Statistic evaluation of deviation between guaranteed and measured turbine efficiency

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1. Introduction

Gibson method allows to measure discharge cost effectively and with sufficient accuracy. This method is generally accepted in form described by standard [1], where straight measuring section with constant cross-section area is required. Such field tests conditions are however seldom available. Standard [2] allows use also curved penstock with parts of different cross-section areas. Nevertheless influence of all secondary interferences is discussed during preparatory works on the new standard prepared for site acceptance tests.

Large set of Gibson measurements tests results provided on HPP with variety of different penstock dimensions and shapes is available by OSC company. Due to customer usual requirement to reduce costs for acceptance test there are only a few cases for direct comparison between Gibson method and other flow measurement methods used for turbine efficiency evaluation in real plant conditions. But recently the CFD methods and precise turbines production enable to predict and guarantee very exactly the turbine prototype parameters. Idea of this paper is contribute to the discussion regarding influence of penstock irregularities on Gibson method results. Statistic evaluation of deviation between measured prototype efficiency and guaranteed value for sample of 47 Gibson guarantee measurements was processed. Similar sample of acceptance tests results using current meters was evaluated as a comparable data too.

2. Gibson method application

Gibson flow measurement method used by OSC can be briefly described as follows:

- separate pressure records are used
- almost the whole penstock length is used as measuring section
- the pressure sensors used are installed in exactly defined cross sections G1 and G2
- measurement with free water upper level is used only when necessary (not for guarantee measurement)
- calculation principles according to standard IEC 41/1991 are used
- measurement may be applied on various penstock's layouts (straight, curved, sections with different diameters, etc.)
- there are no corrections for curved penstock applied
- turbine unit was always stopped by emergency shut down or by similar procedure
- leakage through guide vane is evaluated by Gibson method for intake valve closing or by other exact method (e.g. level drop behind stop log)
- combination of Gibson and index flow measurement is always used

3. Statistic evaluation of Gibson guarantee tests

Set of guarantee measurements provided and used for statistic evaluation is summarized in Tab. 1.

Deviation between measured efficiency and guaranteed efficiency value for each plant unit was evaluated according to following formula:

$$\Delta\eta = \frac{\eta_M - \eta_G}{\eta_M}$$

Where η_M = measured efficiency

η_G = guaranteed efficiency

Various kinds of guarantees relevant to each particular contract (weighted, average efficiency or only one guaranteed point) were used for mentioned equation. Measured efficiency value was than evaluated in accordance with those individual rules.

No.	***Year***	***HPP unit***	***Country***	***Penstock***
1	1999	PSHP Dalešice - pump turbine TG3 - GM before refurbishment - T	CZ	straight, L ~ 30D
2	1999	PSHP Dalešice - pump turbine TG3 - GM after refurbishment - P	CZ	straight, L ~ 30D
3	1999	PSHP Dalešice - pump turbine TG3 - GM after refurbishment - T	CZ	
4	2000	PSHP Dalešice - pump turbine TG1 before upgrade T, GM	CZ	straight, L ~ 30D
5	2001	PSHP Dalešice - pump turbine TG1 after upgrade, GM - T	CZ	straight, L ~ 30D
6	2002	PSHP Dalešice - pump turbine TG1 after upgrade, GM - P	CZ	
7	2002	HPP Vranov - Francis turbine after upgrade	CZ	curved, L ~ 15D
8	2004	PSHP Dalešice - pump turbine TG4 after upgrade - GM - T	CZ	straight, L ~ 30D
9	2004	PSHP Dalešice - pump turbine TG4 after upgrade - GM - P	CZ	
10	2005	HPP Vydra, Francis turbine TG1 after upgrade - GM	CZ	nearly straight, 930D
11	2006	HPP Vydra, Francis turbine TG2 after upgrade - GM	CZ	
12	2006	HPP Les Království, Francis turbine - GM	CZ	straight, L ~ 15D
13	2006	HPP Kalimanci, Francis turbine TG1 - GM	MK	straight, L ~ 30D
14	2006	HPP Kalimanci, Francis turbine TG2 - GM	MK	
15	2006	HPP Orava, Kaplan Turbine - GM	SK	straight, L ~ 6.7D
16	2007	HPP Pena, Francis turbine TG2 - GM	MK	straight, L ~ 63D
17	2007	HPP Pena, Francis turbine TG1 - GM	MK	
18	2008	HPP Patikari, Pelton turbine TG1 - GM	IND	curved, L ~ 500D
19	2008	HPP Patikari, Pelton turbine TG2 - GM	IND	
20	2008	HPP Sapunčica, Pelton turbine TG1 - GM	MK	nearly straight L = 1730 m ~ 3150D
21	2008	HPP Sapunčica, Pelton turbine TG2 - GM	MK	
22	2008	HPP Pesocani, Pelton turbine TG1 - GM	MK	nearly straight L ~ 1300D
23	2008	HPP Pesocani, Pelton turbine TG2 - GM	MK	
24	2008	HPP Concepción, Francis turbine TG1 - GM	PA	Curved L ~ 50D
25	2008	HPP Concepción, Francis turbine TG2 - GM	PA	
26	2008	HPP Matka, Kaplan turbine TG2 - GM	MK	2x curved L ~ 15 / 14 D
27	2008	HPP Matka, Kaplan turbine TG1 - GM	MK	
28	2008	PSHP Dalešice - pump turbine TG2 after upgrade - GM T	CZ	straight, L ~ 30D
29	2008	PSHP Dalešice - pump turbine TG2 after upgrade - GM P	CZ	
30	2009	HPP Došnica, Pelton turbine TG1 - GM	MK	curved, L ~ 380D
31	2009	HPP Došnica, Pelton turbine TG2 - GM	MK	
32	2009	HPP Došnica, Pelton turbine TG3 - GM	MK	
33	2010	HPP Soběnov, Francis turbine TG1 - GM after upgrade	CZ	curved, L ~ 101D
34	2010	HPP Soběnov, Francis turbine TG2 - GM after upgrade	CZ	
35	2010	HPP Ampelgading, Francis turbine TG1 - GM	RI	L ~ 490 D
36	2010	HPP Ampelgading, Francis turbine TG2 - GM	RI	
37	2010	HPP Penz, Zeltweg, Kaplan turbine TG1 - GM	A	L = 2845 m L ~ 1224 D
38	2010	HPP Penz, Zeltweg, Kaplan turbine TG2 - GM	A	
39	2010	HPP Rendelstein, Bolzano - 1 Kaplan Turbine - GM	I	L ~ 105 D
40	2010	HPP Meziboří, Francis turbines TG1, GM after refurbishment	CZ	curved, L ~ 1600 D
41	2010	HPP Meziboří, Francis turbines TG2, GM after refurbishment	CZ	
42	2011	HPP Vír II, 1 Kaplan turbine - GM	CZ	straight, L ~ 12D
43	2011	HPP Colmeda, Pelton turbine TG1 - GM	I	curved, L ~ 2040 D
44	2011	HPP Colmeda, Pelton turbine TG2 - GM	I	
45	2011	HPP Seč, Francis turbine, GM after refurbishment	CZ	curved, L ~ 27D
46	2011	HPP Slapy TG3, GM after upgrade	CZ	curved, L ~ 8D
47	2012	SHPP Agia Barabara, S turbine, GM	GR	curved, L ~ 15D

T = turbine mode, P = pump mode of operation

Tab. 1 - List of Gibson guarantee measurements

Efficiency deviations were assorted into categories with band width 0.5 %. Percentage rates are plotted in Fig. 1. The rate distribution corresponds roughly to normal distribution with centre -0.34% and confidence interval ±2% around this value for probability level 95%. Curve shape is in compliance with expected error distribution. Deviation -0.34% for point with highest probability may be explained as consequence of the bid strategy regarding guaranteed efficiency. Set of 47 acceptance tests results allows very simple statistic evaluation, which is too low to get smooth distribution curve.

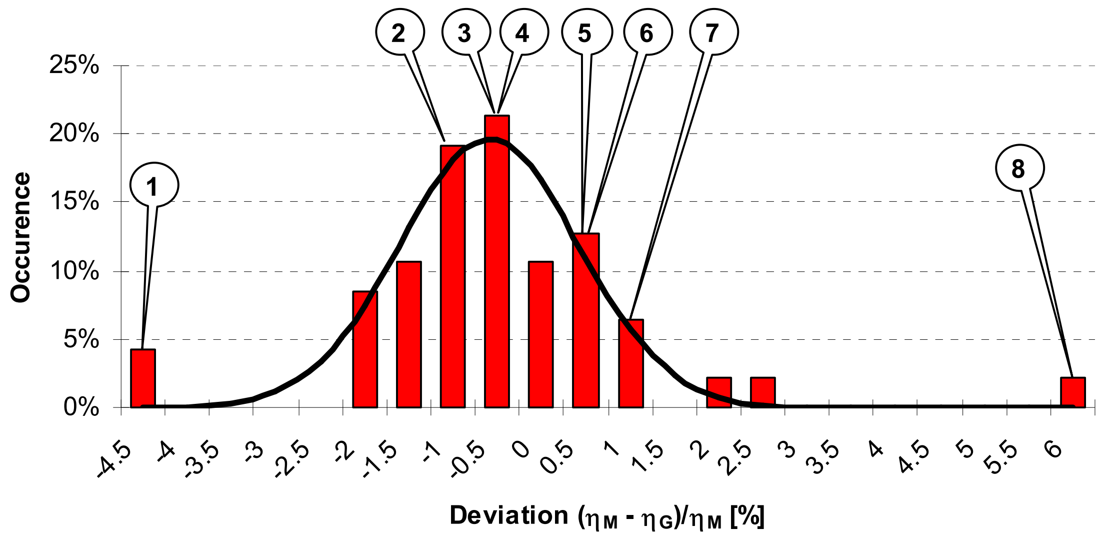

Fig. 1 - Deviation from guaranteed values for Gibson method

Some interesting examples / deviations presented on Fig. 1 are mentioned in following, where marking corresponds to numbers used there. The particular column covers of course also the other cases not mentioned below.

1. Lower efficiency value for this case was confirmed by other independent measuring team using different method.
2. There is excellent correlation between Gibson and ultrasonic transient time method (ΔQ = 0.12%). One path ultrasonic flowmeter, 100 D in front of measuring section, 5D after measuring section, measuring path lies in plane going through penstock centre also in elbow.
3. Reversible Francis turbine, pump mode.
4. Double curved penstock - see Fig. 2
5. Reversible Francis turbine, turbine mode.
6. Curved penstock with differential penstock protection using ultrasonic measurement in two cross-sections. Excellent correlation with the ultrasonic measurement (four path) - see Fig. 3.
7. Curved penstock - see Fig. 4
8. In this case was guaranteed efficiency improvement for upgraded turbine, where turbine condition before upgrade was very bad. The efficiency improvement was significant higher than expected value.

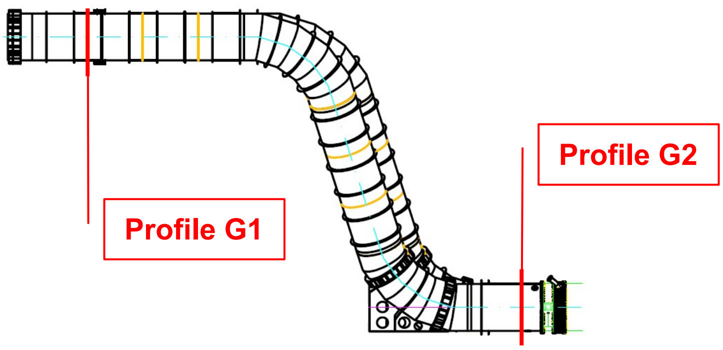

Fig. 2 - Double curved penstock - example 3

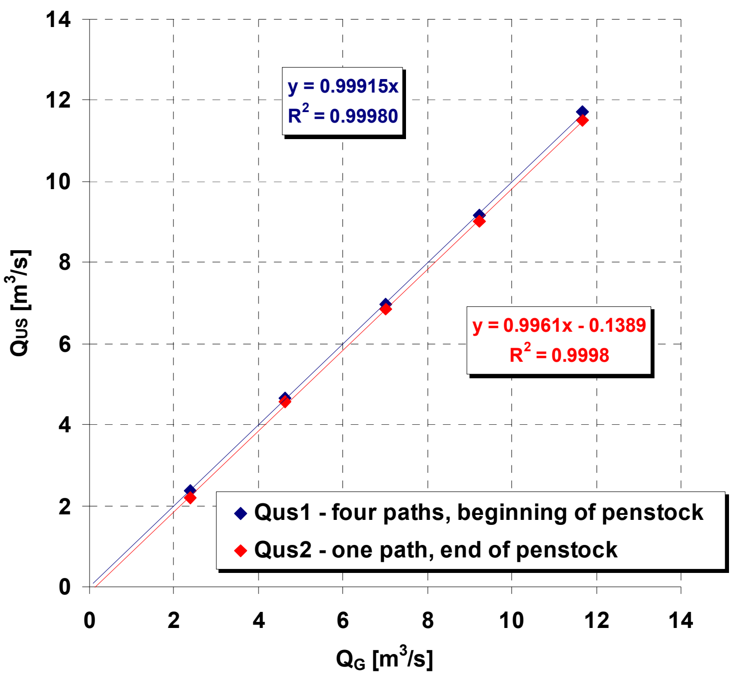

Fig. 3 - Correlation between Gibson flow measurement and ultrasonic flow meters - example 6

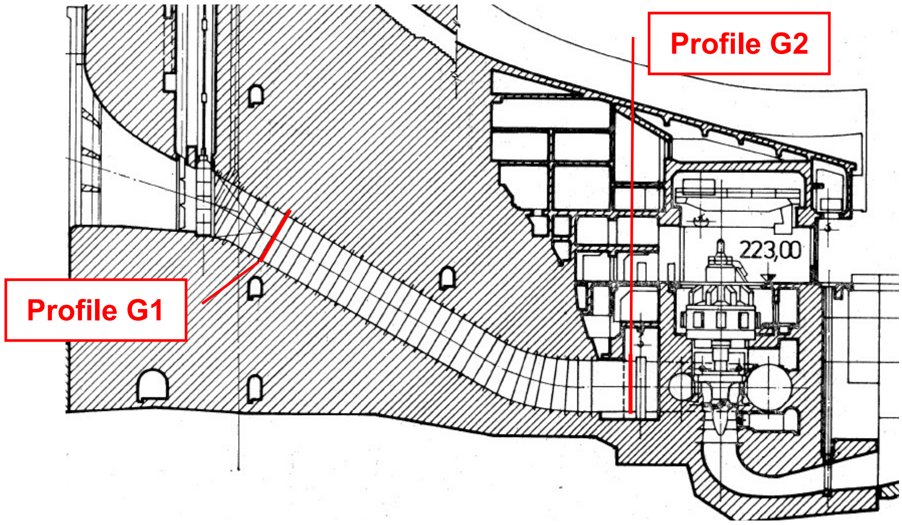

Fig. 4 - Single curved penstock - example 4

4. Flow measured by current meters

Set of acceptance tests results with flow measurement using current meters (propellers) was also evaluated in similar way like discharges obtained by Gibson method. List of these measurements is presented in Tab. 2. Percentage rates are presented in Fig. 5.

No.	Year	HPP unit	Intake	Country
1	1995	HPP Slapy, Kaplan turbine - GM after reconstruction	Penstock	CZ
2	1996	PSHP Dlouhé stráně - pump turbine TG1, T - GM	Penstock	CZ
3	1996	PSHP Dlouhé stráně - pump turbine TG1, P - GM	Penstock	CZ
4	1996	HPP Obříství - Kaplan PIT turbine 1 - GM	Low head	CZ
5	1996	HPP Obříství - Kaplan PIT turbine 2 - GM	Low head	CZ
6	1996	HPP Veletov - Kaplan PIT turbine 1 - GM	Low head	CZ
7	1996	HPP Veletov - Kaplan PIT turbine 2 - GM	Low head	CZ
8	1997	PSHP Štěchovice - pump turbine T - GM	Penstock	CZ
9	1997	PSHP Štěchovice - pump turbine P - GM	Penstock	CZ
10	1998	HPP Libčice - Kaplan PIT turbine 1 - GM	Low head	CZ
11	1998	HPP Libčice - Kaplan PIT turbine 2 - GM	Low head	CZ
12	2000	HPP Žagań - Kaplan turbine 1 - GM	Low head	PL
13	2000	HPP Žagań - Kaplan turbine 2 - GM	Low head	PL
14	2000	HPP Žagań - Propeler turbine 3 - GM	Low head	PL
15	2001	HPP Ladce - Kaplan turbine after upgrade - GM	Low head	SK
16	2004	HPP Kisköre, Bulbturbine TG1 after upgrade - GM	Low head	H
17	2005	HPP Kisköre, Bulbturbine TG4 after upgrade - GM	Low head	H
18	2005	HPP Přelouč TG2, Kaplan turbine - GM	Low head	CZ
19	2006	HPP Kisköre, Bulbturbine TG3 after upgrade - GM	Low head	H
20	2006	HPP Kisköre, Bulbturbine TG2 after upgrade - GM	Low head	H
21	2006	HPP Vraňany, PIT turbine	Low head	CZ
22	2007	HPP Kroměříž, Kaplan turbine TG3 after upgrade	Low head	CZ
23	2008	HPP Kroměříž, Kaplan turbine TG1 after upgrade	Low head	CZ
24	2008	HPP Kostomlatky, Kaplan turbine TG2 after refurbishment	Low head	CZ
25	2009	HPP Kostomlatky, Kaplan turbine TG1 after refurbishment	Low head	CZ
26	2008	HPP Hradištko, Kaplan turbine TG1 after refurbishment	Low head	CZ
27	2008	HPP Hradištko, Kaplan turbine TG2 after refurbishment	Low head	CZ
28	2008	HPP Tiszalök, Kaplan turbine TG1 - after upgrade	Low head	H
29	2009	SHPP Lakatnik, 1 Kaplan turbine - GM	Low head	BG
30	2009	SHPP Svrajen, 1 Kaplan turbine - GM	Low head	BG
31	2009	HPP Tiszalök, Kaplan turbine - after upgrade	Low head	H
32	2009	SHPP Spytihněv, 2 Kaplan turbines	Low head	CZ
33	2010	SHPP Troja - Kaplan turbine TG1- GM	Low head	CZ
34	2010	HPP Tiszalök, Kaplan turbine - after upgrade	Low head	H
35	2011	SHHP Miřejovice - Kaplan turbine TG1 GM	Low head	CZ
36	2011	SHHP Miřejovice - Kaplan turbine TG2 GM	Low head	CZ
37	2012	SHPP Dobrohošť - 1 Kaplan turbine	Low head	SK
38	2012	SHPP Pardubice - 1 Kaplan turbine	Low head	CZ

Tab. 2 - List of propeller guarantee measurements

The rate distribution corresponds very approximately with normal distribution with centre +1.25% and confidence interval ±3%. Efficiency value obtained by flow measurement with current meters has higher dispersion of deviation from guaranteed values in comparison with Gibson method. One of the possible reasons is the fact, that approx. since 1997 no propeller flow measurement in penstock has been carried out. Current meters are applied recently only for low head power plants with rectangular intake to concrete semi spiral. Measurements with current meters installed on 6- or 8-beam spider in penstock are marked in Fig. 5. These results are closer to zero deviation in comparison with low head plants. Calculation procedure in accordance with standard [5] was used for all these tests.

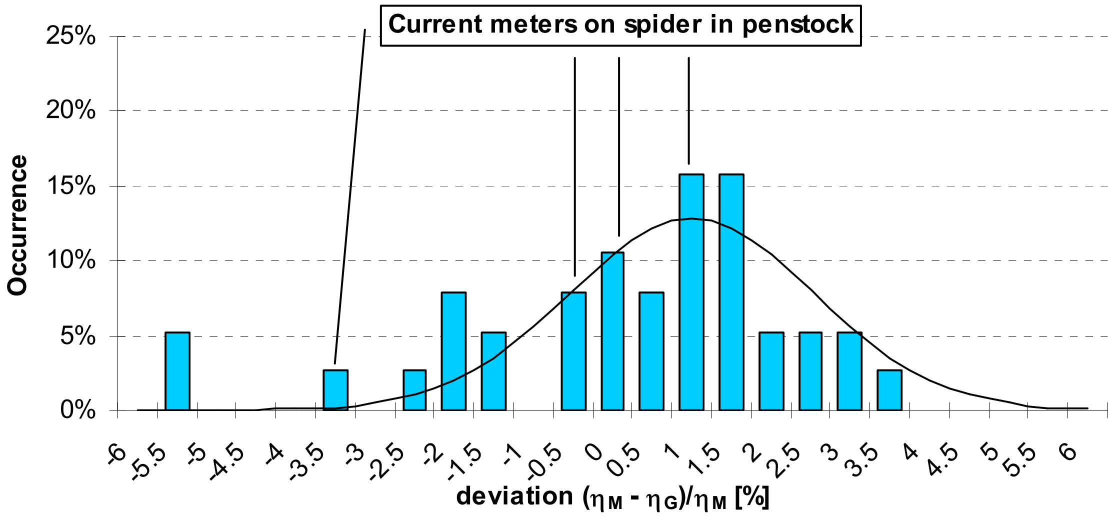

Fig. 5 - Deviation from guaranteed values for current meters

5. Summary

The comparison of statistic evaluation between both mentioned flow measurement methods used for water turbine efficiency evaluation is presented in Fig. 6. Reliability of Gibson method application in this case is better than method using propellers. For more serious conclusion from this comparison is necessary take in mind that the particular flow measurement methods weren't used under identical conditions. Current meters flow measurements were usually carried out at low head power plants and also at the units following rehabilitation. Therefore it is not fully comparable with Gibson method, which was used for measurement under better conditions.

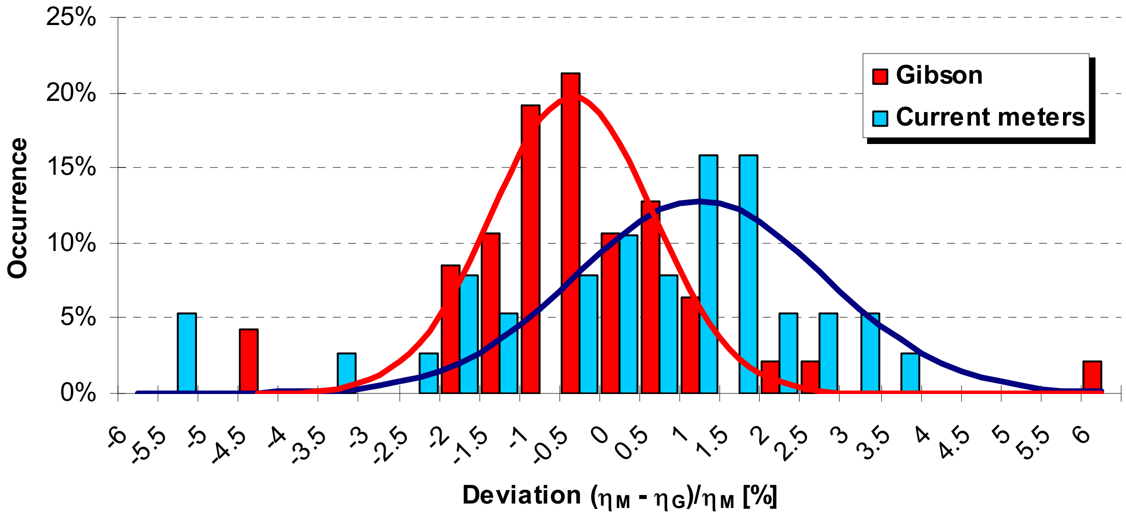

Fig. 6 - Comparison between deviation distributions for Gibson method and current meters.

Percentage occurrence of deviation between measured and guaranteed efficiency values for Gibson method corresponds with expected normal statistic distribution. Following conclusion can be derived from this deviation distribution:

- Average deviation of measured efficiency from guaranteed efficiency value -0.34% corresponds very well with expected commercial efficiency increase often used for the bid.
- Deviation dispersion is done by measurement uncertainty and also by real deviation of measured efficiency against guaranteed one.
- Hydraulic design based on CFD method recently used is associated with improved reliability of guaranteed parameters.
- Influence of penstock layout (bends, cones etc.) on measured discharge accuracy wasn't confirmed.

- Outliers in dispersion graph (Fig. 1) were checked and fully explained.
- Very good reliability of Gibson flow measurement was confirmed as well as it's independency on penstock geometry. No any significant abnormality during all mentioned tests was noticed.

References

[1] Standard IEC 41: „Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump turbines", standard issued by CEI, 1991.

[2] Standard IEC 62006, Ed. 1.0: "Hydraulic machines – Acceptance tests of small hydroelectric installations", approved committee draft, CEI, 2007.

[3] Adamkowski A., Krzemianowski Z., Janicki W.: "Improved Discharge Measurement Using the Pressure-Time Method in a Hydropower Plant Curved Penstock", Journal of Engineering for Gas Turbines and Power, September 2009

[4] Jonson P., Ramdal J., Cervantes M., Dahlhaug O., Nielsen T.:"The pressure-time measurement project at LTU and NTNU", Paper for IGHEM-2010, Roorkee, India.

[5] Standard ISO 3354 "Measurement of clean water flow in closed conduits -- Velocity-area method using current-meters in full conduits and under regular flow conditions", Czech edition, issued by ČNI 1993.

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