New test rig for micro and mini hydraulic axial turbines in Uruguay

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Abstract. In Uruguay, the potential for small, mini and micro scale hydropower has not been exploited yet, being the high investment costs the main reason. In order to overcome this issue and enhance the development of mini and micro hydropower in the country, the Hydropower group of Universidad de la República (Uruguay) decided to demonstrate the technical and economic feasibility of designing and manufacturing a propeller turbine with national capacities. Furthermore, it was believed that the existence of a test rig for scale model turbine evaluation in the facilities of a public university would be of great relevance for the enhancement of micro hydropower in the country. The hydraulic, mechanical and electrical installations of the test rig are presented, together with the acquisition system. The limitations of the test rig, owed to the dimensions of the piping and the ranges of the instruments within the acquisition system, are stated. The test rig is complemented with a SLA 3D printer for rapid turbine prototyping. The installation will serve not only for evaluation of the designed turbine within the current project, but also for the evaluation of future designs, teaching and other research activities of the university.

1. Introduction
In Uruguay, the potential for large scale hydropower is already exhausted or inconvenient to be exploited. However, in contrast with several other countries, the potential for small (rated power between 1 MW and 50 MW), mini (rated power between 100 kW and 1000 kW) and micro (rated power lower than 100 kW) hydropower has not been exploited yet, being the high investment costs the main reason. In order to overcome this issue and enhance the development of mini and micro hydropower in the country, we developed a project to demonstrate the technical and economical feasibility of designing and manufacturing a low cost hydraulic turbine with national capacities. The unexploited potential for small hydropower in Uruguay was estimated in 230 MW distributed in 70 sites [1, 2]. Also, many sites with existing dams have been studied for micro hydropower generation [3], but there has been no development because of economical reasons.

It was believed that the existence of a test rig at the Institute of Fluid Mechanics and Environmental Engineering (IMFIA in Spanish) for performance evaluation of the specifically designed turbine within the current project [4] and later manufactured turbines would be of great relevance for the enhancement of micro hydropower in Uruguay. It is worth noting that although the international standard for model turbine tests [5] was used as a guide for erecting the test rig, some of the specifications were not met (as it is allowed for the case of mini and micro hydropower). The test rig differs from a typical universal test rig for hydraulic turbines, such as the ones of other universities and institutions like École Polytechnique Fédérale de Lausanne [6, 7], Haute École Spécialisée de Suisse...
Occidentale [8, 9], or Universidad Nacional de La Plata [10], because it was thought as an adaptation of an already existing hydraulic installation, rather than erecting a new one (in order to reduce time and costs).

Although the actual setting up of the test rig is only suitable for axial turbines in horizontal “S” configuration, such as the one that motivated its construction [4], with some modifications it could also be used to test turbines with inclined shaft or vertical shaft with spiral casing. Due to the range of flow rates and heads provided by the installation, radial turbines cannot be tested in this bench.

A description of the measuring procedure of every significant variable is presented, along with the hydraulic, mechanical and electrical characteristics of the installation. The test rig limitations, based on the piping dimensions and measuring range of the acquisition system, are stated.

2. Hydraulic installation
The existing installation consisted in an open loop circuit with an atmospheric pressure water reservoir, a submersible variable velocity pump, several fittings, valves and pipes with nominal diameters of 315 mm and 250 mm that ended at the entrance of a long sediment transport canal (item 1 in figure 1), after of which the water drained to the reservoir by gravity, closing the circuit. Most of the pipes were located roughly at 4 m height from the water reservoir free surface, presented as the first challenge for the adaptation. The feeding pipes for the turbines test rig were added to the existing pipes after the entrance to the canal, at the mentioned height. Fortunately, very close to this site there was a big and resistant platform at nearly 3 m height from the water reservoir free surface (used in the past as a street for the modeling of storm drain), which was used to lie down the pipes and the whole test rig (see figure 2).

![Figure 1. Isometric view of the test rig installation.](image-url)
The water flows through the installation by means of a submergible pump Flygt NP 3202 LT 3~610 (item 2 in figure 1), with rated power of 37 kW at rated speed of 970 rpm. The speed is controlled through a variable frequency drive Danfoss VLT Aqua Drive FC 200.

As mentioned, the test rig was installed as an extension of the existing installation, consisting in the inlet part in PVC pipes with nominal diameter of 250 mm. A change in direction of 90º (item 3 in figure 1) was made in order to accommodate the pipe direction over the platform. Immediately after the 90º bend, a gate valve (item 4 in figure 1) was installed to isolate the test rig when the water is intended to flow through the canal. This valve won’t be used to regulate the flow rate through the turbine as it would generate non-uniform conditions immediately upstream of the turbine. Instead, the speed variation of the feeding pump will be used with this purpose. Nevertheless, a long straight pipe (over 20 diameters length) was installed between the mentioned valve and the beginning of the test rig to allow the uniformization of the flow (item 5 in figure 1).

Even though it has not been constructed yet, a honeycomb is being designed to reduce the flow turbulence and eliminate the tangential flow in the inlet pipe to ensure a uniform flow entering the turbine. As it can be seen, the test rig doesn’t have a high head tank, so the stability of the flow rate must be checked prior to the tests.

The actual turbine being tested [3] is an axial horizontal turbine in “S” configuration. Firstly, the “S” part (item 6 in figure 1) was constructed in one piece with an inspection window made of acrylic immediately downstream both elbows, where the rotor and stator would be installed, in order to visualize the flow and cavitation phenomenon. After some trials, it was determined that this piece was not acceptable because of its too pronounced curves that would affect the hydraulic performance of the turbine. Then, it was re-designed divided in four parts. First, a 45º elbow made of stainless steel, followed by a short straight acrylic tube, then another 45º elbow made of stainless steel and finally another short straight acrylic tube where the stator and rotor would be fitted. The visualization of the hydraulic performance of the turbine as well as the cavitation phenomenon was significantly improved.

After the “S” piece, a short straight pipe was attached in order to install a pressure measurement section immediately downstream of the rotor. As the velocity most likely present non-negligible tangential component, it was installed a way to measure it. A special type of pitot tube was installed immediately downstream of the pressure measurement section that allows to know the direction of the flow. In fact, assuming that there is no radial velocity and the axial mean velocity is the one measured with the flowmeter, the tangential velocity could be known. Actually this piece was installed only thinking in the functionality of the test rig, but it is not necessary in the prototype hydraulic installation.
After this short straight pipe, a transition piece working as a draft tube was installed (item 7 in figure 1). The transition piece, which was designed as a scale model of the draft tube to be installed in the prototype turbine, has a circular inlet section of the same diameter of the “S” piece (235 mm) and a rectangular outlet section of 300 mm x 400 mm, presenting an area ratio of 2.8. The prototype of the draft tube was designed through empiric methods [11].

The outlet section of the draft tube was connected to a free surface tank (item 8 in figure 1) that simulates the submergence presented in the prototype. The water leaves the tank to the drain by means of a guillotine type gate, which was designed so that it can be smoothly regulated during operation to model different submerges of the turbine (figure 3).

![Figure 3. Image of the discharge tank with its guillotine gate and piezometric tube.](image)

### 3. Turbine mechanical installation

#### 3.1. The “S” piece

Since the power of the scale model of the current turbine being tested is very low (around 500 W), the minimization of friction losses was the main objective in the mechanical installation of the turbine in the test rig, in order to have a good accuracy in the measurement of mechanical power. Therefore, the use of mechanical seal was avoided. The solution was to place the shaft along an axially fitted pipe contained by the second 45° elbow of the “S” piece, to facilitate the exit of the shaft. This smaller pipe extends from inside the stator hub, where the interior bearing is placed, to the exit of the “S” piece where a housing for the exterior bearing was installed. The interior of the stator hub was designed with a labyrinth to minimize volumetric losses.

While the inner bearing supports only radial loads, the outer bearing also supports axial loads, as it butts up against the “S” piece.

The curved parts (45° elbows) of the piece are made of stainless steel, while the straight section between them and the section where the turbine is mounted are made of acrylic pipes to enable an easy visualization of the flow.

#### 3.2. The shaft

As we were dealing with a test rig that is intended for testing several turbines, the easiness of mounting and dismounting was a big issue, especially in the design of the shaft.

In order to facilitate the installation of two bearings, it was necessary to design the shaft with five sections of different diameters, as it can be seen in figure 4. The left end with the smallest diameter is where the shaft connects with the rotor hub though a flange and a keyed joint, whereas the right end with the highest diameter is where the shaft connects with a torque transducer through flexible couplings.
The friction losses introduced by the bearings will be assessed by a no-load test of the generator at several rotating speeds.

![Figure 4](image_url)  
**Figure 4.** Representation of the shaft showing the different sections for bearing installation, with the dimensions in millimeters.

### 3.3. Rotor and shaft coupling and stator anchoring

A flange with a keyseat was designed so that the rotor is coupled to the flange and the flange is coupled to the shaft by a keyed joint. This coupling also acts as a power transmission between the rotor and the shaft.

For the same purpose of facilitating the mounting and dismounting of this and other turbines to be tested, an anchoring system for the stator was designed. The stator is not fixed to the shroud, but to the pipe used for housing the shaft, so a flange was designed with that purpose. Because of this design of the coupling system, it will be necessary for all the models to be tested in the test rig to have rotors and stators with especially designed hubs.

### 3.4. Special considerations and general assembly

The longitudinal gap between the rotor hub and stator hub was settled as 2 mm. This value was chosen as a midpoint between having the smallest gap in order to avoid flow perturbations previous to the rotor entrance and the need for leaving a sufficient gap in order to avoid the contact between a rotating and a stationary part.

A general assembly of the rotor and stator hub is presented in figure 5 and images of the turbine mounted inside the “S” piece are shown in figure 6.

![Figure 5](image_url)  
**Figure 5.** General assembly of rotor, stator and shaft.
4. Electrical installation
The turbine in the test rig could operate in two modes: with the generator connected to the electric network of the lab; or with the generator working off-grid. An induction motor working as generator with 8 poles and rated power of 746 W is used in either case. This machine was selected for the specific turbine being tested to avoid transmission belts or a frequency drive, but could be changed for another of similar size if it is required by another turbine. Also, in the future, it is expected to complement the electrical installation with a variable frequency drive for the generator. With this improvement, model turbines that generate higher powers could be tested (with its corresponding generator).

In the network connected mode, the voltage and the frequency of the generator are settled in almost constant values by the network itself, so there is no need for auxiliary equipment. The power generated by the induction motor is supplied to the network of the lab and used within it.

On the other hand, in the off-grid mode, not only it is relevant to maintain the voltage and frequency in nearly constant values (and this must be done by auxiliary equipment), but also to get the necessary excitation for the induction motor to work properly. These functions are accomplished by a bank of capacitors with a well calculated fixed capacitance, or with better results by a variable capacitance in order to accommodate the generator work under different loads [12]. The power generated by the induction motor needs to be dissipated through a bank of resistances. Because of the low power ratings, the resistances could work in air, but in case of higher power ratings a bank of resistance in water could be installed.

5. Measuring instruments

5.1. Flow measurement
The flow rate through the test rig is measured with a non-intrusive ultrasonic flowmeter GE TransPort PT878, with a range of 12 m/s and accuracy of ± 1-2 % of reading. The flowmeter is attached to the external pipe walls in the straight section between the gate valve and the “S” piece. As it is a portable flowmeter, it can be calibrated before and after the tests in a separated calibration bench.

5.2. Pressure measurement
A collector ring was installed for averaging the pressure at the inlet section of the turbine (upstream the “S” piece). The pressure in the outlet section of the turbine is averaged by means of another collector ring located at the end of the diffuser prior to the discharge into the tank. All the pressure taps were performed, symmetrically disposed around the perimeter of the measuring sections, according to [3]. Pressure drop across the turbine can be assessed with the use of one of two available
differential pressure transducer Omega with ranges of +/-70 mbar and +/-170 mbar and accuracy of 0.08% BSL (best straight line), connected to each of the mentioned collector rings.

The submergence of the turbine is measured through the level of the water inside a vertical pipe connected to the discharge tank (to eliminate free surface pulsations), with an ultrasonic level transmitter Nivelco Easy TREK SPA-5A0-4 with a range of 0.15m – 3m and accuracy of 0.2% measure + 0.05% FS.

Another pressure collector ring was installed immediately upstream the inlet section of the draft tube, to measure the head loss through it.

In any case, the location of the differential pressure transducers is of no importance, as the pressure differential will not change as a result of the location of the instruments. However, they will be located between the sections considered, at a height lower than the top of the pipes to prevent air from disturbing the measurements (there are also air purges located at the top of the collector rings).

5.3. Torque and rotating speed measurement
Both magnitudes are measured by a torque transducer Interface Force T25-20-F3A with a range of 20 Nm and accuracy of ± 0.1 % FS for torque measurement and a range of 20,000 rpm and same accuracy for rotating speed measurement. The torque meter is coupled between the shaft of the turbine and the shaft of the generator through flexible couplings.

5.4. Electrical magnitudes measurement
All the relevant electrical magnitudes involved in the tests are measured by a power analyzer Chauvin-Arnoux – AEMC 8333. The accuracy and range of this instrument for each of the relevant magnitudes are presented in table 1.

| Magnitude             | Accuracy                              | Range          |
|-----------------------|---------------------------------------|----------------|
| Voltage               | ± 0.5 % reading + 200 mV              | 2-1000 V       |
| Intensity             | ± 0.5 % reading + 2 mA                | 1-1300 A       |
| Power                 | ± 1.5 % reading                       |                 |
| Power factor          | ± 1º                                  | 0-1            |
| Reactive and active energy | ± 1 % reading                  |                 |
| Frequency             | ± 0.01 Hz                             | 40-69 Hz       |

All electrical measurements will be taken at the main board of the test rig, as this involves using current and voltage clamps. Distances from the generator to the measuring board are negligible so no correction for electrical losses is necessary.

6. Test rig limitations
As a consequence of several intrinsic limitations of the already existing installation, some of the new equipment and the ranges of some of the measurement apparatus, the test rig came out with a set of limitation values or working ranges, which are summarized in table 2. Some of them could be easily modified, such as the maximum electrical power that could be increased by installing a generator with higher power rating, or the maximum torque that is dependent on the range of the torque transducer. Actually, the maximum power of a tested turbine could be around 8 kW, which is imposed by the maximum flow rate (130 l/s), the maximum head corresponding to that flow rate (around 10 m) and an efficiency of 60%.
Table 2. Range of utilization of the test rig.

| Magnitude       | Unit     | Upper limit |
|-----------------|----------|-------------|
| Flow rate       | [l/s]    | 130         |
| Net head        | [m]      | 22          |
| Model diameter  | [mm]     | 235         |
| Electrical power| [HP]     | 1           |
| Torque          | [Nm]     | 20          |

7. Scale model manufacturing

A stereo lithography (SLA) 3D LCD printer LC Magna was incorporated to the laboratory (figure 7), as a complement of the test rig, for rapid prototyping of the different parts of the model turbines. The printer has the capacity to manufacture pieces as big as a prism of 510mm x 280mm x 350mm, made of tough resin (ABS-like).

Figure 7. 3D LCD printer incorporated to the lab’s equipment.

An example of rotor and stator that could be prototyped with this printer with all the specifications for allowing its installation in the test rig is presented in figure 8.
Figure 8. Images of a rotor and a stator made with tough resin in a SLA 3D printer.

8. Conclusions
With the aim of enhancing the exploitation of mini and micro hydropower in Uruguay, by encouraging the national industry to provide low cost turbines, a test rig for scale model performance evaluation of axial turbines was designed and installed, as an extension of an already existing hydraulic installation of the laboratory of IMFIA – Universidad de la República.

It is an open loop system with its main piping made of PVC with 230 mm diameter, suctioning the water by means of a submergible pump from an underground reservoir, to which is returned after discharging in a constant head tank. The test section is made of an acrylic tube to enable visual inspection. It is equipped with an acquisition system composed by a non-intrusive ultrasonic flowmeter, differential and absolute pressure transducers, an ultrasonic level transmitter, a torque transducer and a power analyzer.

The test rig will serve for obtaining the characteristics curves of the operation of the turbines such as the head-flow, power-flow and efficiency-flow, as well as for visual inspection of cavitation effects through the turbine. It will also allow to study and analyze different modes of operation of the generator, i.e. grid connected and stand alone. This new test rig will serve for teaching and research purpose as well.

This installation increases the heritage of Universidad de la República, and specifically that of the Institute and the research group on hydropower, increasing the capacities for developing research, teaching and services activities.

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