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Determining the turbine discharge and efficiency at low-head hydropower plants

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Abstract: *The efficient exploitation of the hydropower facilities requires obtaining the highest possible energy production with the optimal management of water resources, as well as an exploitation regime of the hydro aggregates that ensures high reliability for as long as possible a period of exploitation. According to the energy prescription (PE301/93), the operating characteristics are periodically restored, through "in situ" measurements, at intervals of a maximum of 10 years, for turbines with powers between 3 and 50 MW, or at intervals of a maximum of 5 years for turbines with higher powers of 50 MW, as well as after each major repair or re-engineering/modernization of equipment. The paper presents a way of improvement and simplification of the methodology for in situ determination of the discharge to low head hydropower plants by using a mobile frame that has the possibility to change the angle between the axis of the current meter and the tangent to the current lines of the flow spectrum, thus reducing the calculation error of the dischaege and increasing the measurement precision.*

Keywords: *Hydraulic turbine, Hydropower plant, Measurement methods, Discharge.*

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I. INTRODUCTION

To be able to implement requirements of the EC directive 2009/28, it is necessary to use efficiently the water reserve of a hydroelectric facility, in order to obtain a higher quantity of electricity by machining the same volume of water. In order to be able to make an efficient use of the hydro energy, it is necessary to have an optimal framing of the operation of a hydropower plant in the intervals of gross head and electric power, so that the process of energy conversion takes place in the interval of optimal efficiency of the operation characteristics of the hydropower plant.

To determine the optimal operation of a hydropower plant, it is necessary to know and precisely measure the quasi-constant parameters (P - power, Q - discharge, H - gross head) of the hydropower plant.

Among these parameters the parameter whose measurement raises the most difficult problems is the discharge because it requires a complex measurement methodology.

According to the international standards in force (CEI 41 / 1991, SR EN 60041 / 2003, ASME PTC / 2002), CEI 62006 / 2010, ISO 3354 / 2008), among the measurement methods for discharge at low-head hydropower plants, the method current meter is one of the most accurate methods of measuring discharge.

Current meter method is frequently used as a reference method for comparing discharges determined by means of other measurement methods ultrasound method (Proulux et al. 2004; Lampa et al. 2007), Gibson method (Adamkowski 2012), or thermodynamic method (Cote 2012).

II. EXPERIMENTAL PROCEDURE

The main method of determining the discharge at low-head hydropower plants, method for determining the discharge by measuring local velocities utilizing the current meters, a method also known as the current meter method, represents the adaptation to the actual discharge in the penstock under pressure, or open channels of the velocity-area formula. We assume that the streamline is perpendicular to the measuring section.

According to the rotational speed of the current meters n in acertain period of time t the flow velocity will be measured in the chosen measurement section. The relation between the rotational speed of the current meters *n* and the water flow velocity *v* is experimentally determined by means of Equation (1).

$$v = a\, n + b \qquad (1)$$

In the Equation (1) is represents the calibration equation of the current meters determined in the laboratory, where a and b are the calibration coefficients of the current meter.

The rotational speed of the current meter n is calculated by means of Equation (2).

$$n = N \cdot I / t \qquad (2)$$

where: *N* is the number of pulses generated by a current meter during one measurement;

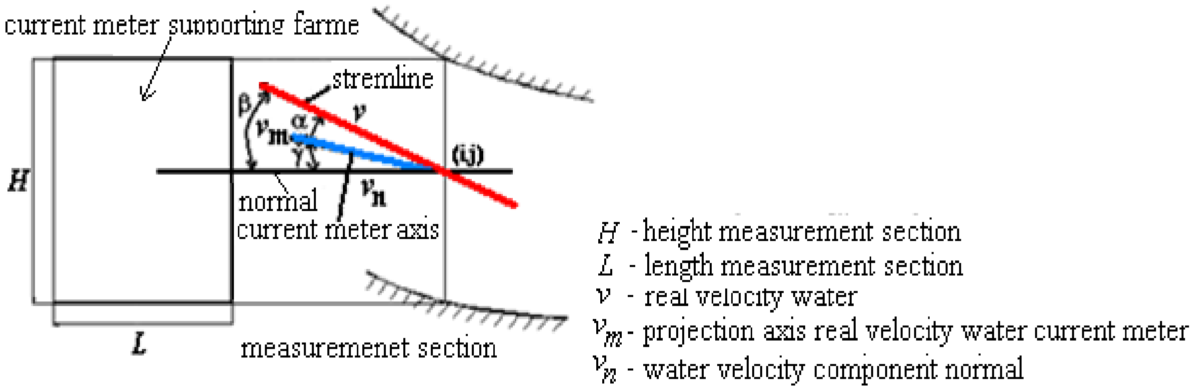
I is a constant and represents the number of revolutions required for generating a pulse:

t is the pulse recording duration.

The local velocities were measured by means of the current meters and represent the normal component of water velocity, measured according to Equation (3) and given in Figure 1.

$$v_n = v_w \cos\beta \tag{3}$$

Figure 1. Normal component of the water velocity and the real flow velocity in the measuring section



Between velocity measured by means of a current meter and the local velocity vector we have the following calculation relation:

$$v = k_m\, v_w \cos\alpha \tag{4}$$

Inserting equation (4) into equation (3) we will get the equation of the normal component of water velocity:

$$v_n = v \frac{1}{k_m} \frac{\cos\beta}{\cos\alpha} \tag{5}$$

The equation for calculating the normal component of the local water velocity $v_n(i,j)$ for a current meter located on the horizontal i and vertical j is given by the following equation:

$$v_n(i,j) = (a(i,j) \cdot n(i,j) + b(i,j)) \cos\beta(i,j) \;/\; k_m \cdot \cos\alpha(i,j) \tag{6}$$

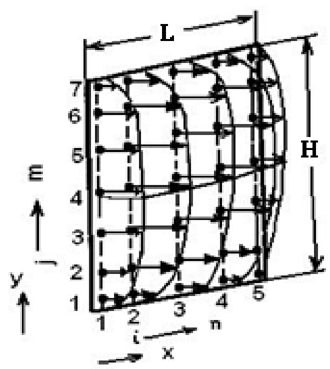
where: $\beta(i)$ is the flow angle, the angle between the local velocity vector and the perpendicular to the measuring section;

$\alpha(j)$ the angle between the local velocity vector and the axis of the current meter;

$\gamma(i)$ the angle between the axis of the current meter and perpendicular to the measuring section; a

k_m is a correction coefficient for the current meter type and is experimentally determined in the laboratory.

Figure 2. Determination of discharge through a rectangular section



Discharge through a rectangular or trapezoidal section for an elementary area d*x*·d*y* can be written in the form equation:

$$dQ = v\,(x,y)\,dx\,dy \tag{7}$$

And for the entire measuring area the discharge is calculated using the following Equation:

$$Q = \sum_i v_i \Delta x_i \Delta y_i \tag{8}$$

Written in integral form (Adamkowski 2009), the flow calculation formula for the entire measurement area is:

$$Q = \iint_S v(x, y)\,dx\,dy \tag{9}$$

Also Equation (7) can be written in the form of a simple integral so:

$$Q = \int_0^x dx \int_0^y v\,dy \qquad \text{or} \qquad Q = \int_0^y dy \int_0^x v\,dx \tag{10}$$

Calculation of the integral (8) can be done by means of a cubic or spline cubic interpolation function, with Lagrange interpolating polynomials or by means of Simpson's rule.

For to draw the velocity distribution in the border area must be considered that the water velocity from the walls to the first current meter can be expressed by means of Kármán law:

$$v_x = v_a \left(\frac{x}{a}\right)^{1/n} \tag{11}$$

where v_x is the velocity in the extrapolation area at x distance against the wall of the section;

v_a is the velocity in the measurement point a, the closest to the section wall;

n is a coefficient that takes into consideration the roughness of the wall and the flow conditions when there are no special contraindications it is $n = 7$.

Calculation of the average speed through Simpson's rule

Simpson's rule consist in dividing the interval in a number of steps h of integration (10 ÷ 20), establishing the velocity in the division points and calculating the integral from formula (10) by means of the equation:

$$I \approx h/3(v_0 + 4v_1 + 2v_2 + 4v_3 + \ldots + 2v_{2i} + 4\,v_{2i+1} + v_n) \tag{12}$$

The first time is determined integral $\int_0^y v\,dy$ means of the relationship (12), then average velocity on the vertical v_{mv} is calculated as follows:

$$v_{mv} = I / H \tag{13}$$

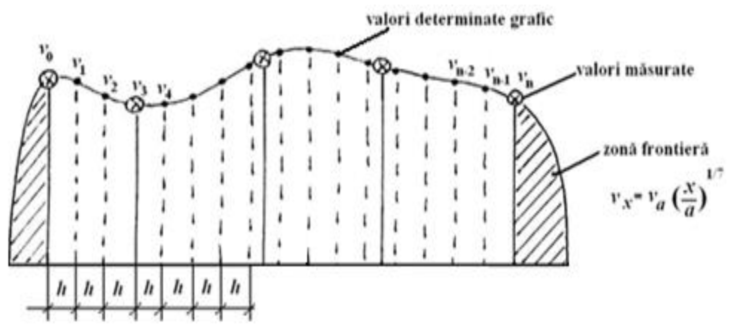
where: H is the height of the measurement section.

After calculating the average speeds on the measurement verticals the graph of the speed distribution on the horizontal is drawn, and average velocity for the entire measurement section v_m is:

$$v_m = \frac{1}{L}\int_0^L v_{mv}\,dx \tag{14}$$

where: L is the width of the measurement section.

Figure 3. Determining the average velocity by graph-analytical integration using Simpson's rule



The determination of the average velocity and of the discharge, implicitly, by means of Simpson's rule can be carried out both graphically (Figure 3) and numerically, through the development of a computation program.

Determining the discharge at HPP Fughiu

For the application of the current meter method, the low-head hydropower plant HPP Fughiu (Figure 4) was chosen (ICEMENERG 2019).

HPP Fughiu is a low-head hydroelectric plant located on the river Crişul Repede. It consists of two Kaplan turbines of 5 MW each.

The characteristics of the hydro aggregates that equip HPP Fughiu are the following:
Hydropower characteristics
- installed discharge Q_i = 90 mc/s
- installed power P_i = 10 MW
- maximum gross head of the plant: 15 m
- electricity production: 20.6 GWh / average year
- PIF year: 2007

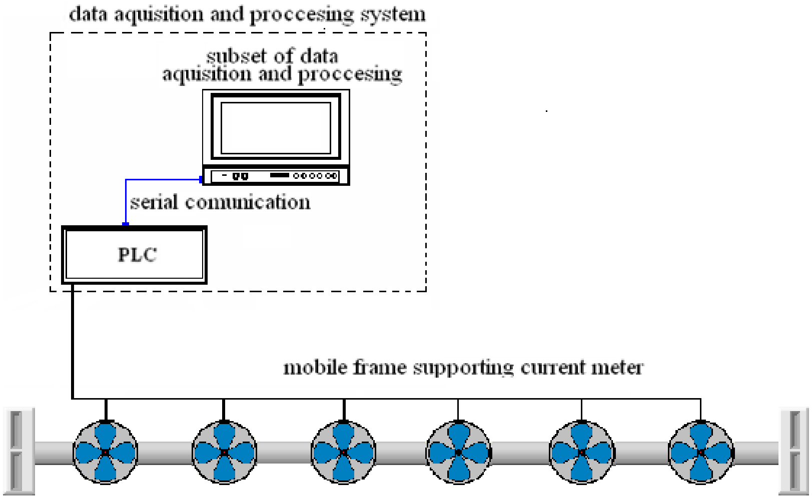
Turbine characteristics
- type turbine KVB 5.9-14.7
- net head Hmax. = 14.7 m
- nominal speed n = 166.7 rpm
- maximum packaging speed na = 315 rpm
- nominal discharge Qn = 45 mc/s (per group)
- torque power = 5830 kW
- rotor diameter = 3000 mm
- no. director wicket gate = 24

Figure 4. Image of Fughiu HPP

The mobile measurement system used to determine the turbine discharge and to calibrate the differential pressure taps on the spiral chamber of the hydraulic turbines in the low-head hydropower plants is shown schematically in figure 5 and is described below:

- Mobile frame support current meter;
- OTT type current meters;
- Data acquisition interface, PLC;
- Portable PC, laptop.

Figure 5. The mobile system used for the determination of the turbine discharge



III. RESULTS AND DISCUSSIONS

For determine the actual characteristics of the operation of the turbines at HPP Fughiu, respectively of the turbine flow rate. the current meter method was used, and the measuring section was the stop logs upstream of the turbine from the hydropower plants hydro aggregate HA1 from Fughiu. Gross head and power at the hydro-generator terminals were kept constant throughout tests.

Figure 6. Measuring section of the discharge - stop logs upstream of the turbine from the hydro aggregate HA1 from HPP Fughiu.

Tests were performed for a 3,2 MW power to the hydro generator from the hydro aggregate HA1 and a net head of 14.4 m.

After the discharge measurements in the stop logs upstream of the hydro aggregate HA1, the following average velocities and discharges were obtained:

- for the left stop logs an average velocity v_{m1} = 0.686 [m/s] and an average discharge Q_{m1} = 12.61 [m^3/s];
- for the right stop logs an average velocity v_{m2} = 0.624 [m/s] and an average discharge Q_{m2} = 11.47 [$m^{3/}$s];
- for HA1 an average velocity v_m = 0.655 [m/s] and an discharge Q_m = 24.08 [m^3/s].

Table 1. Velocities measured at right stop logs from HA1

Vert. no / horiz. no	1	2	3	4	5	6	7	Y[m]
1	0.401	0.404	0.371	0.402	0.420	0.470	0.425	0.40
2	0.946	0.963	0.879	0.949	0.982	1.115	1.006	0.50
3	0.924	0.941	0.860	0.932	0.949	1.077	0.973	0.50
4	0.942	0.958	0.872	0.945	0.967	1.111	0.999	0.50
5	0.804	0.814	0.743	0.806	0.829	0.870	0.794	0.50
6	0.808	0.801	0.726	0.733	0.664	0.630	0.571	0.50
7	0.795	0.805	0.724	0.694	0.679	0.468	0.420	0.50
8	0.720	0.733	0.671	0.683	0.585	0.267	0.240	0.50
9	0.670	0.693	0.637	0.627	0.563	0.257	0.230	0.50
10	0.514	0.586	0.561	0.534	0.474	0.273	0.235	0.50

X [m]	0.25	0.50	0.50	0.50	0.50	0.50	0.50	0.25

Table 2. Velocities measured at left stop logs from HA1

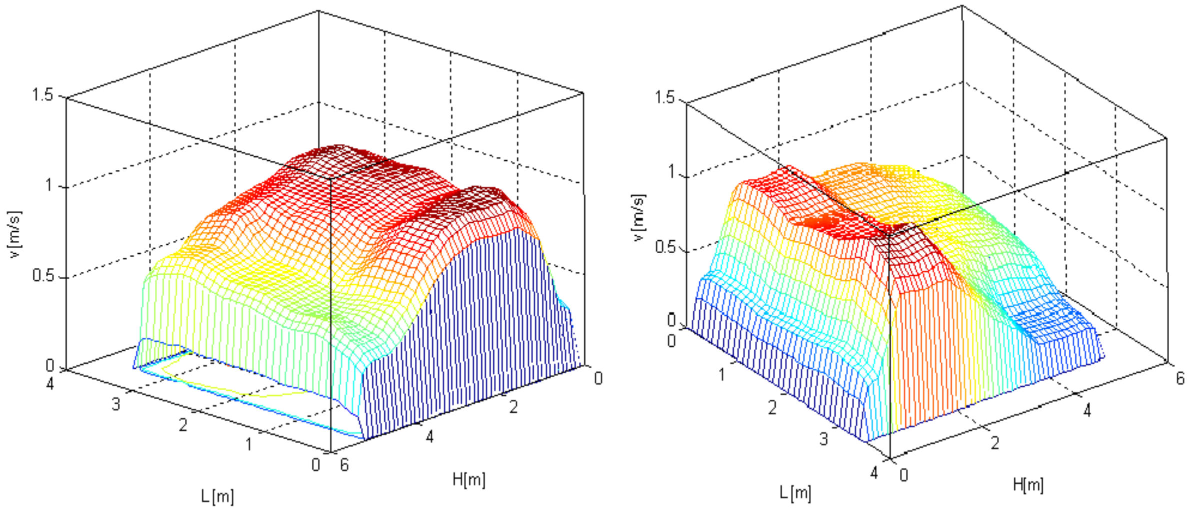
Vert. no / horiz. no	1	2	3	4	5	6	7	Y[m]
1	0.412	0.429	0.419	0.450	0.455	0.499	0.451	0.40
2	0.860	0.969	0.884	0.955	0.934	0.950	0.868	0.50
3	0.984	1.018	0.892	0.968	0.973	1.020	0.927	0.50
4	0.978	0.997	0.887	0.958	0.964	1.007	0.918	0.50
5	0.996	0.965	0.846	0.912	0.915	0.940	0.855	0.50
6	0.942	0.948	0.817	0.886	0.884	0.906	0.829	0.50
7	0.820	0.827	0.674	0.784	0.816	0.881	0.794	0.50
8	0.621	0.605	0.568	0.622	0.647	0.841	0.762	0.50
9	0.468	0.521	0.546	0.609	0.619	0.704	0.637	0.50
10	0.452	0.555	0.536	0.594	0.604	0.672	0.611	0.50

X [m]	0.25	0.50	0.50	0.50	0.50	0.50	0.50	0.25

Where X is the distance between the current meter, and Y is the vertical distance between the measurement points

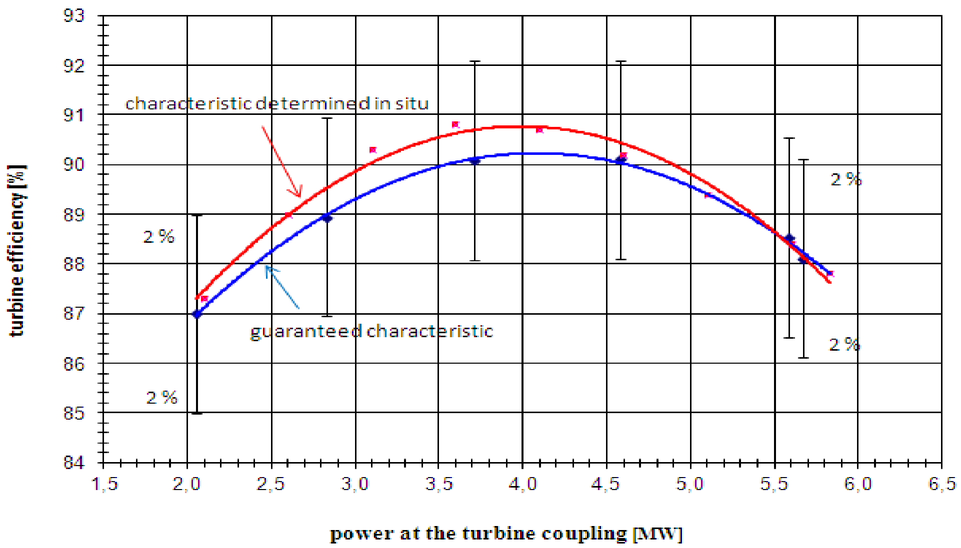
Next, we present the evolution of the spectrum of the volume of velocities in the measurement section of the stop logs upstream from HA1

Figure 7. Velocities distribution in the left stop logs and in the right stop logs from the hydro aggregate HA1



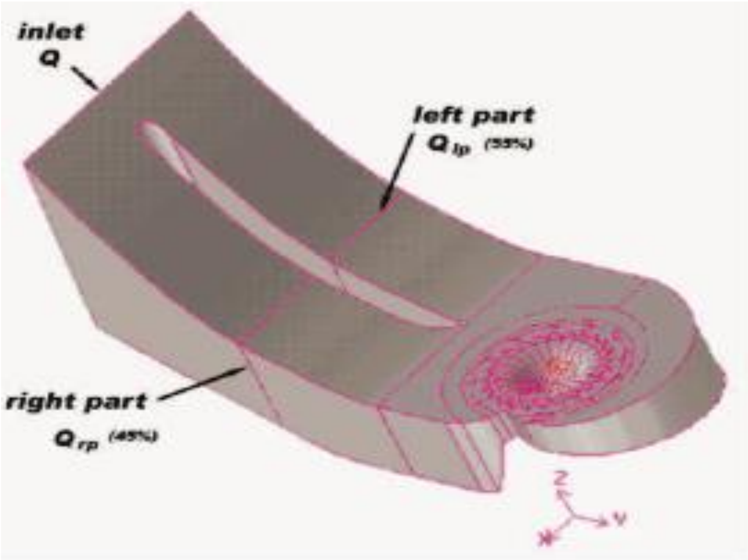
Following the in situ tests, the actual performance characteristics of the HA1 hydropower plant from HPP Fughiu were determined (Figure 8).

Figure 8. Graphic representation of efficiency characteristic determined in situ and guaranteed characteristic for HA1 from HPP Fughiu



After analyzing the results of the discharge measurements performed by means of the mobile frame in the hydropower plant intake stop logs, there has resulted that the discharge in the left stop log is greater than the discharge in the right stop log, which confirms the assumption presented by Muntean et Resiga (2006) according to which the discharge in the left stop log is about 55 % of the total discharge, while the discharge in the right stop log is about 45 % of the total discharge.

Figure 9. Discharge distribution in the measuring section between the two intake stop logs



The optimal operation of a hydropower plant (respectively its functioning in the optimal area) is equivalent to an increase of energy or the existence of (theoretical) facilities that would have an additional electricity production of at least 2%.

The location of the mobile system to determination in situ of the discharge to low head hydropower is intake entrance in stop logs upstream of the hydraulic turbine (Figure 10).

Figure 10. Section for determination discharge to low head hydropower plants

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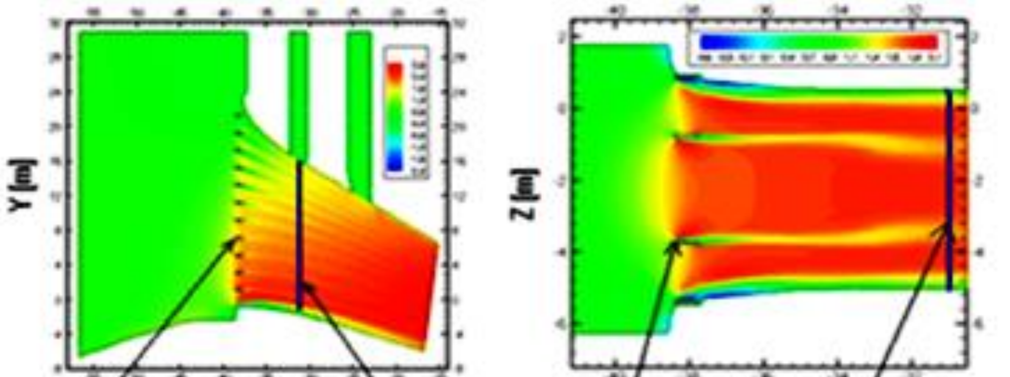

IV. CONCLUSION

By carried out turbine flow measurements with by means of a mobile frame it was allowed the modification of the angle between the axis of the current meter and the local velocity vector so that this angle be as close to 0 as possible and cos $\alpha = 1$, thus reducing the calculation error introduced by the α angle.

The hypothesis according to which the discharge in the left stop log is 55% of the total discharge and the discharge in the right stop log is 45% of the total discharge should be verified through should be verified through several in situ tests carried out at and other hydropower plants, and, in case it proves to be correct, a simplified methodology measuring only the discharge in the left bay, following that the discharge in the right bay be determined on the basis of these measurements, should be developed. This would diminish the time necessary for carrying out the measurements, as well as the cost price of the method which would make the this method more attractive from the economic point of view.

Figure 8 points out that the efficiency curve obtained by means of the discharge measured using the mobile frame are within the uncertainty range of ± 2 % from the code CEI 41 /1991.

A general conclusion of this paper is that the simplification and improvement of the discharge measurement methodology using the current meter is feasible. The solutions proposed in this paper are viable and perfectly applicable in the usual practice, resulting in the simplification the methodology for in situ discharge determination and lower its cost price.

Conflict of interest
There is no conflict to disclose.

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