ORIGINAL PAPER

EXPERIMENTAL RESEARCH ON A KINETIC HYDRO TURBINE - GENERATOR ASSEMBLY

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Abstract. *The present paper is part of a larger project whose purpose is to develop a new hydrokinetic turbine-generator assembly, suitable for very low head water courses. It presents the experimental results of a turbine–generator physical model, installed on the tailrace of Mihailesti Hydropower Plant. In order to carry out the measurements, a floating structure and an anchoring system was installed on the power plant tailrace. This system also allowed the translation of the assembly between the two shores. A first set of measurements followed the water velocity and depth in the channel at various load values of the hydropower plant units, in order to determine the proper conditions for testing the model. The turbine gives the possibility of blades adjustment at three different angles, 0, 9 and 14 degrees respectively. Therefore, a set of measurements has been performed for each position of the blades. The measured parameters were the electric parameters of the generator such as voltage, current and the power variation with rotation speed. For the blades adjustment of 9 degrees and 1.76 m/s water velocity, the generator reached its maximum power of 500 W. The results retrieved will be used for the optimization and design of a new enlarged scale turbine–generator assembly. They will also be used as input data for the numerical modeling of the generator. Also, the exact knowledge of the channel geometry and flow parameters is valuable in studies preceding testing a prototype in the site.*

Keywords: *hydrokinetic turbine; electric generator; in situ testing.*

1. INTRODUCTION

In the context of mitigating climate change and reducing the carbon footprint, energy production is more and more moving towards renewable technologies. In the last decade, the capacity installed worldwide in renewable energy sources increased from 1329 GW in 2011 [1] to 3068 GW in 2021 [2], reaching a share of 38.3% of the total production capacity [3]. Hydropower represents the largest contributor to this renewable capacity with over 1360 GW installed globally in 2021, reaching around 17% of the worldwide installed capacity [2]. One of the reasons for this growth is the interest in utility-scale renewable energy for converting solar, wind, and hydro potential [4]. In hydropower, besides the large-scale developments, there is a continuous interest in harnessing the small potential in water currents and waves [4]. This can be achieved by using low-head conversion technologies such as hydrokinetic turbines. River kinetic energy is showing its strong potential as an alternative energy supply

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due to its superiority over other renewable energy resources such as predictability and reliability. The river kinetic energy can be turned into electrical energy when a hydrokinetic turbine is placed on the river flow. For this kind of turbine, the installation cost is minimum because do not need the head provided by dams to operate, thus the course of a river remains in its natural state.

The availability of adequate research in the field supports and encourages the development of hydrokinetic projects in the near future. Niebuhr et. al [4] review this type of turbine, classifying them by their characteristics and constructive parameters, and point out their availability on the market. They present the development of a hydrokinetic project from the design to the operation phase, including the economic analysis such a project involves [4]. In the papers [5-8] aspects regarding the increase in the performance of axial kinetic turbines are treated. These represent a small part of the available research in the field of hydrokinetic turbines. In [9] characterization of a reduced scale of hydro turbine model is presented. [10] investigates the flow characteristics for two hydrokinetic turbine shrouds with different hydrofoil type cross-sections, and the same reference diameters.

In Romania, hydropower is the largest contributor to the power system in terms of installed capacity with over 6600 MW installed from a total of over 18300 MW at the level of 2022, hence, a share of 36.3% [11, 12]. Nastase et al. [11] describe the hydropower development in Romania from its beginning in 1884 until 2015. The international context regarding renewable energy sources influences the trends in Romania as well, however, the development of water energy conversion is still in the progress.

ICPE-CA started developing hydrokinetic turbine prototypes since 2003 and the results obtained contribute to a better knowledge of the subject addressed and implicitly of the specific elements of kinetic turbines that influence the conversion yields from hydraulic energy to electrical energy [13, 14]. In order to implement them in small rivers or water channels with a low investment cost, the prototype testing in real conditions is necessary.

This paper presents the design, construction, and experimental data of a real-scale hydrokinetic turbine suitable for water streams. The first step in this project was selecting the location of the experiment, which turned out to be the tailrace of Mihailesti Hydro-Power Plant (HPP), the last development on Arges River in Romania. A series of measurements in the tailrace were performed at first in order to determine parameters such as water depth and water velocity in the tailrace channel, followed by the design, construction and tests of the prototype assembly. The results obtained are promising and represent a milestone in harnessing the hydrokinetic potential in this country.

2. DEPLOYMENT OF THE FLOATING STRUCTURE

A site visit was performed at Mihailesti Hydropower Plant in order to determine the position in the tailrace channel suitable for installing the prototype assembly. During this visit, with respect to the ease of access, lack of trees on the shores and far enough distance from the HPP in order to avoid high turbulence flow, the optimal installation point turned to be 90 m downstream the HPP.

One of the challenges this project involved was the method for the model installation in site. Aiming for minimum alteration of the tailrace channel geometry and structure and also avoiding restrictions in the HPP operation outside the tests schedule, the solution adopted was to install the hydrokinetic assembly on a floating structure anchored by the channel edges. This configuration offered the possibility to translate the assembly between the shores and the possibility to adjust the immersion of the turbine from the water surface.

The anchoring system involved a cable laid in the testing section of the channel and two other cables to drag the assembly from the shores. In this regard, four metallic plates were designed and manufactured with the purpose of fixing the cables on the concrete lining of the channel. Fig. 1 presents the anchoring system, while the site configuration for performing the experimental tests is presented in Fig. 2.

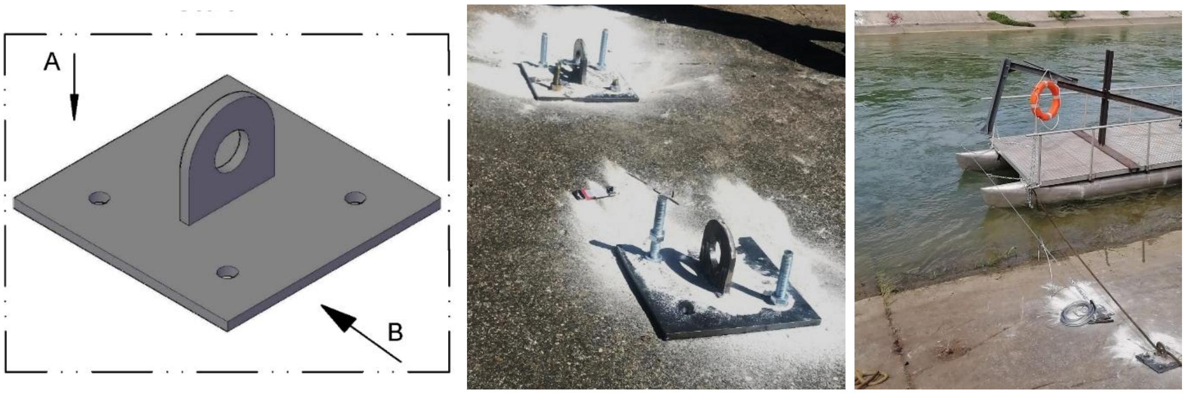

Figure 1. The anchoring system.

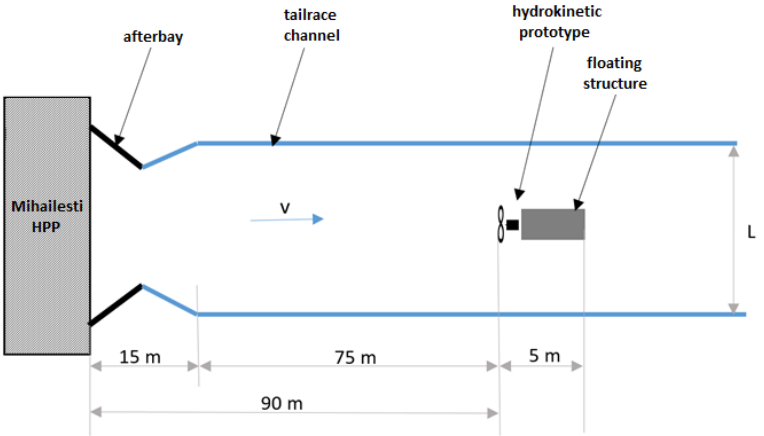

Figure 2. Experimental testing site configuration.

Since experiments would require several adjustments to the prototype model such as changing the tilting angle of the turbines' blades or the immersion depth, the system between the prototype and its floating support structure had to be designed in such manner. Therefore, the solution adopted was a joint-type assembly (Fig. 3), which gave the possibility of fast immersion/extraction of the prototype. The operation of this system was ensured by two project members assigned permanently on the raft during the measurements.

Figure 3. Hydrokinetic prototype – support floating structure.

3. MEASUREMENT OF OPERATIONAL CONDITIONS IN THE TAILRACE CHANNEL

Different water velocities needed for the turbine testing (Fig. 4) were achieved by modifying the water flow rate of the two Kaplan units from HPP Mihailesti, which changes the power output from 2 MW to 6 MW.

Measurements of the water velocity were done with SonTek FlowTracker, a 10 MHz acoustic Doppler effect velocimeter (ADV) for in situ measurements. The SonTek FlowTracker can measure 3D velocities at 100 mm in front of the probe in a cylindrical sampling volume of 60 mm diameter and 90 mm height, with 0.00001 m/s resolution and accuracy of 1% of the measured value (Fig. 5).

Figure 4. Submerging the turbine in the channal.

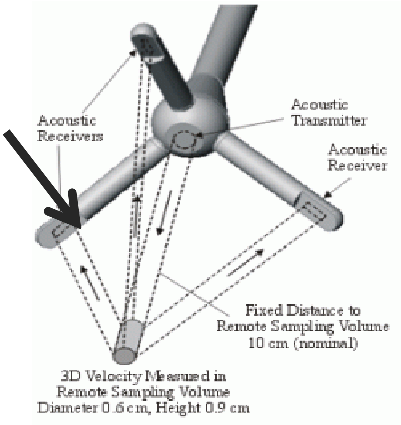

Figure 5. Probe for 3D measurement of velocity using ultrasounds [15].

Assessment of the water velocity was done by two methods. First, before the placement of the turbine, water velocity was sampled at 0.2 m, 0.5 m, 0.7 m, and 1 m relative to the water surface, which fits in 20 % ÷ 40 % of the channel depth. Velocity measurements were done for each operating conditions of the HPP (3, 4, 5, and 6 MW) to be used during turbine tests. As such, depending on the HPP discharge, water velocities were in the range of 1 to 1.8 m/s.

Second, while the turbine under test was running, water velocity measurements were done with the ADV probe placed on starboard of the platform, at same depth as the turbine hub of 0.75 m from water surface (Fig. 6).

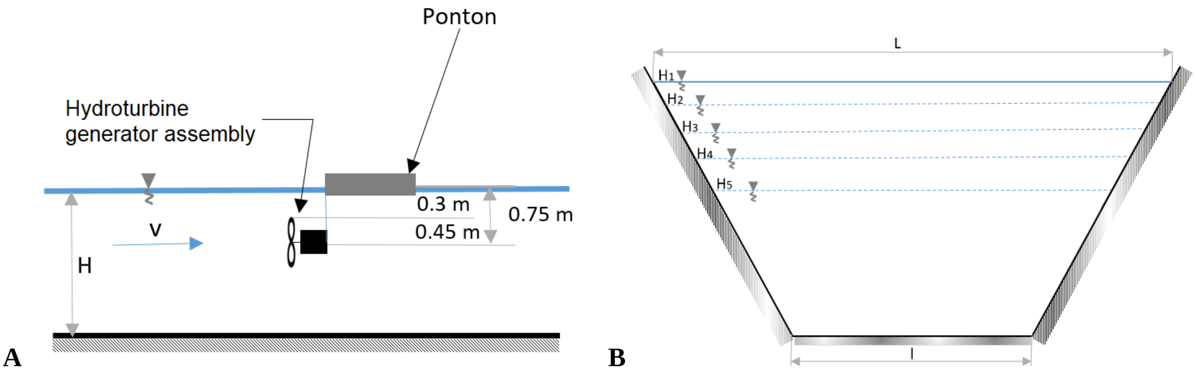

Figure 6. A) Placement of floating structure and assembly under test; B) Channel geometry.

Simultaneously with the velocity measurements, water level measurements in the channel were also carried out. Table 1 shows the velocity components (*V*x and *V*y [m/s]), the resultant of the water velocity (*V* [m/s]), the elevation of the water in the channel (*H* [m]) and the width of the channel at the free surface of the water (*L* [m]), *l* = 12.5 m – the width of the channel at the base (Fig. 6.B).

Table 1. Measurements of water velocity and channel geometry

HPP output [MW]	Water velocity			Water depth, *H* [m]	Width at surface, *L* [m]
	*V*x [m/s]	*V*y [m/s]	*V* [m/s]		
2	1.03	0.19	1.05	1.60	22.1
3	1.26	0.28	1.29	1.75	23.0
4	1.58	0.27	1.60	2.00	24.5
5	1.62	-0.15	1.63	2.15	25.4
6	1.79	-0.40	1.83	2.25	26.0

4. PERFORMANCE ASSESSMENT OF THE EXPERIMENTAL MODEL

The tested turbine was a hydrokinetic axial turbine with four blades and a diameter of 0.9 m. The blade angle can be adjusted for experimental purposes and it was set to 0°, 9° and 14°. The submersible electric generator was a sealed type, designed for direct drive. The sealing was achieved by using a closed housing with internal bearings and sealing rings bushing for the drive shaft. The armature, which has a three-phased wounding, is the stator and the inductor with permanent magnets is the rotor. This electric generator can provide usable power from 100 to 1000 W.

Measurements aimed to obtain the power versus rotational speed characteristics of the hydro turbine – electrical machine assembly at different conditions. The schematics of the measurement setup are presented in Figure 7. A power analyzer, Fluke 434, was used to acquire parameters of the three-phased output of the electrical generator: effective values for currents and voltages, active power, reactive power, power factor.

The frequency was measured with Fluke 1587 and used to determine the rotational speed of the electrical machine using equation (1)

$$n = \frac{60\,f}{p}, \tag{1}$$

where n – rotational speed in rpm, *f* – frequency, $p = 8$ – number of magnetic pole pairs.

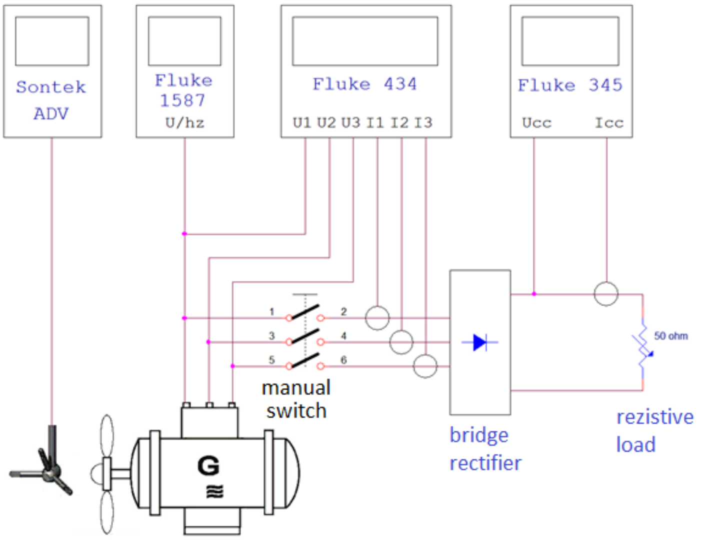

Figure. 7. Sketch of the measurement setup.

The electrical machine was loaded with a set of variable rheostats, connected behind a bridge rectifier to eliminate potential issues with unbalanced three-phase loads. Measurements of DC current and voltage was done using Fluke 345.

5. RESULTS AND DISCUSSION

The power coefficient (*Cp*) and the tip speed ratio (λ) were computed using the acquired data and presented in Figures 8 to 10 as *Cp* = f(λ) curves. These experimentally determined characteristics generally describe the performance of a horizontal axis turbine and are particularly important to estimate the power output in different operational conditions, as well as further optimizations. The power coefficient, *Cp*, is the ratio between the output power (measured) and available power of the fluid, and it is determined with the equation (2).

$$C_P = \frac{P_{meas}}{1/2\rho A v^3}, \tag{2}$$

where P_{meas} is the measured power, ρ is water density, A is the area exposed to flow, and *v* is the fluid velocity.

The tip speed ratio (λ) is the ratio between the liniar speed of the blade tip and the velocity of the fluid and relates to relative angle of attack of the blade. The tip speed ration was evaluated with the equation (3).

$$\lambda = \frac{1}{4}\frac{f\pi R}{v}, \tag{3}$$

where, *f* is the measured frequency, *R* is the radius of the turbine rotor, and *v* is the water velocity.

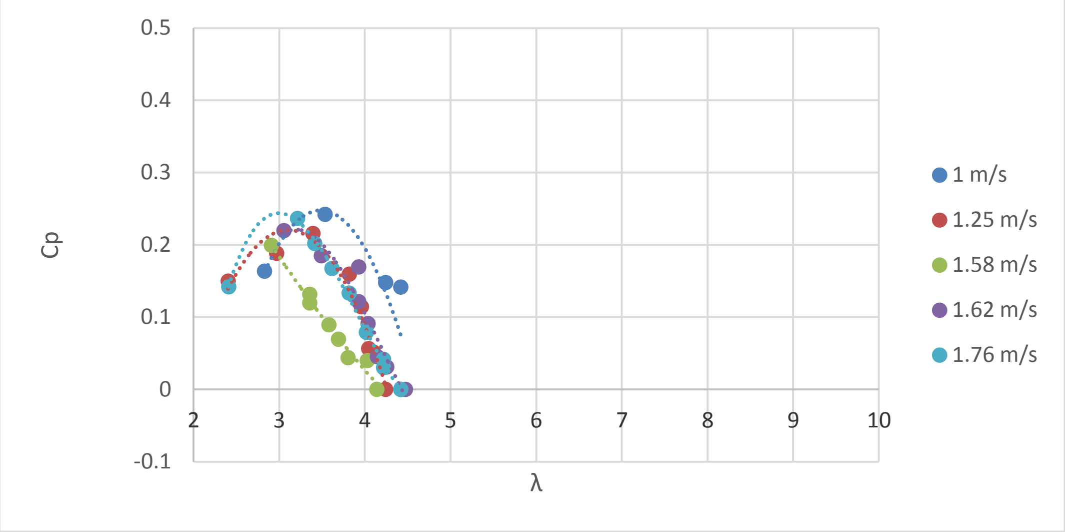

Figure 8. ***Cp* = f (λ) curve for blade angle of 0°.**

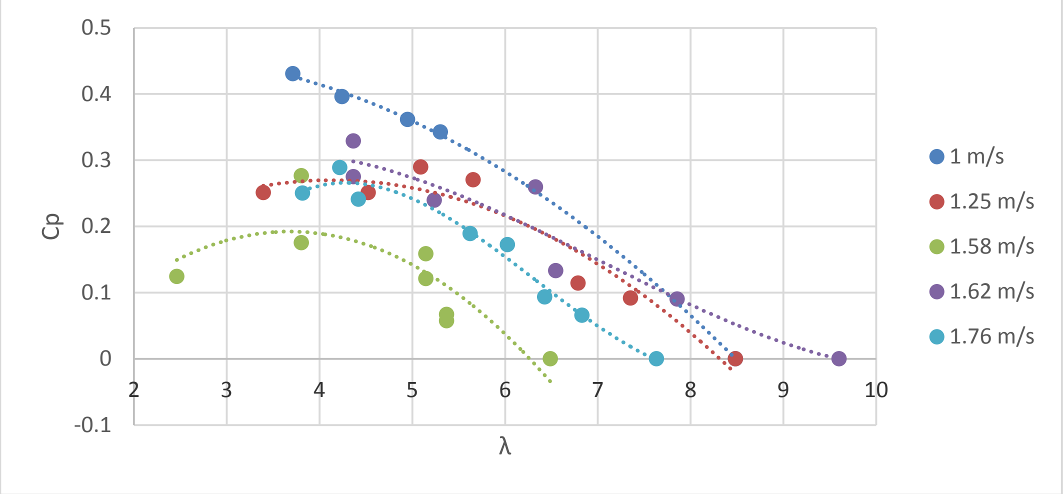

Figure 9. ***Cp* = f (λ) curve for blade angle of 9°.**

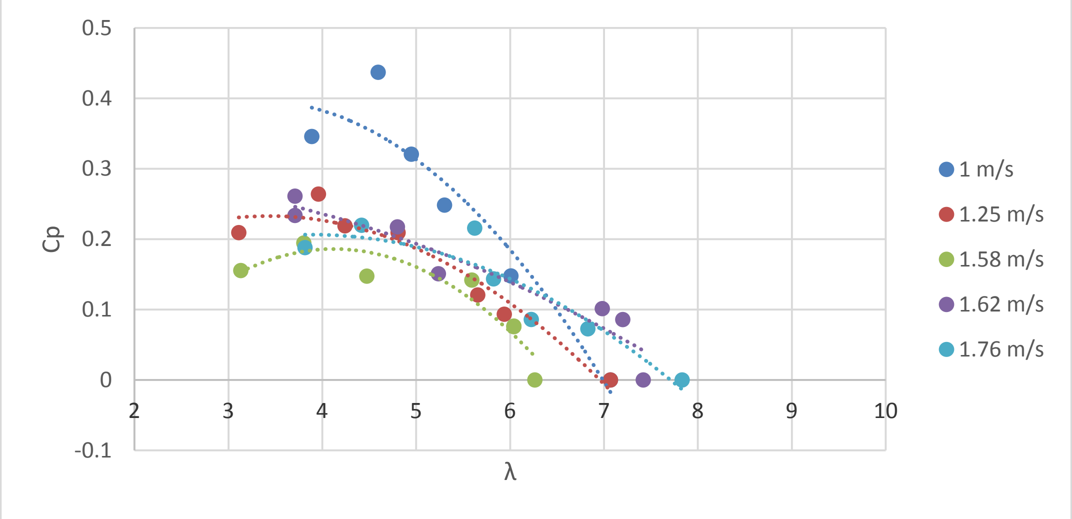

Figure 10. ***Cp* = f (λ) curve for blade angle of 14°.**

In situ measurements allowed the characterization of the hydrokinetic turbine – electric generator assembly. Combined with measurements of the electrical generator done on the test bench, these results will contribute to the design of a new assembly at large scale. Comparing the power curves at the three different angles it can be concluded that the optimal angle for blades is around 9°, where the maximum power is close to 500 W at 160 rpm, when water velocity was 1.76 m/s. The “joint-type” assembly between the floating structure and the prototype involved high effort in operation, thus, in the future for a larger scale model this system shall be improved.

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