APPLICATION OF THE GIBSON METHOD FOR DETERMINING THE DISCHARGE AT A LOW HEAD HYDRO POWER PLANT

APLICAREA METODEI GIBSON PENTRU DETERMINAREA DEBITULUI TURBINAT LA O CENTRALA HIDROELECTRICĂ DE MICĂ CĂDERE

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Abstract: *The paper presents the Gibson method (pressure - time method) a measurement methodology used to determine the turbine discharge at a hydropower plant. The Gibson method is not very well known in Romania, because this method has not been applied so far for determining the discharge respective of turbines hydraulic efficiency at hydro power plants in Romania. The paper also briefly presents the mathematical model of the Gibson method as well as an in situ application of the method to a hydro unit equipped with a 16 MW Kaplan turbine.*

Keywords*: discharge, hydro unit, turbine efficiency, head.*

Rezumat: *În lucrare este prezentată metoda Gibson (metoda presiune - timp) o metodologie de măsură utilizată pentru determinarea debitului turbinat la o centrală hidroelectrică. Metoda Gibson nu este foarte cunoscută în România, deoarece această metodă nu a fost aplicată până în prezent pentru determinarea debitului respectiv a randamentului turbinelor hidraulice la centralele hidroelectrice din România. De asemenea în lucrare este prezentat pe scurt modelul matematic al metodei Gibson precum şi o aplicaţie in situ a metodei la un hidroagregat echipat cu o turbină Kaplan de 16 MW.*

Cuvinte cheie: debit, hidroagregat, randamentul turbinei, cadere

1. Introduction

Knowing the technical condition of hydroelectric power plant installations based on testing in nature is one of the means without any realistic policy on running, maintenance and refurbishment of hydropower equipment in hydroelectric power plants cannot be designed.

In order to substantiate some measures regarding the operation, maintenance and/or refurbishment of the hydro units from the hydroelectric power plants, energy performance tests/trials performed *in situ* are used more and more frequently.

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Energy performance tests are performed in accordance with the provisions of the IEC 41/1991 [1] (currently transformed in SR EN 60041/2003 [2]), IEC 62006/2010 [3], ASME PTC 18/2002 [4] measurement codes and are performed with a periodicity regulated by the PE 301/1993 energy prescription [5]. These energy performance tests/trials provide an image of the actual performance compared to the design of the hydro unit under test.

This paper presents *in situ* determination of the discharge at a hydraulic turbine that equips a low head and high discharge hydroelectric power plant using the Gibson method.

The *in situ* measurements performed at a hydro unit equipped with a Kaplan turbine of 27 MW are the basis of this paper.

2. The objective of the experimental tests

The objective of the tests was a hydro unit equipped with a 27 MW Kaplan turbine [6].

Some data regarding the arrangement:

- Accumulation made by damming the Prut River near Stânca; dam made of local materials with concrete mask; dam height is 45 m; the total volume of the accumulation lake is 1.085 billion [m^3] (one of the largest artificial lakes in Romania; the useful volume about 450 million [m^3]).

- The arrangement is provided with two KVB 16-27 turbines, one for Romanian part and the other for Moldovan part.

- Water access to each turbine is made from a valve with wet pit equipped with a rare grate and a flat valve with quick closing;

The hydroelectric power plant is equipped with Kaplan turbines made by UCM Reşiţa S.A. and have the following energy characteristics:

- Installed turbine discharge Q_i = 65 [m^3/s]
- Maximum net head $H_{n\ max}$ = 29,50 [m]
- Minimum net head $H_{n\ min}$ = 18,70 [m]
- Nominal net head H_n =27,3 [m]
- Turbine power at rated head P_i = 16 [MW]
- Annual average energy for project E_m = 65,00 [GWh/an]

3. The determination of the discharge at hydropower plants

According to the international measurement codes IEC 41/1991 and IEC 62006/2010, the main methods for determining the turbine discharge:

✓ at low head hydropower plants (equipped with Kaplan turbines) are: current meter method, acoustic method, Gibson method, dilution method.

✓ at high head hydropower plants (equipped with Francis, Pelton turbines) are: acoustic method, Gibson method, dilution method.

Lately, the acoustic methods for determining the flow have had a special development, especially Acoustic Scintillation Flow Meter (ASFM), method developed by the Canadian company AQFLOW [7].

Also, in Romania implementation attempts of Acoustic Scintillation Flow Meter method were made at low head and high flow hydropower plants equipped with Kaplan type turbines, but the implementation of the method, still remains a project for the future assessment of the technical state of the refurbished turbines. The prohibited price of the method is a problem in its implementation.

Because it is for the first time in Romania, when the discharge is determined using the Gibson method, the theoretical principle of the Gibson method or the pressure-time method is presented below.

3.1. The theoretical description of Gibson method

The Gibson method is based on Newton's and fluid mechanics laws, which give the relationship between the force corresponding to the change of pressure difference between two sections (S1-1 section and S2-2 section in Figure 1) and the acceleration or deceleration of the water mass between these two sections.

The method is based on the following principle: in a frictionless fluid flowing through an A cross-section penstock, the variation of the velocity dv/dt of a mass of fluid ($m = \rho L A$), can lead to a Δp difference of pressure between the upstream cross section and the downstream cross section of a penstock section of L length.

$$\rho L A \frac{dv}{dt} = -A \Delta p \,, \tag{1}$$

where:

$$\Delta p = p_{av} - p_{am} \ . \tag{2}$$

p_{am} is the pressure in the upstream cross section;
p_{av} – pressure in the downstream cross section.

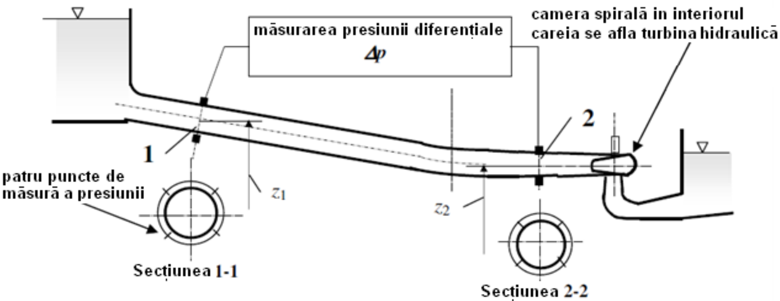

Figure 1. Penstock segment with marking of measurement sections required to explain the theoretical basis of the Gibson method [8]

In order to obtain a calculation relationship for a Q discharge, it is considered a penstock with an *A* area of the flow section (area that can change along its length, figure 1). It is assumed that the discharge is stopped by closing the valve or the wicker gate, taking into account a penstock segment of *L* length, located between S1-1 section and S2-2 section. It is assumed that the velocity and pressure distributions in the cross sections of this segment are constant. It is also assumed that the density of the fluid and the area of the flow section do not change due to the hammering effect.

According to these hypotheses, the relationship between the parameters of the unstable flow between two selected cross sections from a penstock can be described using Bernoulli's relation [9],

$$\alpha_1 \frac{\rho Q^2}{2A_1^2} + p_1 + \rho g z_1 = \alpha_2 \frac{\rho Q^2}{2A_2^2} + p_2 + \rho g z_2 + \Delta P_f + \rho \frac{dQ}{dt} \int_0^L \frac{dx}{A(x)} \tag{3}$$

where:

- α_1 and α_2 are the Coriolis coefficients for S1-1 and, respectively, S2-2 sections,
- p_1 and p_2 are the pressures in S1-1 and, respectively, S2-2 sections,
- z_1 and z_2 - the piezometric heights of the centers of gravity of S1-1 and S2-2 sections,
- ρ is the average density of the liquid,
- g - gravitational acceleration,
- ΔP_f pressure loss caused by friction losses between the two measuring cross sections, S2-2 section and S1-1 section.

The following terms are introduced in equation (3):

- the difference of static pressure between S2-2 and S1-1 sections in the penstock,

$$\Delta p = p_2 + \rho g z_2 - p_1 - \rho g z_1 \tag{4}$$

- the difference of dynamic pressure between S2-2 and S1-1 sections in the penstock,

$$\Delta p_d = \alpha_2 \frac{\rho Q^2}{2A_2^2} - \alpha_1 \frac{\rho Q^2}{2A_1^2} \tag{5}$$

- the geometric factor of the examined penstock segment of length *L*

$$F = \int_0^L \frac{dx}{A(x)} \quad . \tag{6}$$

Using the above notations equation (3) can be rewritten as:

$$\rho F \frac{dQ}{dt} = -\Delta p - \Delta p_d - \Delta p_f \quad . \tag{7}$$

The term $\frac{dQ}{dt}$ in relation (7) is an unstable term, which takes into account the variation of the volumetric discharge, registered during the transient flow. This term represents the inertia effect of the liquid in the examined penstock segment.

After integrating equation (7) in the time domain (t_0, t_k), namely the discharge exchange between the initial and final conditions, it is obtained the discharge difference between these conditions:

$$Q_0 = \frac{1}{\rho F}\int_{t_0}^{t_k}(\Delta p(t) + \Delta p_d(t) + \Delta p_f(t)) + q_k \ , \tag{8}$$

where q_k is the discharge due to leaks through the closing device.

The result of the integral in the right side of equation (8) can be obtained by planimetry from the pressure-time diagram, figure 2. In other words, the discharge calculation is done by a graphical or numerical recording of the variation of the pressure over time, namely, the function $p = f(t)$ which can be obtained by closing the valve or the wicket gate with constant speed.

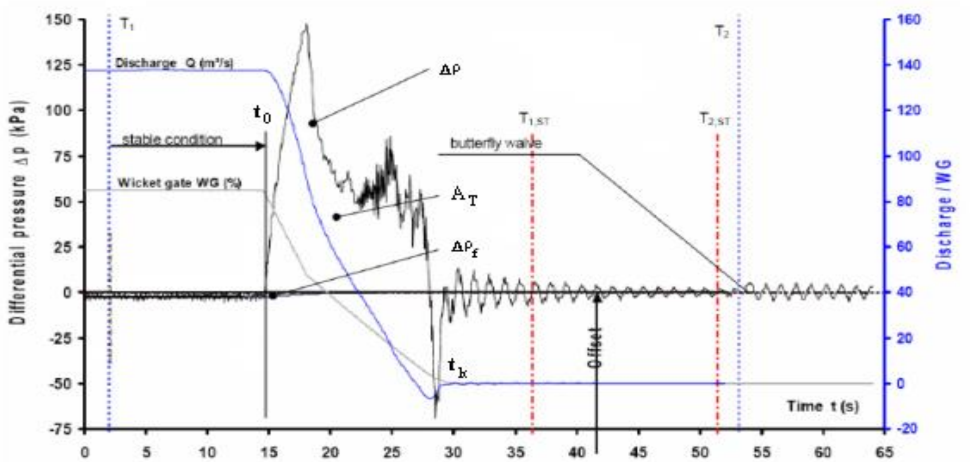

Figure 2. Pressure-time diagram according to IEC 62006

If it is considered that the area of the surface resulting from the planimetry is A_T then equation (8) can be rewritten as:

$$Q_0 = \frac{g}{F}A_T + q_k \tag{9}$$

If the term q_k in equation (9), the loss discharge due to leaks through the closing device, is non-zero, then it must be measured or evaluated using a separate measurement method.

From the integration formula (8) it is observed that, in order to determine the discharge Q_0, the pressure drop ΔP_f caused by the hydraulic losses in the examined penstock segment and the dynamic pressure difference Δp_d between S2-2 and S1-1 sections of the penstock should be extracted from the static pressure difference measured Δp between these pressures.

The values of the parameters Δp_d , ΔP_f can be calculated based on their dependence on discharge square (relations no. (5) and (10)).

$$\Delta P_f = kQ^2 \tag{10}$$

There are several variants of the Gibson method, the difference between them consisting in the instrumentation and calculation technique used for the integration of pressure-time diagrams (method with pressure difference transducer and separated diagram method, with two relative pressure transducers).

The application domain of this method results from several conditions that must be met, namely:

- the distance between two measuring sections must be greater than 10 [m];
- the product between the distance between the two measuring sections and the average speed in penstock, when the group is operating at full capacity, must be greater than 50 m^2/s;
- the area between two measuring sections must be horizontal and of constant section;
- there must be no intermediate free surface between the two pressure measuring sections;
- water losses through the closed shut-off device (shut-off valve or wicket gate) must not exceed 5% of the measured discharge; this discharge must be determined with an accuracy of 0.2% of the total discharge.

When performing the measurement under favorable conditions, the uncertainty of the discharge measurement is estimated at ±1,5% ÷ ±2% in the case of applying a differential computerized calculation method and at ±1,8% ÷ ±2,3% with other measurement techniques, both with a 95% confidence level.

4. In situ determination of the turbine discharge with Gibson method

The successful application of the Gibson method in the case of the hydro unit equipped with the 16 MW Kaplan turbine was possible due to the long length of the hydroelectric power plant supply penstock, approximately 205 m, and the long distance between the two measuring sections, S1 and S2, as in figure 3.

Two relative pressure transducers were used to determine the turbine discharge using the Gibson method for the hydro unit equipped with a 16 MW Kaplan turbine.

The pressure transducers required for measuring the pressure difference and plotting the pressure - time graph were placed in two different measuring sections, upstream of the turbine and, respectively, near the water intake of the hydro power plant, as in figure 3. Data acquisition of the from the two pressure transducers was done with a National Instruments specialized acquisition board, made of a cDAQ 9172 chassis and the Ni 9203 and Ni9215 acquisition modules. Data acquisition was done with an acquisition speed of 1ms.

The determination of the discharge with Gibson method was done for two operating regimes of the hydro unit, at 5 [MW] and, respectively, at 7 [MW].

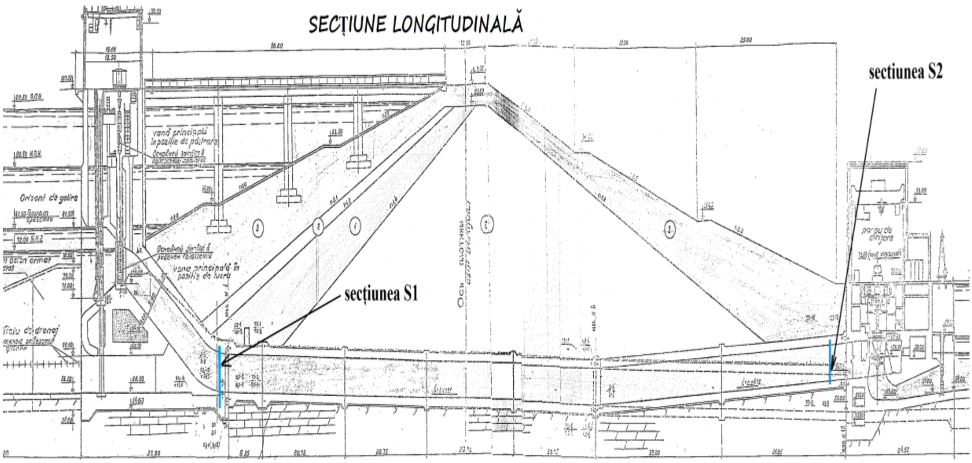

Figure 3. Longitudinal section through the hydroelectric power plant

When the hydro unit worked with a terminal power of 5 [MW], it was obtained the graph in figure 4.

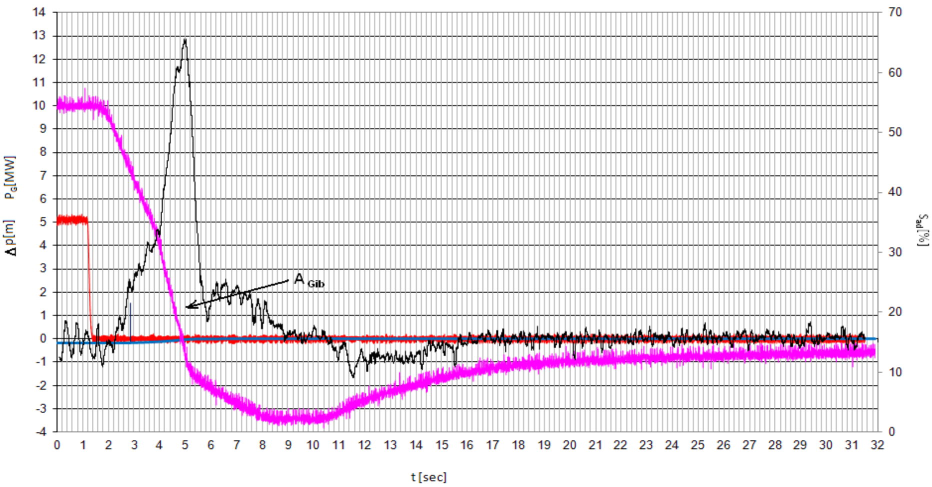

Figure 4. Static and dynamic characteristics obtained with Gibson method at a power of 5 [MW]

The maximum overpressure recorded for the power of 5 [MW] at the generator terminals was 3.58 [bar].

The discharge obtained for a power of 5 [MW] at the generator terminals was 25.17 [m^3/s].

When the hydro unit worked with a terminal power of 7 [MW], it was obtained the graph in figure 5.

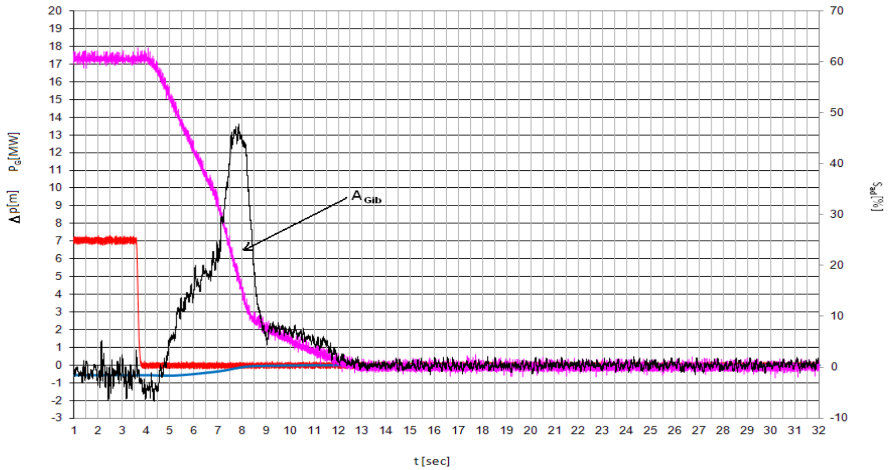

Figure 5. Static and dynamic characteristics obtained with Gibson method at a power of 7 [MW]

where:

The purple line represents a sudden shutdown of the wicket gate, when the discharge in a penstock is stopped using a cut-off device, (turbine wicket gates)

The red line represents the evolution of the power at the terminals of the generator P_G [MW] during the sudden closing of the wicket gate;

The blue line represents the pressure loss by friction between the two measuring sections [m];

The black line represents the pressure difference between the two measuring sections, S2 and S1;

The maximum overpressure recorded for the power of 7 [MW] at the generator terminals was 3,62 [bar].

The discharge obtained for a power of 7 [MW] at the generator terminals was 33,32 [m3/s].

The above values were the basis for calibrating the pressure taps by determining the *k* discharge coefficient using Winter Kennedy relation (11) and Gibson method.

$$Q = k\sqrt{\Delta h} \quad (11)$$

where:

Q is the turbine discharge measured using Gibson method;

k – the discharge coefficient of the differential pressure taps on the spiral casing of a hydraulic turbines;

Δh – differential pressure measured on the differential pressure taps on the spiral casing of a hydraulic turbine.

5. Verification of the results obtained with Gibson method

In order to verify the discharge metric results obtained with Gibson method at the energy efficiency tests performed at the 16 MW hydro unit, the turbine discharge was also measured with the dilution method but also with the acoustic method of transit time.

The results obtained after performing the discharge metric measurements with the Gibson method Q_{Gb}, dilution method Q_{dil} and acoustic method Q_{ac} are presented in table 1 and figure 6.

Table 1. **Experimental results obtained at the 16 MW hydro unit**

No.	1	2	3	4	5	6	7	8	9	10	11
P_G [MW]	5,12	6,11	7,07	8,11	9,08	10,11	11,07	12,08	13,05	14,07	15,02
Q_{ac} [m^3/s]	25,90	29,90	33,80	38,02	42,65	47,60	50,50	56,30	60,70	65,20	70,70
Q_{Gb} [m^3/s]	25,17	29,25	32,85	37,09	41,28	45,72	49,92	54,68	59,37	64,50	69,64
Q_{dil} [m^3/s]	24,53	28,51	32,01	36,14	40,23	44,56	48,64	53,28	57,86	62,85	67,87

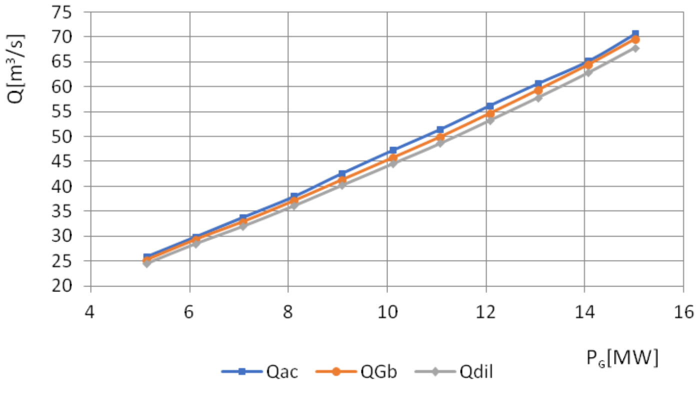

Figure 6. Graphical representation for intake feature $Q = f(P_G)$ for the 16 MW hydro unit

As it can be seen in Figure 6, the discharge obtained with Gibson method have have close values compared with the values of discharges obtained with acoustic method and dilution method.

For the dilution method, it was obtained a calculation accuracy of 1.10%, for Gibson methods - accuracy is 1.07% and for acoustic methods an accuracy of 1.03%.

Following in situ tests and calculations performed, it can be seen that Gibson method has an accuracy comparable to other more expensive methods of *in situ* flow determination. The cost of *in situ* application of Gibson method is about five times lower than the cost of the acoustic method [10]. Also, the in situ application of Gibson method does not imply the unavailability of the hydroelectric power plant for assembly and performing *in situ* tests.

6. Conclusions

At the moment, high accuracy of electronic devices used to measure the pressure and pressure difference, along with the availability of computer recording software and numerical processing of measured data, made Gibson method to be more atractively than a few years ago, when classical measurement techniques were used.

Advantages of Gibson method compared to other discharge measurement methods:

• low price and a simple installation of the measuring system,

• measuring accuracy close to other classical methods of high precision measurement,

• the possibility to determine the discharge over time (most of these methods do not have this much-desired quality).

Disadvantages of Gibson method:

• evaluation or measurement of discharge losses through closing devices,

• requires a quick closing of the closing device during each measurement.

We can consider that the discharge measurement using the Gibson method for the hydro unit equipped with the 16 MW Kaplan turbine was a success.

It is also recommended to check the application of the Gibson method to other hydroelectric power plants equipped with Kaplan turbine but also to high head ones equipped with Francis turbines.

ACKNOWLEDGMENTS

This paper has been financed from the Nucleus Program funds that has been carried out with the support of the MEC. project no. PN 19400401 contract MCI no. 27N /2019.

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