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DISCHARGE MEASUREMENTS USING THE PRESSURE-TIME METHOD: DIFFERENT EVALUATION PROCEDURES

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This paper analyzes the pressure-time method and its developments. The pressure-time method used to determine the discharge in hydraulic turbines is described and applied in a generic test case in well controlled laboratory conditions. Developments of the method are presented: a time dependent friction factor (proposed by Jonsson) and a different upper integration limit (proposed by Adamkowski). Laboratory experiments are used to compute the discharge using the pressure-time method in the standard and modified versions and the results are compared. The precision of the methods is verified by comparing the computed discharge values to the values measured with a magnetic flowmeter.

Keywords: discharge measurement, pressure-time method, time dependent friction factor.

1. Introduction

The pressure-time method is used to estimate the flow rate of hydraulic turbines, because it is based only on differential pressure measurements. It is also known as the Gibson method [IEC 60041, IEC 62006, ASME PTC 18]. The method principle consists in measuring the pressure difference changes between two hydrometric sections of a closed conduit during a complete stop of the fluid flow by means of a shut-off device, i.e., the guide vanes in hydraulic turbines (Fig. 1).

The volumetric flow rate of the liquid in the initial condition is determined by integration of the pressure difference changes less the pressure losses occurring while stopping the liquid stream, see IEC 60041 [1] (Fig. 2). The discharge, Q, is given by

$$Q = \frac{A}{\rho L}\int_0^t (\Delta p + \xi)dt + q \tag{1}$$

where, A is the cross-sectional area, L is the distance between the cross sections, ρ is the water density, $\Delta p = p_1 - p_2$ is the pressure difference, ξ is the pressure loss

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due to friction, t is the time and q is the leakage flow after the closure. It is assumed in the conditions stated in the standards, that the measurement accuracy is not lower than +/-(1.5-2.0)% and it is similar to other primary methods, like the current meter method, for instance.

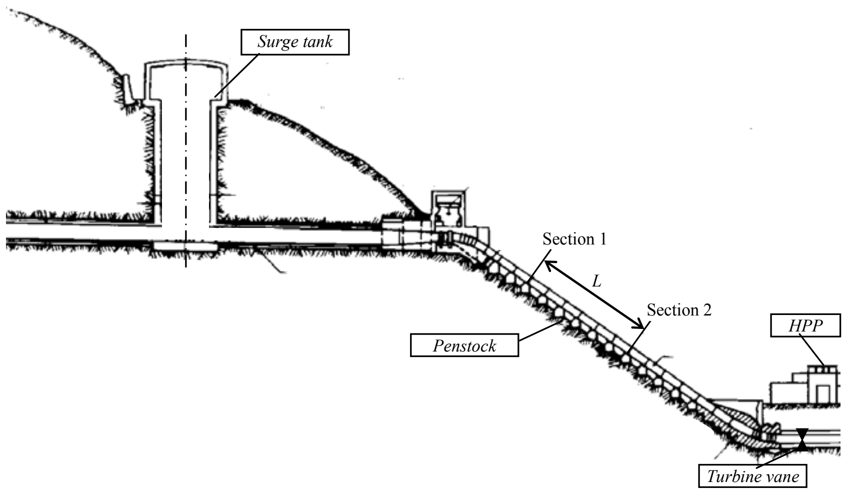


Fig. 1. Schematic of a penstock and the measuring cross–sections for measurement with the pressure-time method: L is the length between the cross-sections, and 1 and 2 are the two hydrometric sections for pressure measurement.

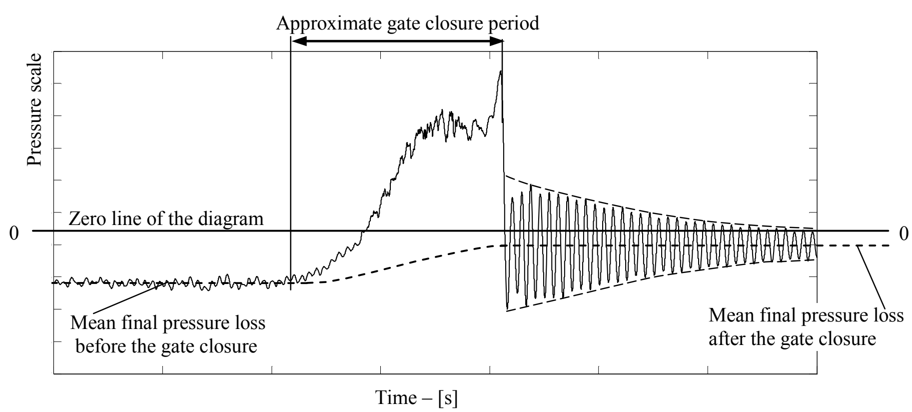


Fig. 2. Pressure-time diagram during a guide vanes closure of a hydraulic turbine

The pressure-time method is subject to limitations in the standard: the measuring length (distance between the cross-sections) must be greater than 10 m, the measuring length times the initial velocity must exceed 50 m^2/s, the residual (free) pressure oscillations in the conduit have a negligible effect, and the friction loss in the measuring segment of the conduit is computed using a simplified method. The first two criteria are basically related to the relative error. The relative error increases by shortening the test section length or the initial velocity, because the pressure wave amplitude becomes smaller relative to the noise amplitude. These two criteria are especially difficult to satisfy in low head machines due to short and non-uniform water passages. Two main issues exist in the method: determination of the losses and upper integration limit. Over time, developments were proposed to remove or at least to relax these limitations.

Jonsson et al. [2, 3] made both numerical and experimental investigations of the pressure-time method for measurement outside the IEC 41 limits for application to low heads hydraulic machines. They developed a numerical model, using the Brunone friction formulation, of the pressure–time method validated with laboratory experiments [4]. Modification of the pressure-time procedure by implementation of the temporal acceleration, together with a time dependent friction factor instead of a constant friction factor, allowed a more accurate estimation of the flow rate compared to the standard pressure-time method procedure. The additional unsteady term corrected both overestimation and underestimation of the flow, which are functions of the flow conditions and measuring length, by up to 0.4%. The improved method was also successfully used for shorter measurement lengths than stipulated in the standard. However, the measurements performed by Jonsson et al. were performed in a laboratory at low Reynolds number.

Adamkowski [5] showed that in the IEC 60041 standard procedure used for obtaining the upper integration limit for the pressure-time curve, the term corresponding to the free pressure oscillations was not taken into account. These oscillations are the result of interaction between inertial effects, the liquid compressibility and deformability of the pipe walls. These effects remain in the pipe after the flow cut-off. Thus, the term corresponding to the free pressure oscillation must be subtracted from the integral value calculated from the recorded pressure difference diagram. The standard procedure does not ensure a zero-value set for the integral free pressure difference oscillations. Adamkowski demonstrated analytically that the term corresponding to these free pressure oscillations has the expression $(B_0 h)/(\omega^2 + h^2)$, where B_0 is the pressure amplitude corresponding to the fundamental harmonic of the free pressure oscillation, $\omega = 2\pi/T$ - the circumferential wave frequency, $h = (1/T)\ln(B_i / B_{i+1})$ - the oscillation damping decrement and T - the pressure wave period (Fig. 3).

From Adamkowski experience [5], the influence of the free pressure oscillations on the discharge measured by means of the standard pressure-time method may come up to 0.5% of the discharge value.

The present paper investigates the effect of a time dependent friction (Jonsson) and a different upper integration limit (Adamkowski). The analysis is performed on the experimental results obtained by Jonsson in a laboratory. The discharge was measured using an accurate magnetic flowmeter beside the pressure time.

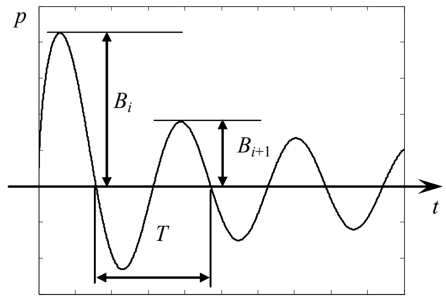


Fig. 3. Free pressure oscillation

2. Measurements and methods

The measurements were performed at the Waterpower Laboratory at NTNU [4]. The measurement procedure consisted in acquiring the differential pressure measured between the two pressure sections, the hydraulic driven gate valve position, the temperature and the absolute pressure used to compute the water density and viscosity and the reference discharge.

The pressure was measured with differential pressure sensors (Honeywell FP2000/FDW). The sensors were calibrated with accuracy below 0.1%. The presented measurements were performed for two constant measuring lengths of 6 and 9 m, and for 3 different values of the discharge, 0.16, 0.3 and 0.4 m^3/s. This corresponds to a Reynolds number Re ≈ $0.65\cdot10^6$, $1.25\cdot10^6$ and $1.70\cdot10^6$, respectively. For each measuring length and discharge value, the measurements were repeated several times.

In the present work, the pressure signals were handled assuming 3 different evaluation procedures, beside the one proposed by the IEC 60041 standard, in order to estimate the effect of time dependent friction and a different upper integration limit as follows:

- Procedure 1: standard pressure-time method
- Procedure 2: standard pressure-time method with an unsteady friction factor stipulated by Jonsson et al. [2, 3]
- Procedure 3: standard pressure-time method with the upper integration limit stipulated by Adamkowski [5]

- Procedure 4: standard pressure-time method with an unsteady friction factor stipulated by Jonsson et al. [2, 3] the upper integration limit stipulated by Adamkowski [5]

The results are presented as errors E in percent between the estimated discharge Q and the reference discharge Q_{ref} measured with the magnetic flowmeter: $E = ((Q - Q_{ref})/Q_{ref}) \cdot 100$. The magnetic flowmeter has an accuracy of 0.3% according to the manufacturer. It was calibrated with a weighting-time system and the deviation was less than 0.1% of the reference.

3. Results

The results obtained with the 4 different procedures are presented for each measuring length in figures 4, 5 and 6 function of the Reynolds number, i.e., the flow velocity, as follows:

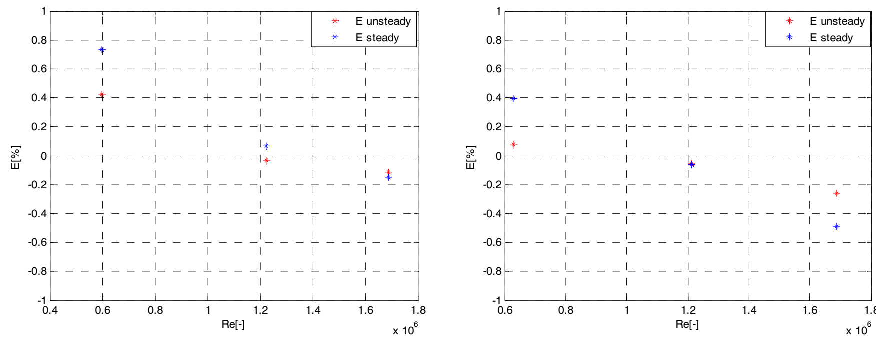
- in figure 4 the results obtained using the standard pressure-time method are presented and compared to the results obtained with the modified method which takes into account the unsteady friction factor
- in figure 5 the results obtained using the standard pressure-time method are presented and compared to the results obtained with the modified method which takes into account the upper integration limit stipulated by Adamkowski
- in figure 6 the results obtained using the standard pressure-time method are presented and compared to the results obtained with the modified method which takes into account the upper integration limit stipulated by Adamkowski applied with the unsteady friction factor

In figure 4, the error obtained with the standard method and the error obtained with the modified method, which takes into account the unsteady friction factor, varies with the Reynolds number.

For a Reynolds number of $0.65 \cdot 10^6$, the error is the largest for both measuring lengths well below 1%. For L = 9 m, the estimation obtained with the modified method is closer to the reference, the error being around 0.4%, while the error obtained with the standard method is around 0.7%. For L = 6 m, the modified method gives an even better estimation of the discharge than for L=9 m, while the standard method overestimates the flow.

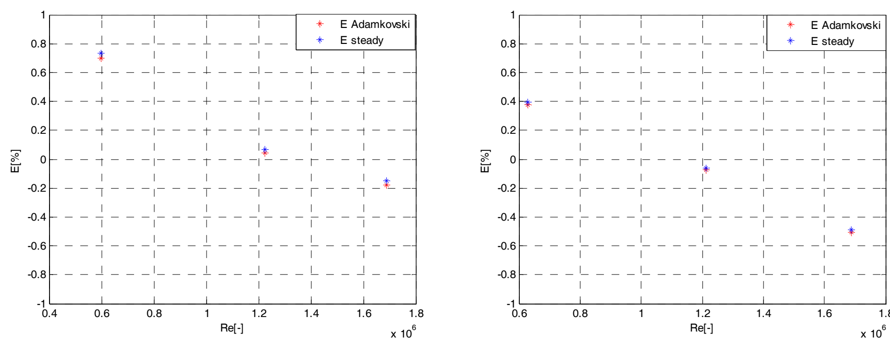
For a Reynolds number of $1.25 \cdot 10^6$, the flow estimation is nearly equal to the reference value for both methods and both measuring lengths. The adjustment resulting from the unsteady formulation is minor.

For a Reynolds number of 1.70×10^6, for L = 9 m both methods produce a slightly lower result than the reference flow rate. For L = 6 m, the methods underestimate the flow, but the modified method gives a discharge closer to the reference one with 0.23% difference. The results are similar to the one presented by Jonsson et al. [4].



a) measuring length of 9 m   b) measuring length of 6 m

Fig. 4. Discharge relative error versus Reynolds number for the standard method and the modified method that takes into account the unsteady friction factor stipulated by Jonsson (Procedure 2)

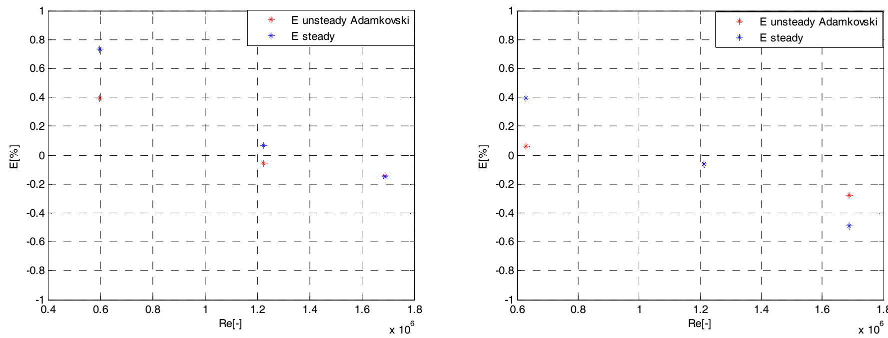


a) measuring length of 9 m   b) measuring length of 6 m

Fig. 5. Discharge relative error versus Reynolds number for the standard method and the modified method that takes into account the upper integration limit stipulated by Adamkowski (Procedure 3)

In Fig. 5 it can be seen that the modified method, which takes into account the upper limit integration proposed by Adamkowski leads to a systematic shift of the error. The difference is around 0.03% for a measuring length of 9 m and 0.015% for 6 m, for all studied Reynolds numbers, i.e., negligible.

The results obtained with the modified method, taking into account the upper integration limit stipulated by Adamkowski with the unsteady friction factor are presented in Fig. 6. The modified integration limit has a negligible influence on the unsteady formulation similarly to the standard method. Thus, the estimation errors are shifted down with an insignificant value compared to the ones obtained with procedure 2.



a) measuring length of 9 m   b) measuring length of 6 m

Fig. 6. Discharge relative error versus Reynolds number for the standard method and the modified method that takes into account upper integration limit stipulated by Adamkowski applied with the unsteady friction factor stipulated by Jonsson (Procedure 4)

In order to determine if the differences are systematic and thus reliable, the uncertainty is calculated for all analysed procedures. The uncertainty is calculated as the deviation from the mean multiplied with the t-distribution term at a 95% confidence level function of the number of samples. Table 1 lists the deviation from the mean for each Reynolds number for a measuring length of 9 m (calculated from 10 runs for the highest Reynolds number and for 9 runs for the other two), and in Table 2 are presented the results for the measuring length of 6 m (calculated from 12 runs). The deviations for the highest Reynolds number are the lowest, which is expected because the relative uncertainty is the smallest in this case.

Table 1

Deviation from the mean in percent at 95% confidence level. for a measuring length of 9 m

Re	0.65×10^6	1.25×10^6	1.70×10^6
Procedure 1	0.129	0.113	0.002
Procedure 2	0.128	0.113	0.002
Procedure 3	0.129	0.113	0.002
Procedure 4	0.128	0.113	0.002

Table 2

Deviation from the mean in percent at 95% confidence level. for a measuring length of 6 m

Re	0.65×10^6	1.25×10^6	1.70×10^6
Procedure 1	0.009	0.008	0.005
Procedure 2	0.009	0.008	0.004
Procedure 3	0.009	0.008	0.004
Procedure 4	0.009	0.008	0.004

4. Discussion or conclusion

Four procedures of discharge estimation using the pressure-time method were applied to experimental laboratory data. The results showed that the standard pressure-time method could be indeed improved by applying some modifications.

The results obtained using the method proposed by Jonsson et al. are closer to the reference compared to the results obtained using the standard pressure-time method. By computing the discharge after extracting the Adamkowski term, it could be seen that the error has a insignificant shift for all Reynolds number values and both measuring length. The error discharge estimation is also systematically shifted by using the method that takes into account upper integration limit stipulated by Adamkowski applied with the unsteady friction factor. Still, this doesn't have a significant influence over the discharge estimation in the present case.

Further, validation of the proposed unsteady pressure-time procedures is necessary for on site measurements of hydropower plants, taking into account different Reynolds number intervals and different measuring lengths.

Acknowledgments

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R E F E R E N C E S

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