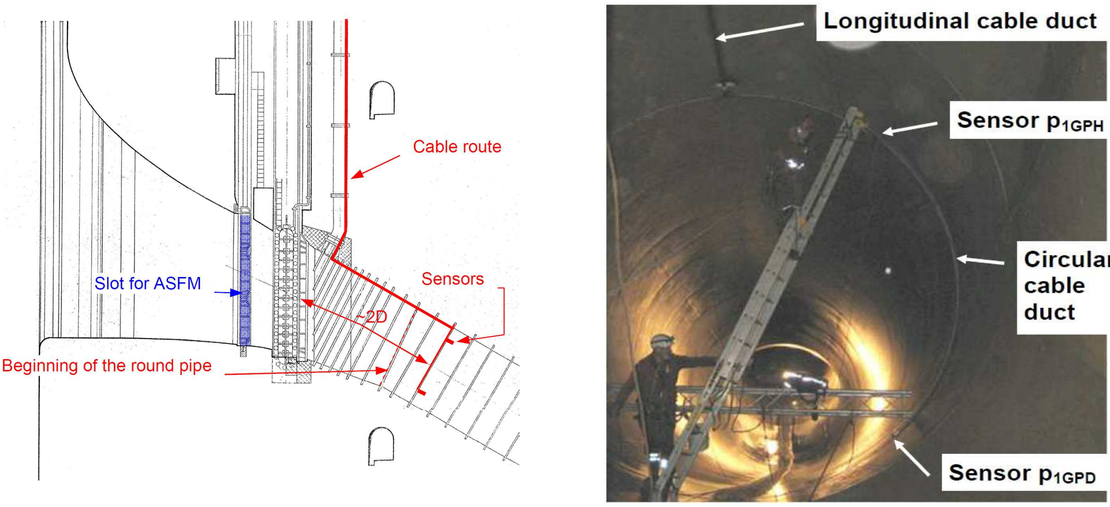
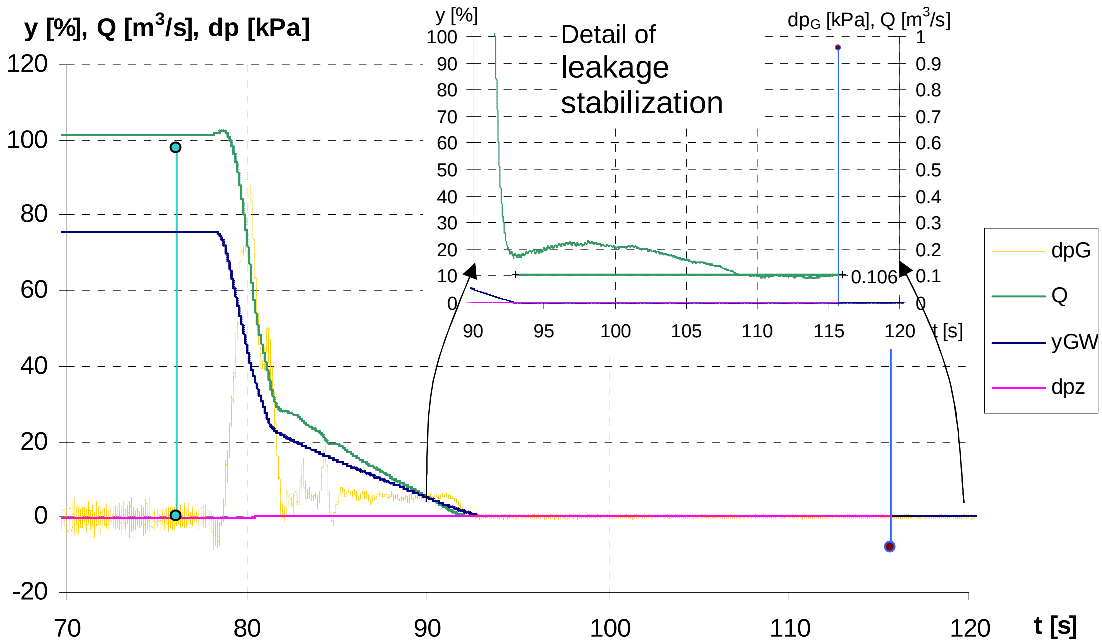


Fig. 2 - Upper part of the penstock with pressure sensors in upstream profile

Four PT 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 an exactly determined zero of the dynamic differential pressure. This procedure was important for minimizing the integration error as described in [1] – 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 reservoir is large, but the lower reservoir is small and very narrow. Therefore, a fast unit shutdown causes waves in the lower reservoir 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 individual ASFM measurements take about 20 minutes, the direct comparison between the two methods was not possible. Instead, WK taps were calibrated by the PT method and the mean values of discharge from the WK 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

4. ACOUSTIC SCINTILLATION FLOW METER

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 Δx/Δt. Because three transmitters and three receivers are used, the average inclination of the velocity vector 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.

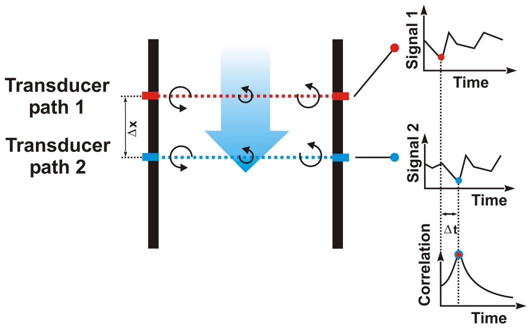


Fig. 4- Representation of the acoustic scintillation principle

The movable frame for the ASFM was designed by OSC and built in the Czech Republic by a sub-contractor of OSC. The design was reviewed by both ASL and EDF 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 Fig. 5, the frame was equipped with one-pair of ASFM transducers. The frame travelled smoothly up and down in the stoplog slot during all tests, and no flow-induced vibration was detected.

Fig. 5 - frame being deployed

5. MEASUREMENT RESULTS

The frame blockage correction factor value of 0.4% has been used for the ASFM discharge calculations; however, the CFD computations performed after the field measurements tend to show that a higher correction value might be appropriate to better account for the systematic error due to the frame transversal beam effect [3]. If the correction factor of 0.6% is used, the average difference between the two measurement methods in Table 1 reduces from 1.8% to 1.6%.

As mentioned earlier, the PT method was used to calibrate the WK taps, as the ASFM and the PT methods could not be run simultaneously: ASFM explorations of the entire intake took about ½ hour, in steady operation mode, whereas the PT method required rapid shut-downs of the unit.

The WK method was therefore used to compare the two methods. Table 1 shows all computed discharge values. The agreement between the PT and WK methods (QG and Qi columns) is excellent, particularly for the higher discharge values. The differences between the ASFM discharge values and the WK values (□Q column) are presented for all the measurement points which were recorded.

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

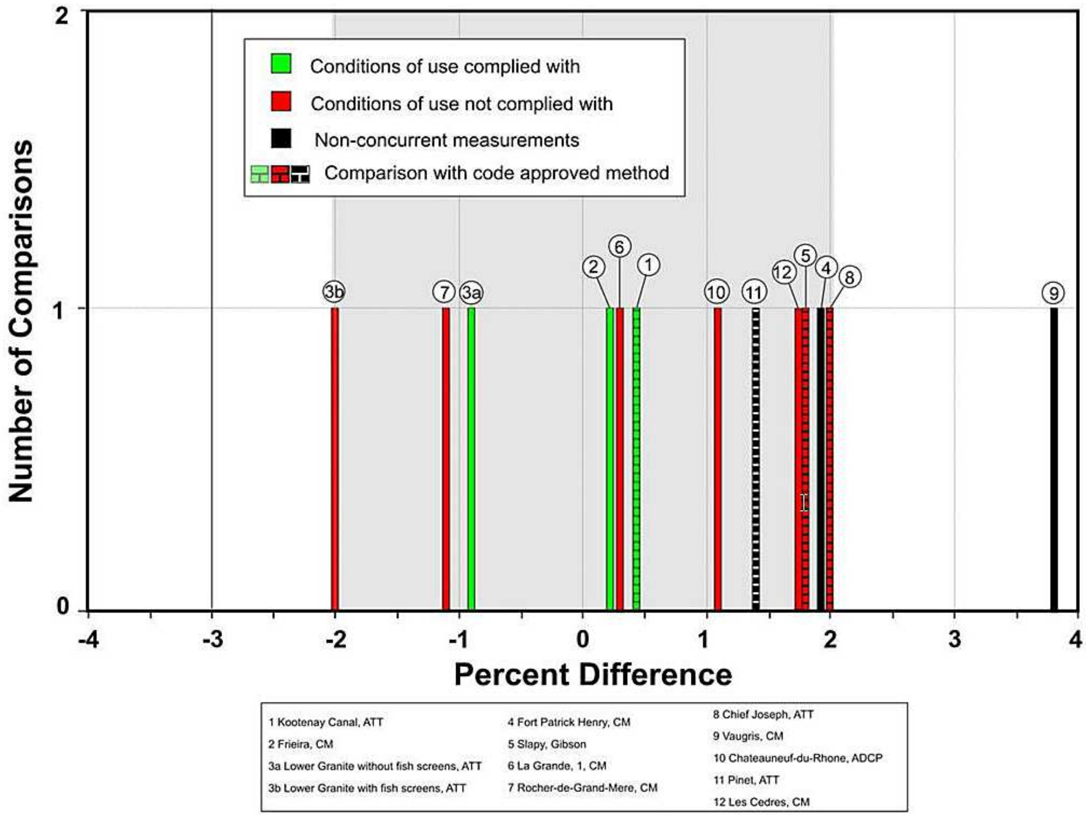


Fig. 6 – ASFM comparison measurements

The expanded total uncertainty of the ASFM measurements is somewhat harder to determine. Recent comparison measurements (Fig. 6) show that an uncertainty as low as ±1.0% can be achieved with the hydraulic conditions at the intake as good as at Slapy. When the conditions of use as defined on the ASL website (http://www.aqflow.com/technology.html) are complied with (shown in green in Fig. 6), all results are within ±1.0%. With the exception of one non-concurrent measurement (HPP Vaugris), all comparison measurements are within ±2.0%, whether the conditions of use are complied with or not. Further details of the individual comparison measurements can be found under appropriate headings at http://www.aqflow.com/reports.html. 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 [2], 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 Q1 and PT acting as reference method and providing Q2);
U_i is the expanded uncertainty associated with the value of the flow rate Qi 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	m³/s	m³/s	m³/s	m³/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	71.00	70.7		69.055	2.3%	0.96
	35	80.70	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
		104.60	104.2		101.510	2.6%	1.05
8				101.16	101.618		
					average =	**1.8%**	**0.74**

Table 1 - comparison of discharge values from the two measurement methods

The hydraulically smooth intake shape and the steel lining of the penstock at Slapy HPP provide good conditions for the PT 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 PT tests, and comparisons with the efficiencies determined from various current meter flow measurements, justify the selection of 1.4% as the total uncertainty of WK calibrated by the PT method.

6. CONCLUSIONS

The hydraulic conditions at the Slapy HPP intake were considered very good for the ASFM. 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 ASFM discharge values are in good agreement with the values obtained with WK calibrated with the PT 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 reduces from 1.8% to 1.6%.

Together with the comparison measurements listed in Fig. 6, the comparison measurements at Slapy HPP help to confirm that when the intake characteristics are suitable, the accuracy of the ASFM is comparable to other established and standard-accepted measurement methods. These results are currently being reviewed in detail by the IEC 60041 and ASME PTC-18 committees as part of their respective processes of publication updating. It is expected that the AS measurement method will be included in the updates of both of these standards.

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7. REFERENCES

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