Development of the pressure-time method as a relative method

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Abstract. The pressure-time method is an absolute method commonly used for flow rate measurements in hydropower plants. The method determines the flow rate by measuring the differential pressure and estimating the losses between two sections in the penstock during a closure of the guide vanes. The method has limitations according to the IEC41 standard, which make it difficult to use at low head hydropower plants. The relative method called Winter-Kennedy is usually used on low head machines to determine the step-up efficiency between the old and refurbished runner. However, due to differences of the flow field in the spiral casing induce by both runners, the Winter Kennedy method might not allow estimate the flow rate similarly and thus the correct step-up efficiency. In cases where the absolute pressure-time method cannot be used because of waterway geometry limitations, the method might be used as a relative method by measuring the pressure difference between the free surface and a section in the penstock or even a point in the spiral casing without knowing the exact geometry, i.e., pipe factor. Such measurements may be simple to perform as most of the spiral casings have pressure taps for Winter-Kennedy measurements. Furthermore, the viscous losses do not need to be accurately determined if they are handled similarly before and after the refurbishment. The pressure-time method may thus become an alternative to the Winter-Kennedy method. The present paper consists in the experimental analysis of the pressure-time method accuracy used as a relative method. The experiments are performed on Porjus U9, a Kaplan prototype turbine operated under a head of 55 m generating 10 MW at full load. The flow rate is evaluated based on pressure-time measurements with different friction models and considering or not the compressibility effect. The accuracy of the flow rate evaluation method is compared using an 8-path transit-time flow rate measurement device as reference.

1. Introduction
The refurbishment of hydraulic turbines allows installing more efficient and powerful runner. It is of importance to verify the efficiency or efficiency step-up between the old and new configuration. Absolute efficiency measurements are challenging, especially in low head machines, as the flow rate is difficult to determine accurately. Usually, the Winter-Kennedy method, a relative method, is used to determine the flow rate and thus the efficiency step-up in low head machines. The Winter-Kennedy method consists in measuring the differential pressure across the spiral casing, which is related to the square of the flow rate. This method has an extremely good repeatability [1] and suits, thus, perfectly such purpose. However, the method becomes uncertain as upstream and downstream conditions are changed [2-3]. The main reason resides in a modification of the secondary flow in the spiral casing,
which alters the pressure distribution. There is a need to find an alternative method to complete the Winter-Kennedy measurements, which is simple to install and economically affordable.

The pressure-time method is an absolute method. Its basic principle consists in measuring the pressure difference between two cross-sections during a deceleration of the fluid, transforming momentum into pressure, see Figure 1. Assuming the axial component of the time dependent conservation of the momentum equation, the flow rate is obtained by integrating the area delimited between the differential pressure measurements and the viscous losses, see figure 1:

\[ Q = \frac{A}{\rho L} \int_0^t (\Delta P + \zeta) \, dt + q \]  

(1)

where \( Q, A, L, \rho, \Delta P, \zeta \) and \( q \) represent the flow rate before closure, the cross-sectional area of the pipe, the pipe length, the fluid density, the differential pressure, the viscous losses and the leakage flow rate, respectively. The first term in front of the integral (\( A/L \)) is called the pipe factor. According to the IEC41 standard, the pressure-time method performed well under specific conditions when the straight pipe length (\( L \)) times the mean velocity (\( U \)) before closure is above 50 \( \text{m}^2/\text{s} \). This method is simple to implement and affordable as it consists of pressure measurements. Much work has been performed on the method during the last decade [4-8]. The main objective has been to decrease the uncertainty, by considering the compressibility of the fluid, propose appropriate friction models and extend its use to conditions outside the IEC41 standard.

As any absolute measuring method, the pressure-time method can be used as a relative method. This method is simple to implement as pressure taps in spiral casings are usually available at the inlet and to perform Winter-Kennedy measurements. The pressure-time method as a relative method was previously investigated by Jonsson and Cervantes [9]. However, the measurements were not satisfactory because only one measuring section was considered. After the guide vanes closure, large oscillations of the headwater free surface appeared making any evaluation the measurements subjective.

In the present work, the pressure-time method capability to be used as a relative method is further investigated. The measurements are performed on a Kaplan turbine at 3 locations: the head-water, one cross-section in the penstock and one pressure tap in the spiral casing used for Winter-Kennedy measurements. The relative measurements are compared with an 8-path transit-time flow rate measurements installed on the penstock.

![Figure 1. Illustration of the pressure-time method. The pressure is measured in the penstock between 2 cross-sections separated by a distance L, left figure. The resulting differential pressure (blue line), losses (red line) and mean velocity (black line) are illustrated in the right figure.](image-url)
2. Material and methods

2.1 Instrumentation and measuring program

The measurements were performed on a Kaplan turbine situated in Porjus, Sweden. The turbine is part of the Porjus Hydropower Centre where two hydraulic turbines, one Kaplan and one Francis, exclusively dedicated to research and development, are available. Both machines have a head of about 55 m and a maximum power of 10 MW. The Kaplan turbine used for the measurements has a full spiral casing and a distributor consisting of 18 stay vanes and 20 guide vanes. The runner has 6 blades and a 1.55 m diameter. The machine rotates at 600 rpm.

The penstock, at the headwater, starts with a circular intake 11.7 m long and 10.5 m in diameter, see figure 2. Follows a contraction (d=10.5 m to 4.6 m), an elbow (135°), a straight pipe (d=4.6 m, L=17 m), an elbow (130°), a contraction (d=4.6 m to 1.8 m), a straight pipe (L=16.5 m), an elbow (90°) and finally a straight pipe (d=2 m, 15.5 m) before the spiral inlet.

A drainable pressure sensor (GE, UNIK 5000, ±7000 mbar, 0.04% FS) was installed near the penstock inlet, about 2 m below the free surface. Four absolute pressure sensors (GE, UNIK 5000, 0-10 bar, 0.04% FS) were installed 53 m below the free surface on the wall of the penstock. Another absolute pressure sensor was installed at a pressure tap of the spiral casing usually used for the Winter-Kennedy measurements. The pressure measurements were simultaneously recorded together with the guide vane angle, runner angular velocity and active power with a sampling frequency of 1200 Hz.

Three operating points were investigated. They consist in 40%, 60% and 90% of the turbine maximum load. All measurements were repeated 6 times, i.e., 18 measurements were performed. For each measurement, the machine was run at a steady state for about 5 minutes. The flow rate obtained from an 8-path transit-time flow rate sensor from Accusonic installed on the penstock was recorded. Then, an emergency shutdown was performed to perform the pressure-time measurements.

![Figure 2](image_url)

Figure 2. Complete penstock (left figure), junction in the penstock (middle figure) and spiral (right figure) of the Kaplan turbine investigated. The emplacement of the pressure sensors on the penstock is indicated with a red line.
Figure 3. Left figure: absolute pressure measured at the spiral casing during the guide vanes closure starting from 40% load to complete stop. Right figure: differential pressure (blue) between the pressure sensor near the penstock inlet tube and the absolute pressure sensor placed at the spiral casing together with the guide movement (brown) from 40% load to complete stop. The x-axis on both figures have different scales.

Figure 3 illustrates the signal obtained by the different absolute pressure sensors in the penstock. The machine is initially operated at a steady state. Then, an emergency shutdown is performed on the machine. The guide vane closure is operated in 2 phases; an initial fast phase followed by a slower one to minimized pressure oscillations after the complete closure. After the complete closure of the guide vanes, oscillations appear in the surge tank, see left plot in figure 3. The oscillations are removed by considering the differential pressure between the absolute pressure sensor in the penstock and the pressure sensor in the surge tank at the inlet of the penstock, see right plot on figure 3.

2.2 Evaluation methods

Several evaluation methods have been developed during the years to evaluate the pressure trace obtained with the pressure-time method to determine the flow rate. All of them use a one-dimensional description of the flow. The differences reside in the modelling of the fluid compressibility and the viscous losses. In the present work, 2 variants are used:

- Standard pressure-time (SPT) method following the evaluation in the IEC41 standard
- Compressible pressure-time (CPT) method as developed by Dunca et al. [5]

In SPT, the flow rate is determined by estimating the integral between the pressure trace and the viscous losses, see Figure 1, and knowing the leakage flow according to equation 1. As the losses are function of the flow rate, which is initially unknown, a linear variation of the losses is initially assumed. An iterative loop is considered until a desired residual of the flow rate (difference between the flow rate obtained from two consecutive estimations) is reached. A constant friction factor is assumed. The leakage flow was estimated to 0.044 m$^3$/s by measuring the headwater level change with closed guide vanes and intake gate. The penstock contains contractions, elbows and pipe of different diameters. The pipe factor (A/L) should guessed or computed. In the present case, the pipe factor is chosen to obtain the same flow rate value as the one obtained with the Accusonic flow sensor.

CPT is based on the water hammer equations (2, 3) in which only the head variation is considered [5]:

$$\frac{a^2}{g} \frac{\partial V}{\partial x} + \frac{\partial H}{\partial t} + V \frac{\partial H}{\partial x} = 0 \tag{2}$$

$$\frac{\partial V}{\partial x} + V \frac{\partial V}{\partial x} + g \frac{\partial H}{\partial x} + f \frac{fV|V|}{2D} = 0 \tag{3}$$
where D, a, and f are the pipe diameter, the speed of sound considering the liquid compressibility and pipe walls deformability and the friction factor. The equations are solved using the method of characteristics (MOC), see Wylie [12]. To evaluate the flow rate, the pressure head difference dH measured between two cross-sections, the geometrical characteristics of the pipe (diameter, pipe walls Young modulus, distance between both cross-sections), and the liquid properties (density, bulk modulus) need to be known. In previous works, this method was used to evaluate the flow rate in pipelines with a constant cross-section yielding good results [5, 10, 11]. In the present analysis, it is adapted to consider the variable geometry of the hydraulic circuit between the intake and the section of the penstock with 4 absolute pressure sensors and the spiral with one pressure tap. The penstock, in the current configuration has four different diameters, last two diameters being comparable in value, two contractions and three elbows, see figure 2. The applied CPT method considers three pipe diameters, and all minor losses as one minor loss occurring between the first two pipes. For the friction factor, f, two formulations are used: a steady evaluation and the Brunone’s unsteady model [13]. The roughness is not considered to determine the friction factors. The speed of sound, a, is determined from the measured pressure trace used as pressure head difference, dH. The computational procedure implies defining specific time moments that characterize the water hammer transient phenomenon:

- t₁: beginning of the analysed time-history
- t₂: end of the steady state
- t₃: end of the flow rate variation regime
- t₄: end of the analysed time-history.

Similarly, to the SPT method, an iterative loop is necessary with an initial guess on the flow rate. The values for the friction factors, f, in the steady state regime for the considered pipes are obtained as a function of the Reynolds number. The minor loss coefficient, ξ, is assumed known, so an initial value is set. The method is applied for the time interval t₁-t₄, along the entire penstock, using the initial guess of the discharge, minor loss coefficient ξ and the previous obtained values for f, together with the boundary conditions:

- upstream section: H(t) = 0, Q(t) results from solving the water hammer equations.
- downstream section: H(t) equals the pressure measured in the penstock/spiral minus the headwater pressure. Q(t) results from solving the water hammer equations
- junction between pipes 1 and 2, and pipes 2 and 3: at each time step, Q_{pipe 1} = Q_{pipe 2} and dH_{pipe1} = dH_{pipe 2} + \xi \frac{Q_{pipe 1}^2}{2gd_{1}^2}, Q_{pipe 2} = Q_{pipe 3} and dH_{pipe 2} = dH_{pipe 3}

The resulting steady state flow rate Q is the average value of the flow rate during the interval t₁-t₂. This value is compared to the previous one and if the difference between them is less than an imposed value, the computation stops. Otherwise, the computation restarts with the value computed for the steady state flow rate as an initial one. At every iteration, a new minor loss coefficient is determined from the steady state condition after obtaining the flow rate:

$$\xi = 2 \frac{g}{a} \frac{dH_0 - h_d}{\left(\frac{Q}{A_2}\right)^2}$$  \hspace{1cm} (4)

3. Results
The flow rate estimated from the compressible pressure-time method (CPT) is presented in figure 4. The results are absolute as the friction and minor loss coefficients are estimated from the flow rate in the evaluation algorithm. The left figure shows that the absolute measurements follow the variation of the ultrasonic flow sensor output for all flow rate considered and repetitions performed.

The deviation between the CPT measurements and ultrasonic flow sensor measurements, right plot in figure 4, presents a quasi-systematic deviation function of the friction model used. The variation in the deviation of both methods follow each other closely. Two measurements, number 1 and 16, present
a larger deviation than the other values. These large deviations are not present with the standard pressure-time (SPT) evaluation method and are thus method related. Overall, the deviation with the ultrasonic flow sensor results is 4±1% for the steady friction formulation and 1±1% for the unsteady formulation.

**Figure 4.** Left figure: flow rate estimated with the compressible pressure-time (CPT) evaluation method assuming a steady and unsteady friction formulation and the corresponding ultrasonic flow rate estimates. Right figure: deviation between the CPT and ultrasonic flow sensor flow rate estimates.

**Figure 5.** Left figure: flow rate estimated with the standard pressure-time (SPT) evaluation method with pressure taps at the penstock tube walls and at the spiral casing and the corresponding ultrasonic flow rate estimates. Right figure: deviation between the SPT and ultrasonic flow sensor flow rate estimates.

The flow rate estimated from the standard pressure-time method (SPT) is presented in figure 5. The results are relative as a pipe factor is assumed for both configurations; 4 pressure sensors on the penstock tube and one pressure sensor on the spiral casing. The flow rate is well estimated, left plot on figure 5, for all measurements and flow rate investigated.

The deviation between the measurements of the SPT and the ultrasonic flow sensor, right plot on figure 5, are in a narrow range: ±1%. The deviation presents a random pattern between both method and should be attributed to the method itself. The outliers present for the CPT method are not present with
the SPT method. The ability to use the SPT method as a relative method is found to be potentially good from these results.

Figure 6 present the mean flow rate deviation and corresponding error bar for a 95% confidence interval for the CPT, left plot, and SPT, right plot, methods for the different configurations investigated. Each evaluation method follows a specific trend and they do not follow each other.

The estimates of the CPT method with an unsteady friction loss formulation are remarkably close the ultrasonic measurements. As a steady friction formulation is used, a nearly systematic biased appear with the other friction model. The standard deviations vary with the friction model considered; a large standard deviation at low flow rate for the unsteady formulation and an opposite variation for the steady formulation.

The estimates of the SPT method with pressure measurements on the tube and the spiral are matching the ultrasonic flow measurements. These measurements are relative as the pipe factor has been estimated from the ultrasonic measurements. The standard deviation of both measurements is smaller than for the CPT method. The mean value obtained in the spiral casing is also remarkable and may need further investigation to understand if these results are a coincidence or can be expected at each measurement. The impact of a semi-spiral casing may be another parameter to investigate.

Figure 6. Left figure: mean flow rate deviation from the ultrasonic flow sensor estimate using the CPT method. The error bars represent the 95% confidence to obtain the mean value. Right figure: average flow rate deviation from the ultrasonic flow sensor estimate using the SPT method. The error bars represent the 95% confidence to obtain the mean value.

4. Conclusion
The pressure-time method as a relative and absolute method has been investigated on a full scale hydraulic machine. The results indicate the ability of the method to be used as a relative method independently of the evaluation method considered, compressible or not. A single pressure measurement in the spiral is found enough to perform such relative measurements together with a pressure sensor at the penstock intake to account for the surface fluctuations after a closure of the machine. Furthermore, the CPT method show the ability to determine with good accuracy the absolute flow independently of the geometry considered assuming a time dependent friction model.

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