Comparison of Methods for Determining the Pressure Difference for the Pressure-Time Method

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Abstract

Standards IEC 60041 and ASME PTC 18-2020 provide two different ways of determining the pressure difference in a measuring section of penstock caused by a deceleration of the water column velocity. These are:

- Direct measurement using a pressure differential sensor
- Measurement of the pressures in both measuring cross-sections with separate sensors and subsequent numerical determination of the pressure difference.

There are advantages and disadvantages to both methods and the decision as to which is more appropriate for the measurement conditions must be made with regard to utilizing the good properties of the chosen measurement method. In this paper, the experience of the OSC, a.s. measuring group, gained in more than 100 acceptance tests and a similar number of other tests (fingerprint tests, calibration of flow meters, etc.) using the pressure-time method, is presented.

1. Introduction

Compared to other absolute flow measurement methods, the Gibson method is in most cases significantly cheaper with comparable accuracy. The requirements for the measuring section of the penstock are defined in the standard [1] and this definition is refined in the revision of this standard to be published. A straight pipe section and the absence of major irregularities at a sufficient distance in front of the measuring section as well as after it is required. Most experts in the field focus on solving hydraulic problems resulting from deviations of the flow in the measuring section from the ideal piston flow, mainly due to irregularities in the geometry of the penstock, such as bends, confusors, etc. Usually, however, no consideration is given to other influences that are introduced into the measurement by the measurement chain consisting of sensors with their connecting piping, possible signal conditioning components (separators, filters...) and the DAQ itself.

In this paper, the focus is on the effects of these related devices, which can have a similar effect on the measurement error as, for example, hydraulic phenomena in the pipe elbow. Several examples are then used to document the measurement options for a selected straight section and the entire penstock, and possible measures to mitigate undesirable effects on the measurements are also presented.

2. Application Specifics of Differential Pressure Transducer

Figure 1 shows a typical example of a high-pressure power plant with a well-accessible penstock. The penstock has several bends, usually with a very obtuse angle. However, due to the location above the ground surface, it is possible to use a section where the conditions set by the standard [1] can be met.

The procedure for determining measuring section and appropriate measuring equipment is usually as follows:

- A suitable accessible section is selected where pressure taps can be easily installed to meet the requirements of the standard.
- The length of the section is chosen as long as possible to achieve a sufficiently large pressure differential.
- The water hammer for the closing law of the designed turbine is simulated numerically in a 1D program (example of such simulation given in Figure 2). According to the result, the range of differential pressure transducer is selected.

The example given here is specific because of the restrictions in place during the Covid pandemic. The installation of the measuring instruments and the actual measurements were carried out by the turbine supplier according to a brief methodology developed by OSC. Copper piping from both G1 and G2 cross-sections was connected to the differential pressure transducer for Gibson flow measurement. For illustration, Figure 1 also shows the pressure ratios at the individual measuring points for values close to the nominal flow of one of the Francis turbines installed here.

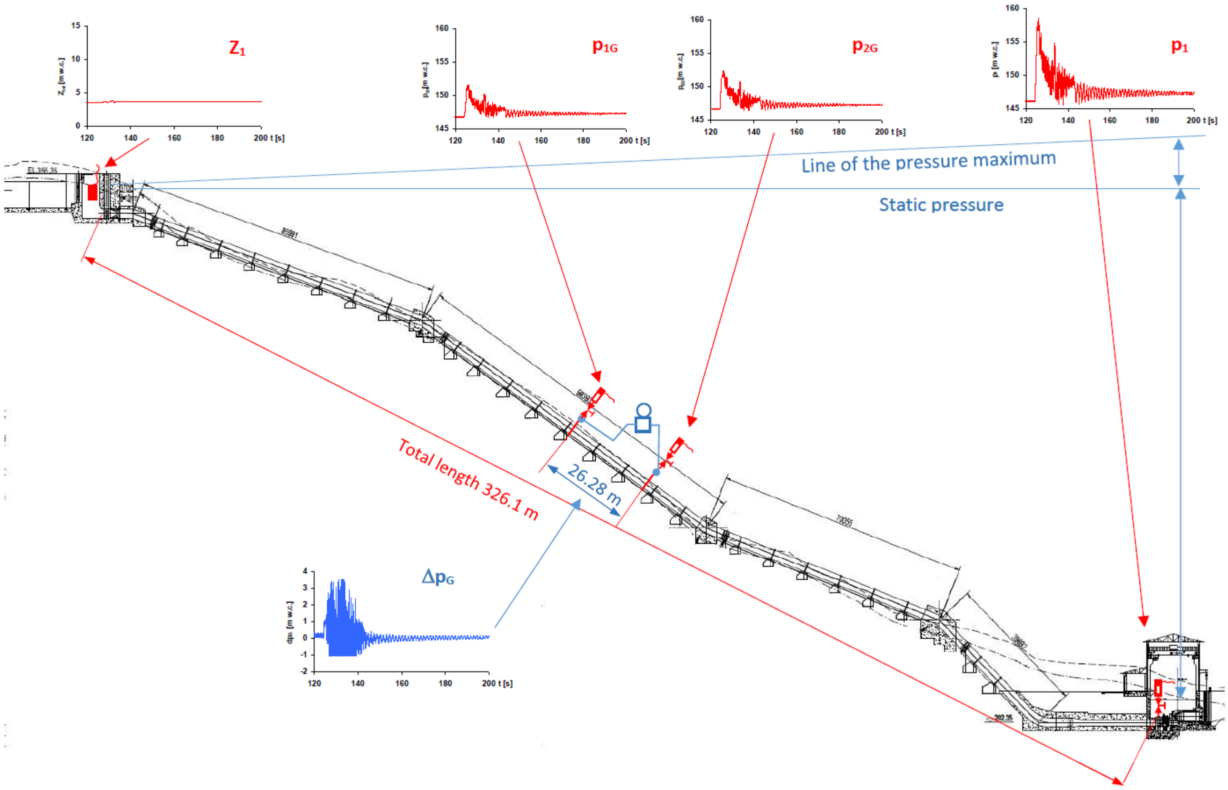

Figure 1: Layout of typical high pressure small HPP with overhead penstock

A typical issue associated with long piping to a differential pressure transducer was encountered - additional oscillations with an amplitude greater than the useful signal for the Gibson method as well as the transducer span. The difference between the simulated water hammer wave and the actual recorded wave for a nominal unit flow rate is shown in Figure 2 and Figure 3. The difference in waveform is partly due to the shorter real closing time (20 s instead of 30 s in the simulation), which results in a higher first maximum. However, the main problem is other rapid oscillations, the cause of which is difficult to identify. This is probably a combination of resonance of the connection pipe to the differential pressure sensor with reflection from inlet irregularities, such as forks upstream of the turbines, and pulsations generated by the interaction of the runner blades and guide vanes. The range of the differential pressure sensor was designed to be between -10 and 35 kPa as a sufficient range according to the simulation. The double amplitude of the oscillation was limited by the minimum and maximum span of the transducer – see Figure 3. Such nonlinear amplitude distortion does not allow further processing and evaluation of the flow rate. The above example illustrates phenomena that occur in many cases, especially when the measuring section is only a small fraction of the total length of the penstock - here less than 10%.

Figure 2: Simulated water hammer wave

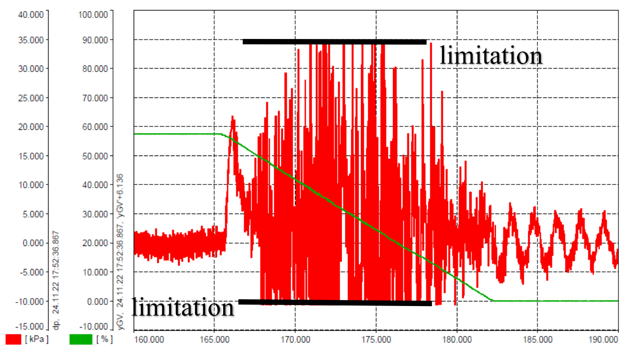

Figure 3: Recorded water hammer wave

Due to our absence on site (remote evaluation) and limited time to perform the tests, it was nearly impossible to solve the problem of measuring the differential pressure at the time of measurement. For this reason, the entire length of the penstock, including the branch to Unit 2, was used as the measurement section. Despite the presence of bends and other irregularities, the results were good and the measurements confirmed the guaranteed parameters. Example of flow rate evaluated on whole penstock length is shown in Figure 4.

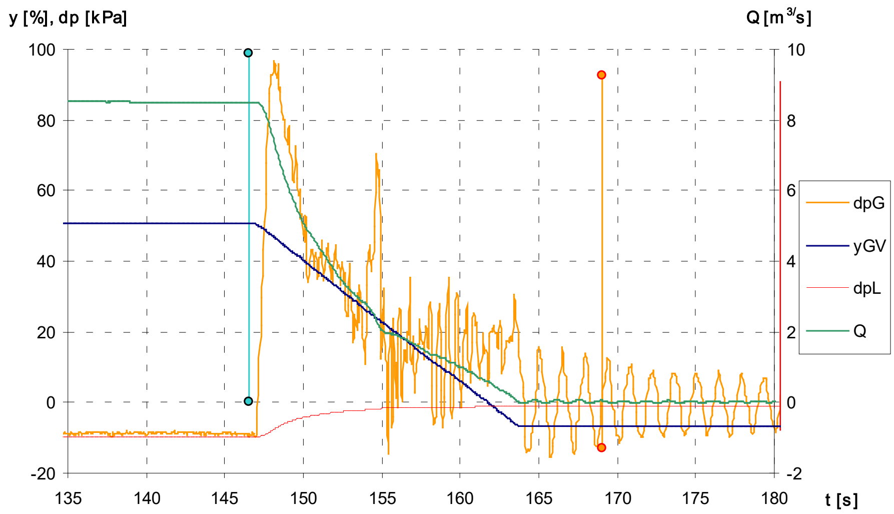

Figure 4: Gibson flow rate evaluation from the water hammer on whole penstock length

2.1 The measures against the propagation of pulsations into the sensor

Variants of the possible pressure measurement loops arrangement are shown in Figure 5. A pressure differential transducer fast enough to quantify the flow by the Gibson method must be used to sense the pressure surge. Typically, transducers with a frequency range up to approximately 100 Hz are suitable. Transducers with large pressure chambers and 'Rosemount' type separating diaphragms, where frequencies in the units of Hz are suppressed, are not sufficient. The use of such transducers leads to an underestimation of the flow rate.

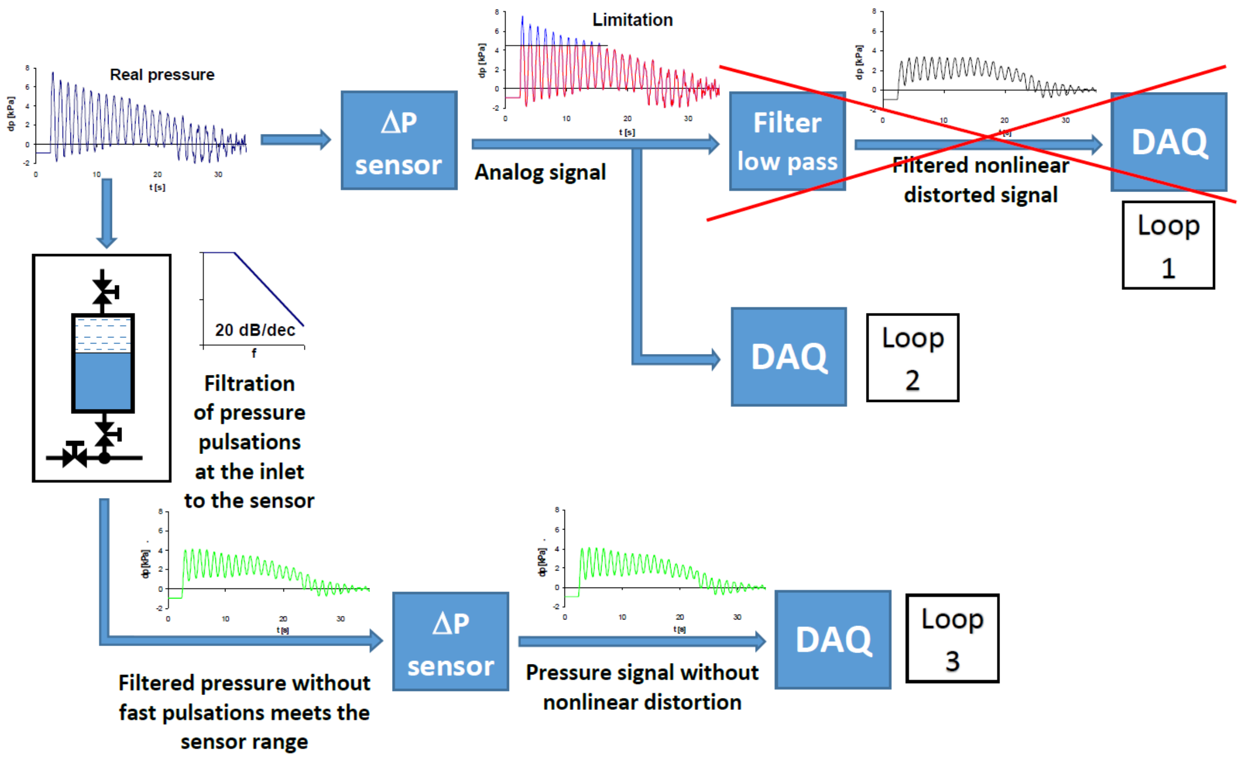

Figure 5: Variants of pressure differential measurement

When using a standard measuring equipment with a well-designed differential transducer range according to the simulated water hammer, the following cases may occur:

Loop 1: If the pressure amplitude exceeds the sensor range, the signal is clipped by the range limit. If an analogue filter element is placed behind the transducer and set to frequencies corresponding to the expected process (e.g., tens or low hundreds of Hz), the sharply clipped oscillations are "rounded off" and the signal limitation is practically undetectable. The result is then an erroneous flow rate value.

Loop 2: The analogue output of the differential pressure transducer is connected directly to the DAQ unit. Before starting the actual measurement, it is recommended to investigate the water hammer wave when the unit is shut down at maximum flow. If a limitation of the differential pressure signal is detected, the measures described in the following paragraph shall be carried out.

Loop 3: If non-linear signal distortion is detected due to the interaction of superimposed additional fast large oscillations on the basic water hammer signal exceeding the range limits of the transducer, it is necessary to provide damping of these oscillations before entering the transducer. The simplest and most reliable solution is to install air cushion vessels with adjustable throttling valves on the connection pipe to the transducer. See below for details.

2.2 Filtration properties of the air cushion vessels

An example of the real application of the cushion vessels during site test at SHPP Augand (CH) is shown in Figure 6. Cushion vessels were installed in both measuring cross-sections G1 and G2. The basic parameters are shown in Table 1.

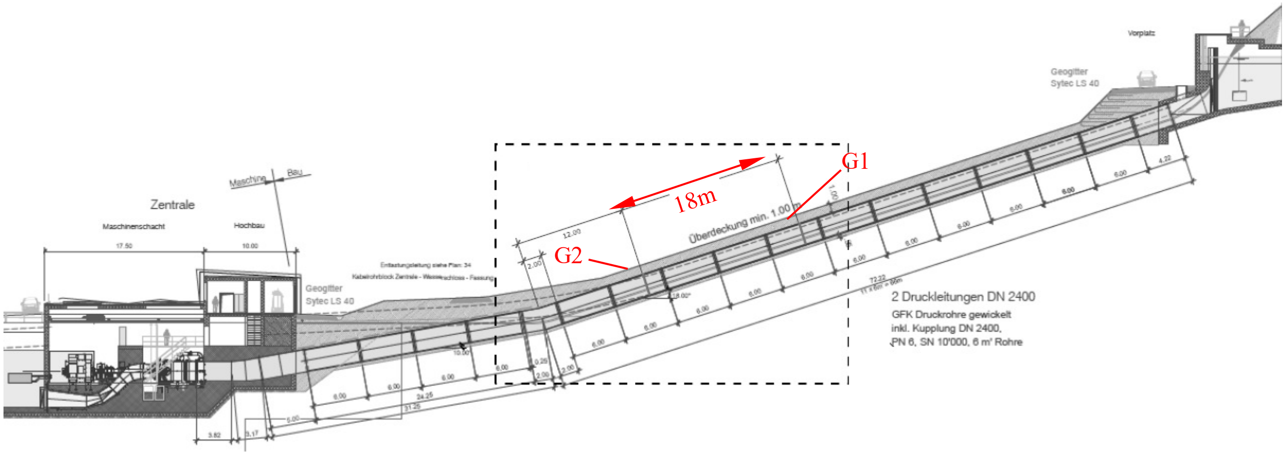

Figure 6: Longitudinal section of SHPP Augand

Table 1: Main parameters of cushion vessel

Vessel dimensions	D = 90 mm, h = 115 mm
Volume	≈ 1 l
Max. Pressure	6 bar
Static pressure	≈ 17 m water column G1 ≈ 23 m water column G2
Max pressure change	30 kPa

The damping properties of the air cushion vessel installed on the impulse line to the transducer can be compared to a first order critical filter corresponding to the equivalent of an RC circuit. For the latter, the determination of the time constant τ (or the cut-off frequency 1/τ) is a matter of evaluating the simple product 2πRC, whereas for the air cushion vessel several more complicated dependencies are encountered expressed in the following description:

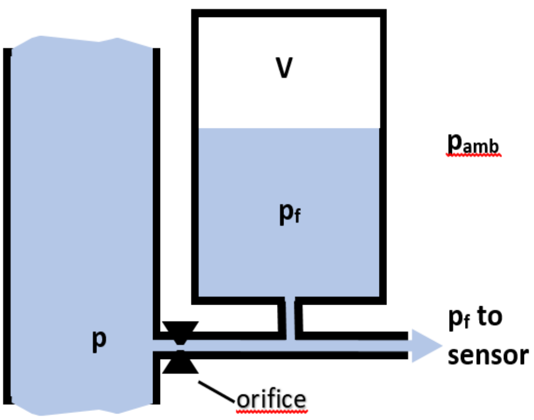

Figure 7: Scheme of cushioning vessel

V [m^3] Air volume

$$V = V_0 \cdot \frac{p_{amb}}{p_f} \tag{1}$$

V_0 is the volume of empty bottle.
An isothermal process is considered for the air volume as a function of the static pressure in the penstock.

A_{pt} [m^2] Cross-section of the orifice in the pressure tap. The inlet diameter to the pressure tap is considered ø 5 mm

$A_{pt} =$ 1.9635E-05 m^2

μ [-] Discharge coefficient through the opening in the vessel wall + connecting pipe

μ ≈ 0.65

A standard method for determining the time constant of the filter is used, namely the step change of the quantity (pressure) at its input. During the measurements at the above mentioned power plant, the amplitudes of the induced oscillations on the pressure signal were about 30 kPa. This value Δp = 30 kPa was chosen for the step change at the inlet to the impulse line of the model. The approximate value of the time constant of the cushioning vessel can be easily estimated as follows:

ΔV [m^3] Change in air volume after the pressure stabilizes after a step change:

$$\Delta V = V - V \cdot \left(\frac{p}{p + \Delta p}\right)^{n} \tag{2}$$

Where: n = polytropic index. For simplicity we consider n = 1 (fully isothermal process).

Q [m^3/s] Flow rate to the cushioning vessel

$$Q = \mu \cdot A \cdot \sqrt{\frac{2 \cdot (p - p_f)}{\rho}} \tag{3}$$

For the initial flow rate Q_0 the difference p - pf = Δp is considered.

τ[s] Time constant of the cushioning vessel

$$\tau = \frac{\Delta V}{Q_0} \tag{4}$$

For the above parameters, τ = 0.34 s.

The response of the pressure in the cushion vessel to the step change in the penstock determined by the more detailed model is shown together with a picture of the actual installation in Figure 8. The time constant determined from the graphical record differs a bit from the simple calculation. This is due to the fact that the hydraulic resistance at the inlet to the vessel is not linear; moreover, in damped oscillations, the degree of polytropic process n cannot be explicitly determined. This also makes the shape of the transition curve slightly different from the classic inertia element transition curve.

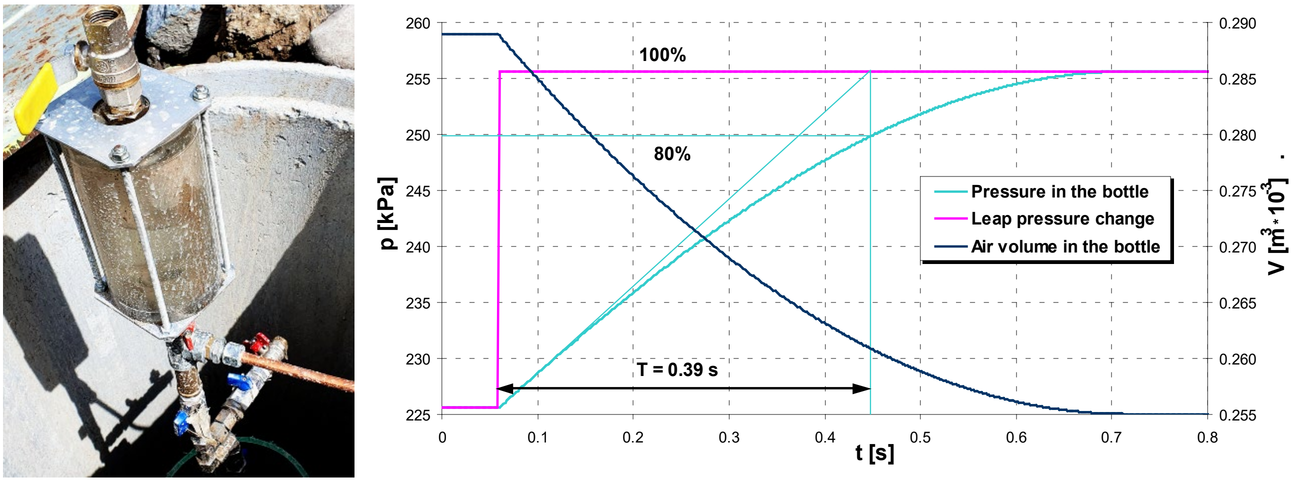

Figure 8: Cushioning vessel and its response to a pressure step change in

However, for an indicative assessment of the damping capabilities of the air cushion vessel, the uncertainty in the determination of the time constant is negligible. For low-pass filtering, the time constants / cut-off frequencies are chosen rather by decades. In any case, fine-tuning of the damping effect by adjustment of valves on the inlet side must be done according to the on-line evaluation of the pressure recording on site.

A comparison of the actual pressure differential records without filtration (green) and with filtration (red) for an almost identical machine operating point is shown in Figure 9. The calculated flow rate values were almost identical (within the measurement uncertainty band). Due to the fact that there was no signal limitation, pressure oscillation damping was no longer used in the measurements.

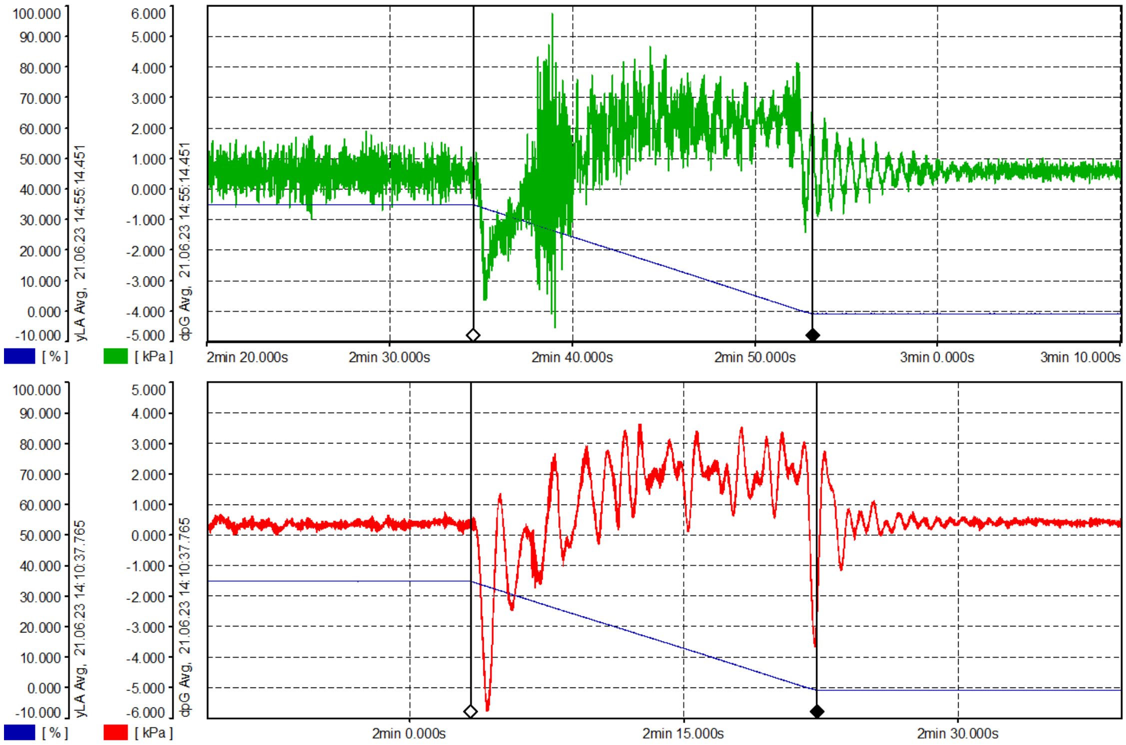

Figure 9: Comparison of non-filtered (green) and filtered (red) pressure for identical working point of the unit

3. Application Specifics of separate Pressure Transducers

Returning to the pressure ratios shown in Figure 1, it is evident that the difference between the pressures in cross-sections G1 and G2 is very small. If the increase in pressure at the transducer relative to the static pressure at this location is about 10%, then the difference between these pressure increases originating from the water hammer in cross sections G1 and G2 is in the lower units of percent of the transducer range. Here, the parasitic properties of the sensors in the area of hysteresis and signal stabilization for small changes in input pressure become apparent. This topic was described in detail in a paper at IGHEM 2022 - see [3].

A suitable arrangement of the measuring section for the use of separate sensors in measuring profiles G1 and G2 is shown in Figure 10. Here, the length of the measuring section represents about 25% of the total length of the penstock, so the change in pressure from the water hammer is large enough for a reliable evaluation of the flow by the Gibson method - see the data in Table 2, which are based on the values presented in the graphs in Figure 11 and Figure 12.

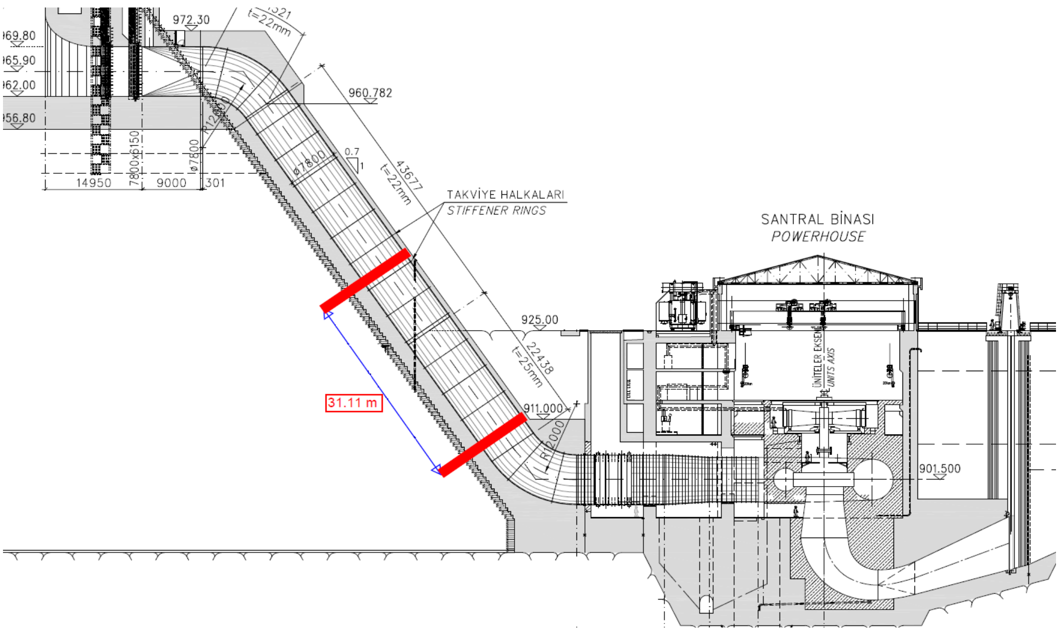

Figure 10: Longitudinal section of HPP Beyhan

Table 2: Ratio of dynamic pressure change to sensor range for flow rate close to nominal value

Pressure	Sensor range [kPa]	Static pressure [kPa]	p_{max} [kPa]	Δp [kPa]	Δp [% of span]
p_{1G}	1000	523	676	153	15.30%
p_{2G}	600	278	357	79	13.17%
$dp_G = p_{2G} - p_{1G} - p_{offset}$				159	15.90%

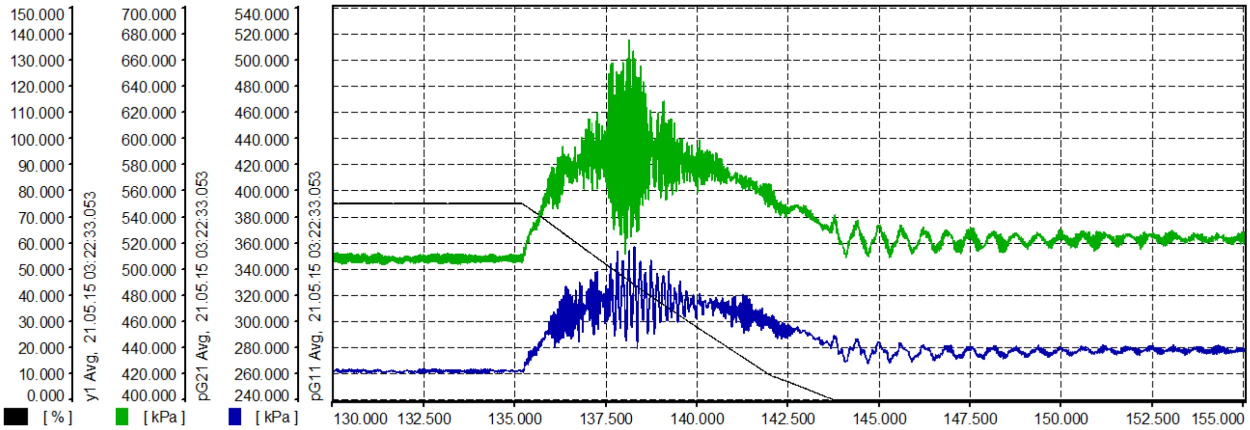

Figure 11: Water hammer in cross sections G1 and G2 recorded by separate sensors

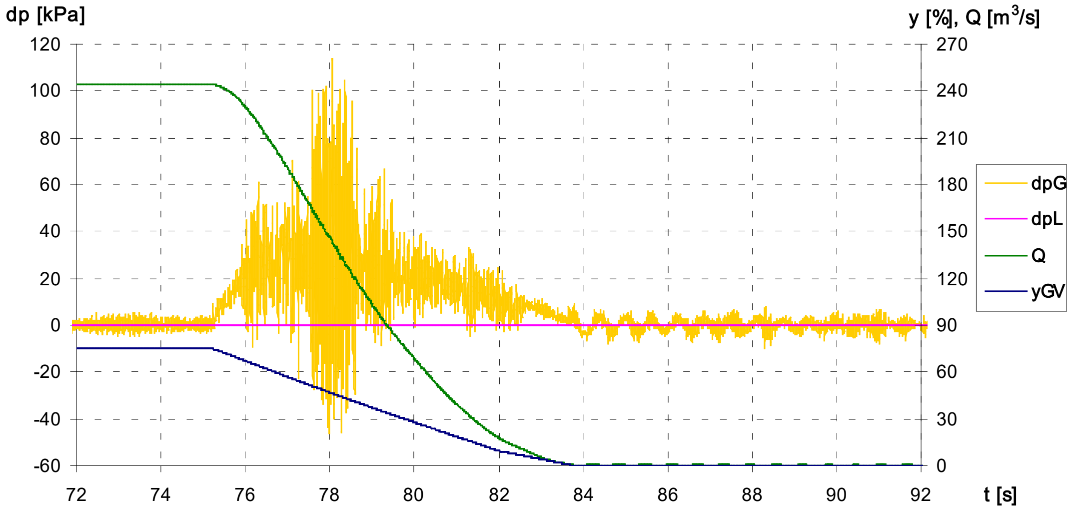

Figure 12: Numerically calculated pressure difference and evaluated flow rate

Even though the use of separate pressure transducers requires a sufficiently long measurement section (in the order of decades of percent of the total length of the penstock), this arrangement offers some additional benefits:

- The sensors can be connected directly to the pressure taps, or with short tubes, which usually eliminates the problem with self-oscillation of long connection tubing.
- Due to the range of the sensors, which must also cover static pressure, additional oscillations are not a serious problem.
- A separate pressure transducer can be used in the measuring sections for each tap. This makes it easier to compare the pressure distribution in the cross-section with a possible numerical model.

4. Conclusion

The two methods of determining the pressure differential described here (directly by a pressure differential sensor or by measuring the individual pressures in each of the measuring profiles) for evaluating the flow by the pressure-time method have their advantages and disadvantages.

Using a differential pressure sensor:

+ Possibility to optimize the sensor range with respect to a given expected pressure increase. By preliminary calculation or simplified simulation, it is possible to determine the appropriate sensor range directly tailored to the specific measurement.
+ Better utilization of the accuracy class of the differential transducer used relative to pressure transducers, resulting in lower uncertainties in flow determination by this method.
− Exceeding the range of the transducer in case of excessive parasitic pressure oscillations induced in the hydraulics. The causes of these oscillations often originate from the interaction between the runner blades and the guide vanes of the machine under test, or arise as resonances in the transducer connection tubing. They are difficult to predict.
− Destruction of the transducer by careless one-sided full pressure overload.

This article describes one way to deal with these oscillations during measurement by using cushioning vessels upstream of the pressure input to the pressure differential sensor. In addition to a simplified theoretical discussion of the problem, practical experience is also presented.

Using separate pressure transducers in measuring cross-sections:

+ Measurement on longer measuring sections, which can give a larger total pressure differential.
+ Installation of sensors directly on the pressure taps or use of only short connection tubes, which prevents self-oscillation in the connection tubes.
+ The possibility to use multiple sensors in a single measuring cross-section to better capture the pressure distribution in a given profile (e.g. for comparison with a numerical model).
+ In many cases, easy replacement of sensors in a given cross-section, allowing the sensor range to be optimized.
− Relatively low change in measured pressure relative to the sensor range (sensors must be dimensioned for the sum of the static pressure and the pressure rise due to the water hammer).
− With a small pressure difference between the measuring cross-sections, the numerically determined pressure difference is in the order of units of percent of the sensor range. In such cases, parasitic properties of the sensors, which are otherwise within the uncertainty band (described in more detail in [3]), become apparent.

However, it is not possible to state unequivocally which method of measurement is generally preferable - it always depends on the specific conditions, the experience of the measuring engineers and the compromises that can be made.

References

[1] Standard IEC 60041: *Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines*, CEI, Third edition 1991-11

[2] Černoch S.: *Mechanical and technical manual*", SNTL Prague 1968

[3] Ševčík P., Habán V., Himr D: *Little known impacts on the accuracy of the Gibson method*, contribution IGHEM 2022.