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ACQUISITION AND CONTROL SYSTEM OF THE PELTON TURBINE INSTALLED AT THE FLUID MECHANICS AND HYDRAULIC MACHINES LABORATORY AT AERONAUTICS INSTITUTE OF TECHNOLOGY

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Abstract. *Given the importance of the recent improvements made in the Laboratory of Fluid Mechanics and Hydraulic Machines of the Aeronautics Institute of Technology, this work was motivated to make one more of these improvements. Thus, an automatic data acquisition and control system was developed with application in the laboratory's Pelton turbine, using the commercial software LabView, from the National Instruments Company. The objective was to experimentally determine the performance curves of the machine under the condition of applying constant shaft force, for increasing flow rates. The curves obtained with the variations of manometric inlet pressure, rotation, shaft force, shaft power, hydraulic power, and efficiency as a function of the flow rate had the theoretically expected behavior, reaching the objective of this research. Possibilities for future work and improvements were identified in terms of changing the turbine's braking system, implementing control subroutines, and replicating the methodology to the other machines in the laboratory.*

Keywords: *data acquisition, control, Pelton turbine, turbine performance*

1. INTRODUCTION

In the following sections, a brief presentation of the Fluid Mechanics and Hydraulic Machines Laboratory (LMH) at the Aeronautics Institute of Technology (ITA) and its recent improvements is made, in order to contextualize and show this research work motivation. Then, the specific objectives are shown, followed by the theoretical background on the operation and performance calculation of Pelton turbines.

1.1 Fluid Mechanics and Hydraulic Machines Laboratory - ITA

The LMH at ITA is a laboratory designed to attend the Mechanical-Aeronautical Engineering (Discipline MMT-01 – Flux Machines) (Tomita *et al*., 2013), Aerospace Engineering (Discipline PRP-41 – Liquid Propellant Rocket Engine) (Whitacker *et al*., 2017), and Civil-Aeronautical Engineering (fluid mechanics and hydraulic experiments) undergraduate courses. There are four different turbines, Pelton (Figure 5), Francis coupled with electric generator (Figure 1), Kaplan (Figure 1) and an axial turbine for the cavitation study (Figure 2).

The Pelton turbine is driven by a smaller radial hydraulic pump (Figure 2), in relation to the larger radial pump (Figure 3) responsible for driving the Francis and Kaplan turbines. The cavitation turbine is driven by a third axial hydraulic pump (Figure 3), in which a cavitation test is also performed. Finally, there is a fourth auxiliary radial pump, responsible for the head loss experiments (not shown). The laboratory has a system of connected reservoirs with a total capacity of 50,000 liters.

Figure 1. Francis turbine coupled with electric generator (left) and Kaplan turbine (right).
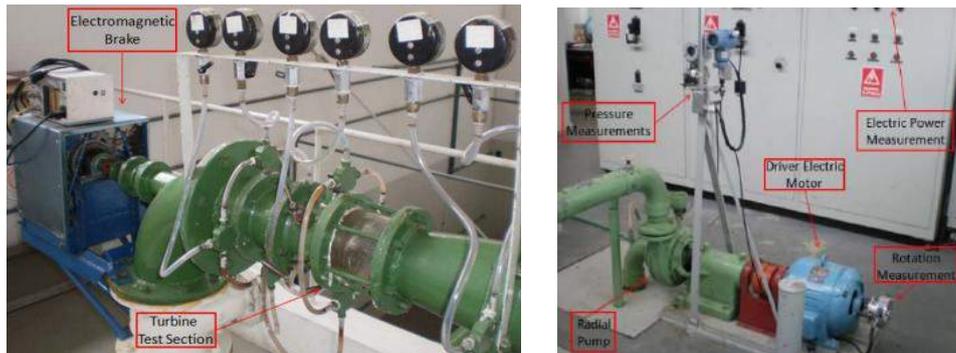

Figure 2. Axial hydraulic turbine cavitation test section (left), and radial hydraulic pump that drives the Pelton turbine (right) (Whitacker *et al*., 2017).

Figure 3. Axial pump cavitation test section, responsible to drive the cavitation turbine (left) (Whitacker *et al*., 2017), and radial hydraulic pump that drives the Francis and Kaplan turbines (right).

The LMH is considerably important for ITA, as it allows students of the different courses cited to observe in practice what is studied in theory, making learning more effective, comprehensive and pleasurable. In recent years, there have been numerous improvements in the laboratory: instrumentation with digital sensors and actuators; development of computational platform for acquisition and control; painting walls, floors, reservoir plates, ducts and equipment; changing windows glasses; replacement of the ceiling lining; construction of the external access sidewalk; modernization of the Francis turbine generator sensors and timing system; replacement of the head loss experiment pump; and replacement of the smaller radial pump inlet valve. The facilities currently have optimal teaching and working conditions. The present research work fits in this LMH modernization and improvement context, through the development of an automatic acquisition and control routine applied in the Pelton turbine, in order to obtain some of the machine performance curves.

1.2 Objective

The objective of this work was to develop an automatic acquisition and control system to obtain experimentally the Pelton turbine performance curves, under condition of application of constant shaft force for increasing mass flow values. The machine installed in ITA's LMH was used. The system was developed using the commercial software LabView.

1.3 Pelton Turbines

Turbines are continuous flow rotating machines intended to extract energy from a fluid in the form of mechanical shaft energy. The hydraulic turbines are designed based on available inlet head and mass flow. The selection of the turbine general type that best operates at a given application to produce a given power is done by the value of the specific velocity. Practice has shown that it is more convenient to use an impulse (action) turbine for high head installation and low flow rate; reaction radial or mixed flow turbines for intermediate head installation and mass flow; and axial flow turbines (propellers) for high discharge and low head installation (Moustapha *et al.*, 2003).

The Pelton type is an impulse turbine used for high head installation and low discharge. It was invented by Lester Allan Pelton (Singal *et al.*, 2009) in the 1870s. As can be seen in Figure 4, the potential pressure energy of water available in high reservoirs is converted into velocity energy. A nozzle is fitted at the end of the penstock, which issues a free and compact jet of fluid, generally water. The water jet sticks a series of buckets mounted around a circular wheel, these buckets are designed in the form of two-lobe elipsoidal discs for high conversion efficiency and balanced hydraulic thrust. Each bucket has a ridge or splitter in the middle to divide the jet into two equal streams. The symmetry of the bucket ensures no axial force on the shaft bearings. By deflecting the jets, the wheel rotates supplying mechanical power to the shaft, carrying the wheel. Therefore, the work generated due to the rotation of the wheel is extracted from fluid jet deflection at constant pressure in the rotor wheel (Singal *et al.*, 2009).
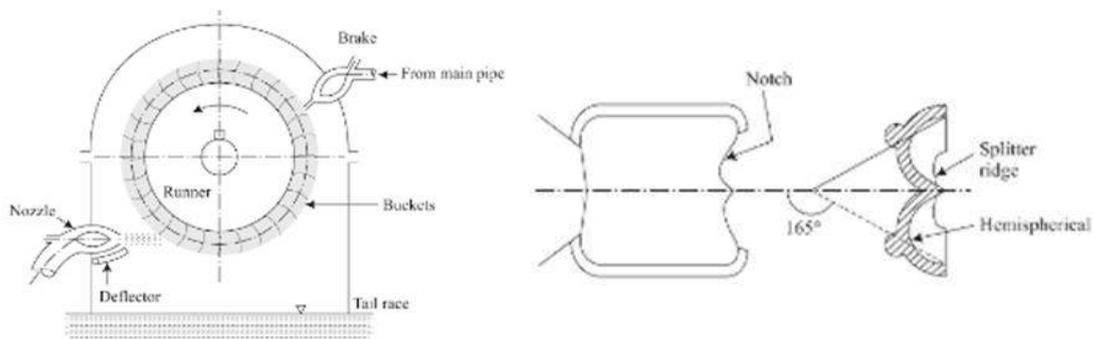

Figure 4. Pelton turbine scheme (Singal *et al.*, 2009).

The power output of a Pelton turbine depends on many variables, such as head and bucket splitter angle (Chukwuneke *et al.*, 2014). Unlike reaction turbines, the hydraulic performance is dynamic due to the unsteady flow in the rotating buckets in time and space (Trivedi *et al.*, 2016). The flow in the bucket is studied using not only experimental tools, but also numerical tools such as Computational Fluid Dynamics (CFD) (Zhang, 2009). With these tools, different numerical schemes and turbulence modeling approaches may be used to simulate hydraulic turbines in steady state and transient conditions (Xiao *et al.*, 2007).

CFD has emerged as an effective tool for the performance prediction of Pelton hydraulic turbines involving multiphase flow. It has also been widely used for design optimization of reaction turbines and is being extended for impulse turbines such as the Pelton type (Gupta *et al.*, 2013). A steady state numerical analysis of flow in the distributor is performed using such tools to provide data on flow energy losses in this distributor and the shape and velocity of jets (Jost *et al.*, 2010). Unsteady numerical simulations based on the two-phase homogeneous model are also performed to obtain wall pressure measurements, torque fields and visualizations of the flow and successive events in different zones of the bucket during a revolution period (Perrig *et al.*, 2004)(Perrig *et al.*, 2006). From the obtained pressure distribution data, the torque on the shaft and the turbine efficiency are numerically predicted.

The Pelton turbine efficiency is defined by Eq. (1) (Singal *et al.*, 2009):

$$\eta = \frac{P_{shaft}}{P_{hydro}} \tag{1}$$

where η is the efficiency, P_{shaft} is the shaft power, and P_{hydro} is the turbine available inlet hydraulic power. Shaft power is the product between the shaft torque, τ, and the angular rotation speed, ω:

$$P_{shaft} = \tau\omega \tag{2}$$

Both quantities, in turn, are calculated with Eq. (3) and Eq. (4):

$$\tau = FL \tag{3}$$

$$\omega = 2\pi N \tag{4}$$

where F is the shaft force, L is the lever arm, and N is the rotational frequency. The hydraulic power available at the turbine inlet depends on the volumetric flow rate, Q, and the fluid available inlet head, H, according to Eq. (5):

$$P_{hydro} = \rho Q g H \tag{5}$$

where ρ is the fluid density, and g is the gravity acceleration. Finally, the inlet head is calculated using Eq. (6):

$$H = \frac{p}{\rho} + \frac{V^2}{2g} \tag{6}$$

where p is the inlet pressure, and V is the inlet velocity. The uncertainties analysis in this research work followed the standard procedure contained in the Guide to the Expression of Uncertainty in Measurement (GUM) (ISO, 2020), from the International Standardization Organization (ISO). Therefore, the direct measurements total uncertainties were calculated from systematic and random uncertainties. The indirect measurements total uncertainties were propagated from the respective uncertainties of directly measured properties.

2. EXPERIMENTAL METHODOLOGY

The following sections detail the experimental methodology used to obtain the Pelton turbine performance curves, in terms of the used materials, the developed acquisition and control system, and the followed procedure.

2.1 Experimental Apparatus

The experimental apparatus, Pelton turbine driven by a radial pump in a complete testing circuit, consists of the following equipment:
- Pelton turbine with 50 cm in diameter, inside a closed enclosure with 1 injector nozzle, coupled to an axis (Figure 5 with front and back views);
- Rotation sensor, model MX-100/60, fabricator DLG, serial number: 550130012 (Figure 5);
- Manometric inlet pressure sensor, model M3, fabricator Smar, serial number: L454195 (Figure 5);
- Shaft force sensor, load cell, fabricator Alfa Instrumentos, serial number: 10DF50 (Figure 5);
- Mass flow sensor, model CF 420, fabricator Sitron, serial number: 534630 (in the duct that connects the pump outlet with the turbine inlet, sensor not visible in the figures);
- Piston actuator for opening and closing the injector nozzle, for mass flow rate control (Figure 5);
- Connection line: pump outlet/turbine inlet (Figure 5);
- Mechanical braking system of the Prony type, for applying force on the turbine shaft, with hydraulic cooling circuit (Figure 5);
- Turbine drive system, consisting of a radial hydraulic pump, connected via the shaft to an electric motor, which in turn is connected to the electrical network, with all ducts and valves necessary for its operation (Figure 2); and
- Acquisition and control system, which connects all sensors and actuators to a system developed in LabView, available on a computer (with numerous electrical connection cables), discussed in detail in the following section.

It is noteworthy that the sensors are annually calibrated at the Institute for Promotion and Industrial Coordination (IFI), central Institute of the Aerospace Metrology System (SISMETRA), certified by the National Institute of Metrology, Quality and Technology (INMETRO). The turbine operates in a closed circuit, with the pump capturing water from the reservoir and sending it to the turbine. After doing work on the buckets, the fluid returns to the reservoir.

2.2 Developed Acquisition and Control System

The system developed in this work was made based on the implementation and instrumentation previously performed in laboratory improvements. Before explaining the system details, it is necessary to understand the existing previous structure. The Pelton turbine sensors are connected with acquisition boards from the company National Instruments.
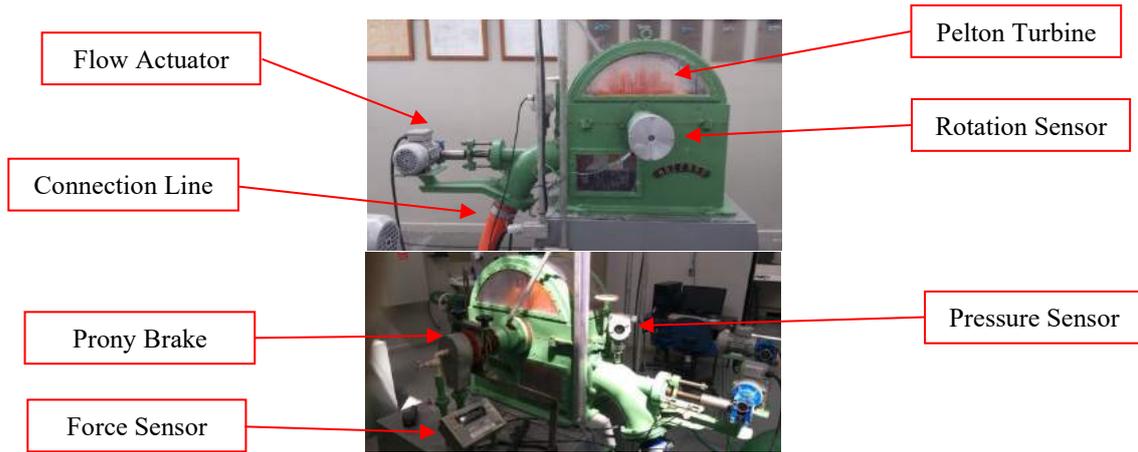
Figure 5. LMH Pelton turbine front view (top) and back view (bottom).

At the central computer, all analog signals received are converted into signals from the system developed in LabView and, through acquisition modules, are transformed into the respective measurements and addressed to their destinations, as shown in Figure 6. In the case of control signals (not shown in figures), the opposite logic is performed: control signals from the LabView system are addressed to the respective control channels and, after conversion to analog signals, are transmitted via the communication board to the respective actuators of the LMH machines.

Figure 7 shows the graphic control interface for the entire laboratory, where it is possible to observe the circuits of the Pelton, Francis and Kaplan turbines. In this window, it is possible to monitor the measurements of all sensors, open or close any actuator, in addition to performing data acquisition, which are transcribed in output files. Clicking on the Pelton turbine circuit (highlighted in red), one can open the control interface for the respective circuit, bottom in the same figure, where it is possible to perform the same actions, but only related to the Pelton turbine.
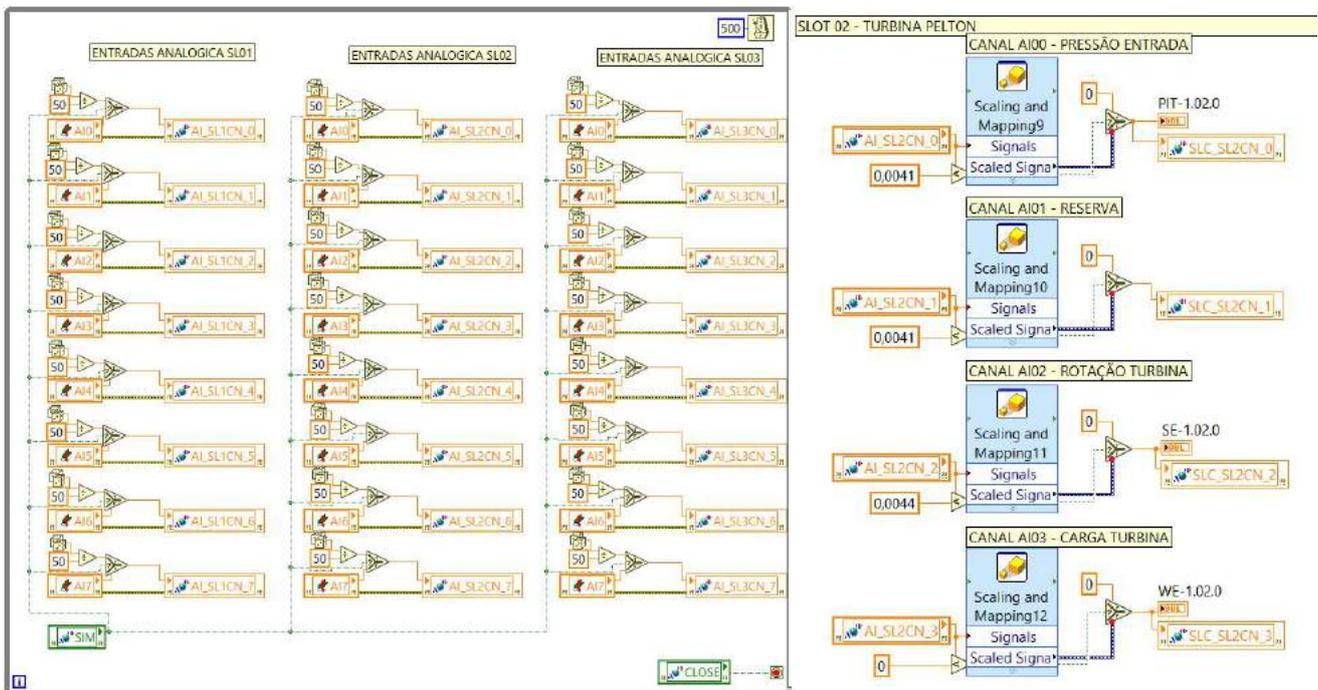

Figure 6. Conversion of received analog signals into acquisition signals at the computer system in LabView.

The system developed for the automatic acquisition and control of the Pelton turbine performance curves uses the existing measurement channels. It has two possible states, named "False" and "True", as shown in Figure 8 top and bottom, respectively. The system was developed to, after being continuously running, always remain in the "False" condition until the "Inicia Ciclo" command on the control panel is activated. In the "False" condition, the system is repeatedly executing the closing of the turbine flow actuator (when the actuator is already completely closed, nothing happens), in order to guarantee that the flux is null and that the machine is stopped.

When the command is executed, the system goes to the "True" state, in which the following actions are repeated, as shown in Figure 8:

- Waiting for the system stabilization time;
- Acquisition of the four measured properties (manometric inlet pressure, mass flow, rotation and shaft force) with transcription in an output file; and

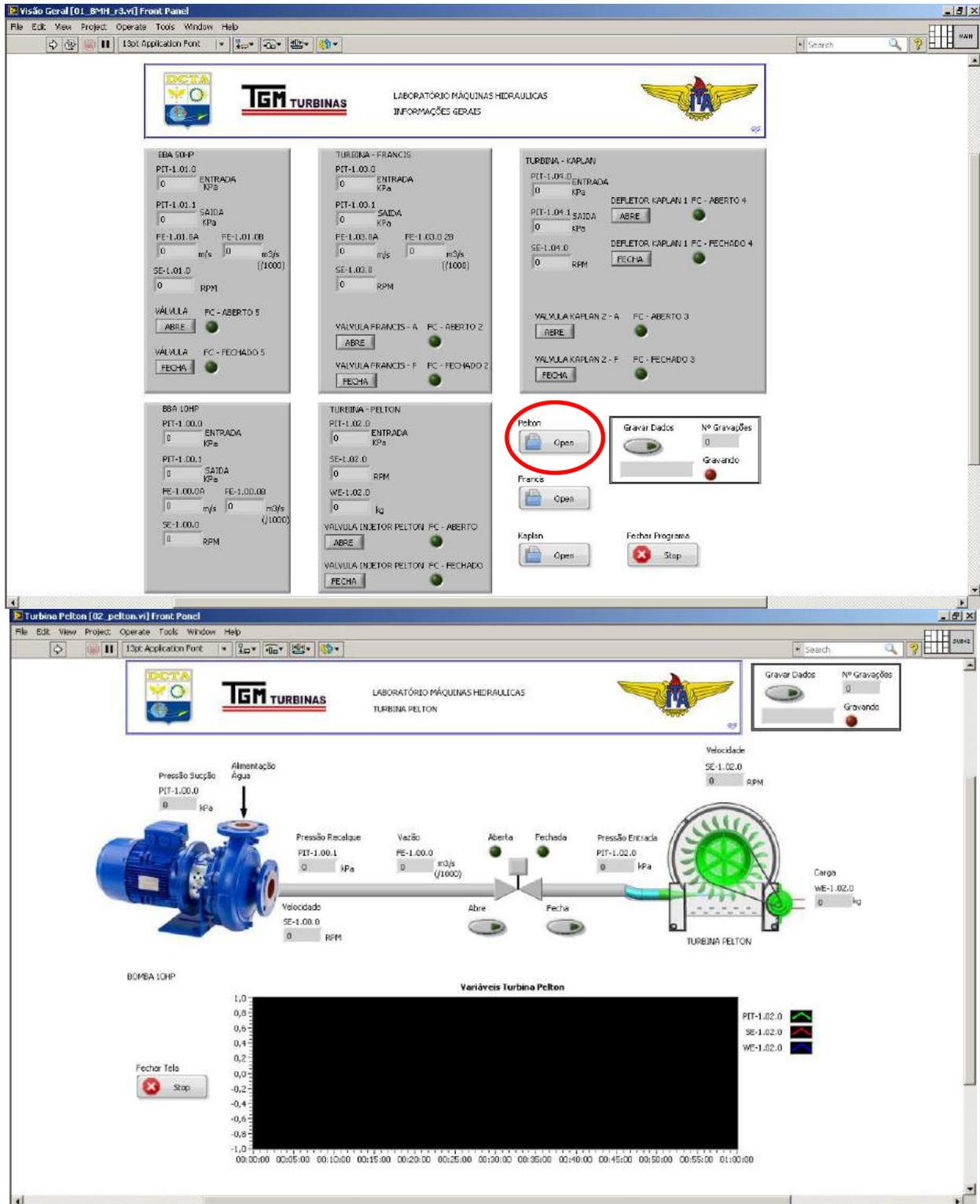Opening (for a specified time) of the flow valve.

Figure 7. Graphical control interface for all LMH circuits (Pelton, Francis, Kaplan turbines), implemented in LabView (top), and graphical control interface for the Pelton circuit, with the turbine and its feed pump (bottom).
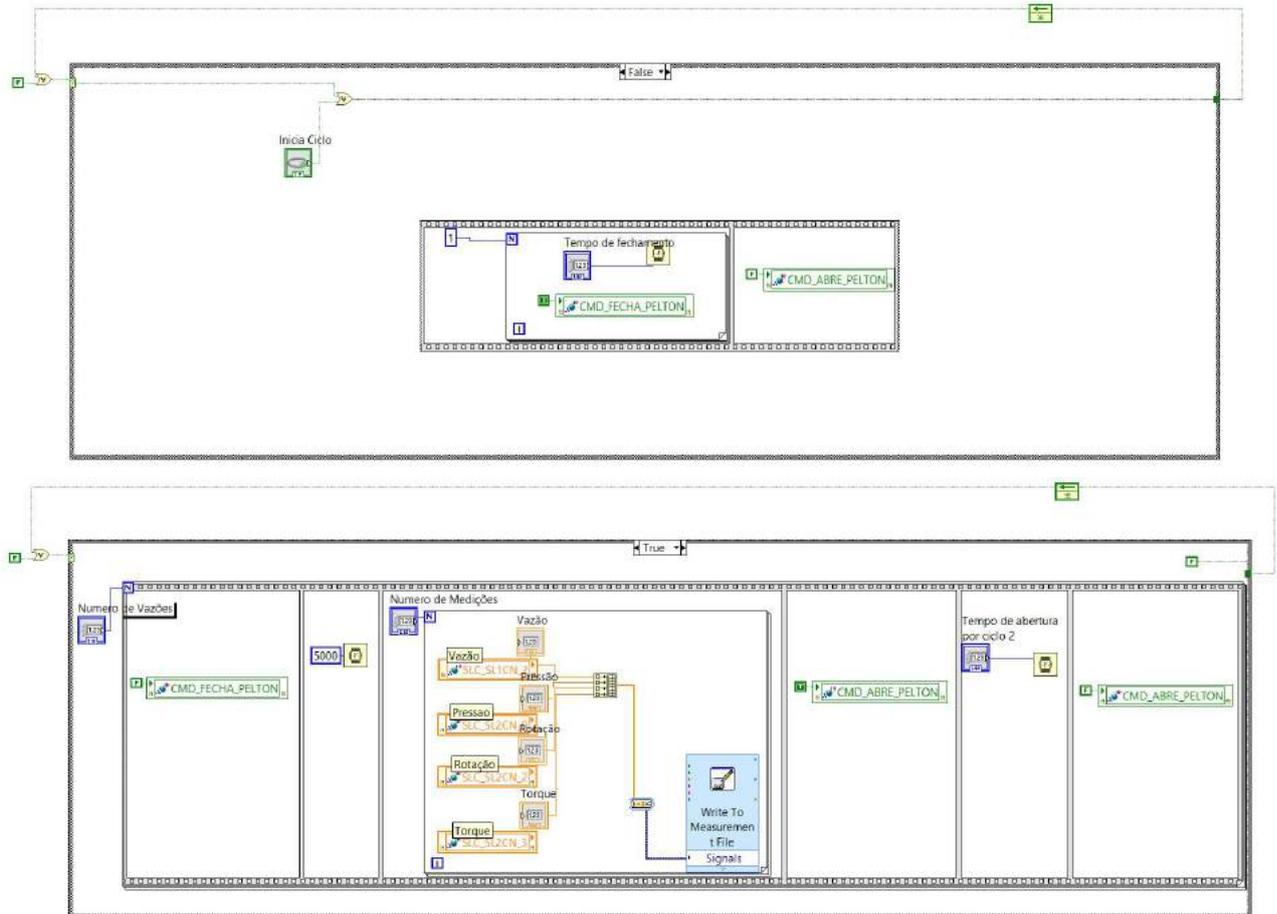
Figure 8. "False" state (top), which guarantees the turbine complete closing before obtaining the performance curves. "True" state (bottom), which makes successive measurements acquisitions and flow valve openings, allowing obtaining the data for determining the Pelton turbine performance curves.

The waiting time was defined so that, after a valve opening, the system can stabilize and return to the steady state operation. The control panel of the developed system allows several configurations that can be defined by the user, such as:

- Number of valve openings, defining the number of operating points of the test, in terms of flow rate;
- Number of measurements acquired for each measured property and at each operating point;
- Flow valve opening time at each turn the command is triggered; and
- Total valve closing time.

2.3 Experimental Procedure

Using the aforementioned experimental apparatus, the experimental procedure consisted of configuring the developed system to perform 4 valve openings (including the fully closed condition), 250 measurements of each property at each operating point (according to the sensitivity analysis explained below), with a total closing time of 25 s, and valve opening time of 1 s in each repetition.

Thus, after applying a constant low magnitude shaft force to the Prony brake, with the hydraulic brake cooling circuit already working, and switching on all equipment, the radial pump (previously full of water) was turned on, with the turbine flow valve fully closed ("False Condition"). Subsequently, the "Inicia Ciclo" command was executed, starting the automatic data acquisition and control. At the end of the system execution, the pump and all other equipment were turned off. The data necessary to obtain the performance curves were obtained.

3. RESULTS AND DISCUSSION

Following the procedure explained above and using the developed acquisition and control system, the performance parameters of the Pelton turbine installed at ITA's Fluid Mechanics and Hydraulics Machines Laboratory were measured for different operating points. The results are discussed below.

3.1 Definition of the Total Number of Measurements

Initially, it was necessary to define the total number of turbine performance parameters measurements for each operating condition through a sensitivity study in which successive averages of these parameters were obtained for an increasing number of measurements. This was done to ensure that the properties variation due to the aleatory and systematic uncertainties themselves, as well as the natural hydraulic system oscillation, was negligible. Figure 9 shows the mass flow, manometric inlet pressure, rotation and shaft force successive averages, respectively.

In the figure, the vertical axes values correspond to the respective operating range of the turbine. For example, the flow in the turbine ranges from 0 l/s to about 10 l/s. On the horizontal axes, flow properties averages with increasing measurement numbers are calculated. For the value 10, for example, the flow rate was averaged using 10 measurements. For 300, the average was calculated using 300 measurements. Note that the average properties vary very little within the turbine operating range, especially for high measurement numbers. A conservative value of 250 measurements from each property was chosen to calculate machine performance.

3.2 Pelton Turbine Performance Curves

After obtaining the experimental measurements, Eq. (1) to Eq. (6) were used to calculate the averages and total uncertainties of Pelton turbine performance parameters. Direct measurements are shown in Table 1, while indirect ones are in Table 2. When necessary, they were considered as constants: ambient pressure, 93.4 kPa; gravity acceleration, 9.81 m/s^2; and lever arm, 0.38 m. Figure 10 shows the graphs containing the calculated parameters variations as a function of the mass flow rate. In interpolated figures, the respective equation and factor R^2 are shown on the lower left sides.
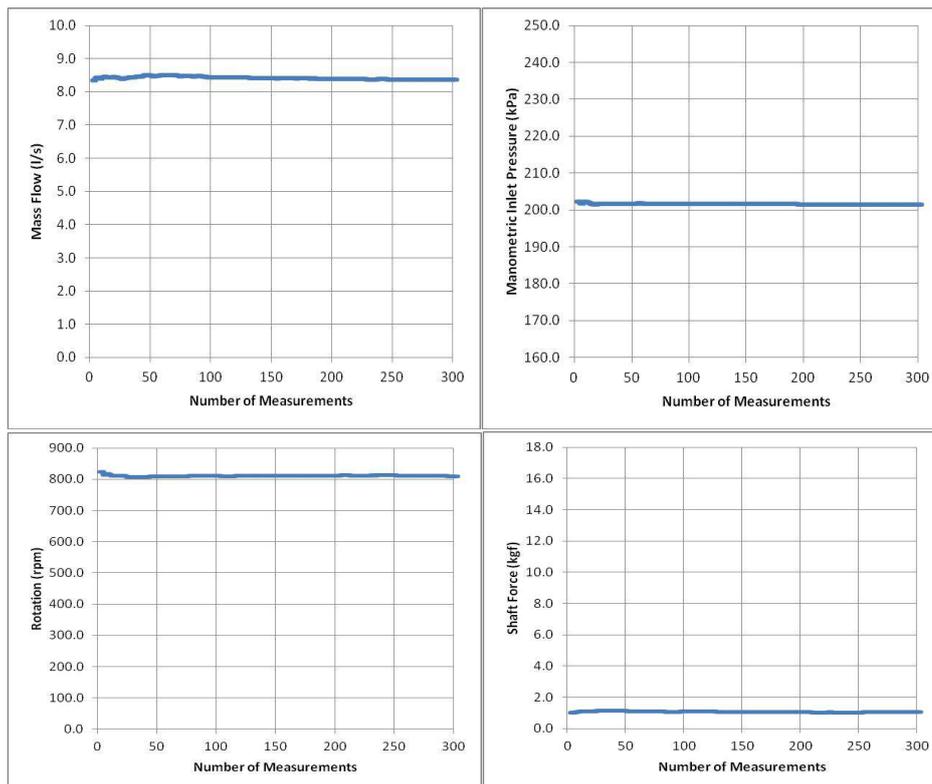

Figure 9. Mass flow sensitivity analysis for the measured variables: mass flow, inlet pressure, rotation, shaft force.

Analyzing the results, the turbine inlet pressure decreases with increasing flow. The interpolation, with R^2 factor above 0.99, shows that this decrease is practically linear. This result is consistent with turbine driving system, which is made by a radial hydraulic pump. For this pump, the higher the flow rate, the lower the outlet head and therefore the lower inlet pressure available at Pelton. It is noted that the rotation increases with the flow to a maximum value and, by extrapolation; it may decreases after this maximum. The interpolation shows an approximately parabolic relationship (R^2 factor above 0.99). This result is consistent with what is theoretically expected: for each nozzle height in relation to the blades, there is an optimal value of jet velocity (and therefore of flow rate) associated with the maximum rotation, for values above and below this optimized one the rotation decreases.

As discussed in the objectives section, the purpose of the developed system is to obtain turbine performance for constant values of force supplied to the shaft. It is observed that this force is not constant, showing an increase with increasing flow, although small (in this analysis, the first zero flow point is excluded, for which the force is approximately zero, for obvious reasons). For the purpose of Pelton performance general analysis, this increase is considered acceptable. This feature, however, represents the greatest difficulty of the performed research work: the force increase associated with the rotation increase provided by the Prony type mechanical braking system. This difficulty is even more evident for high forces and long operating times, for which brake heating is considerably high (even with active hydraulic cooling), making braking unstable. In the near future, it is intended to exchange this mechanical system for an electromagnetic one in order to solve, or at least minimize, this problem.

Table 1. Pelton turbine direct measurements.

Operating Point	Mass Flow (l/s)	Manometric Inlet Pressure (kPa)	Rotation (rpm)	Shaft Force (kgf)
1	0.00 ± 0.28	250.00 ± 0.01	0.00 ± 0.01	0.05 ± 0.01
2	2.31 ± 0.26	231.13 ± 0.01	453.22 ± 2.68	1.06 ± 0.02
3	5.30 ± 0.26	206.13 ± 0.12	791.09 ± 2.17	1.16 ± 0.01
4	6.73 ± 0.26	199.62 ± 0.36	812.62 ± 2.76	1.22 ± 0.02

Table 2. Pelton turbine indirect measurements.

Operating Point	Absolute Inlet Pressure (kPa)	Force (kgf)	Hydraulic Power (W)	Shaft Power (W)	Efficiency (%)
1	343.40 ± 0.01	0.19 ± 0.05	0.00 ± 96.93	0.00 ± 0.00	0.00
2	324.53 ± 0.01	3.94 ± 0.06	751.09 ± 84.98	187.15 ± 2.94	24.92 ± 2.85
3	299.53 ± 0.12	4.31 ± 0.05	1587.06 ± 78.85	357.30 ± 3.93	22.51 ± 1.15
4	293.02 ± 0.36	4.55 ± 0.07	1973.45 ± 76.68	386.84 ± 6.32	19.60 ± 0.83

In Figure 10, it is noted that the available hydraulic power at the Pelton inlet is increasing with the flow at an approximately linear rate (again interpolation with R^2 factor above 0.99). Since this power is the product between flow rate and inlet head, Eq. (5), it is concluded that the inlet pressure drop associated with the flow increase is compensated by the higher flux rate, generating a final result of linear increase as a function of mass flow. The shaft power, Eq. (2), is the product between torque and rotation angular speed. As previously discussed, the force applied to the shaft is approximately constant and thus the torque is also approximately constant, Eq. (3). Therefore, the shaft power variation as a function of flow rate will be similar to the variation of rotation as a function of flux, corresponding to a parabolic behavior ($R^2 = 0.9991$) of downward concavity, presenting a maximum value, as seen in the figure.

Finally, the Pelton turbine efficiency variation. A parabolic behavior is observed, in which the property increases with the flow to a maximum value, followed by decrease. Being the ratio between shaft and hydraulic powers, Eq. (1), this behavior corresponds to what is theoretically expected and to what is observed in the graphs of both powers: hydraulic power increases linearly with flow and shaft one has parabolic variation. For low flow rates, useful power increase compensates available inlet flow power increase, resulting in higher efficiency until the maximum value. For high flow rates, shaft power begins to decrease while hydraulic one continues to increase, resulting in decreased efficiency.

Two interesting conclusions can be made: first, for the operating range analyzed under the tested conditions, it is noted that the flow rate corresponding to the maximum useful power point is greater than that corresponding to the maximum efficiency point. If a nominal operating point has to be chosen, a trade-off between power and efficiency would be required. Second, the graphs show that the total uncertainties of direct quantities are relatively smaller than the uncertainties of indirect quantities. This is theoretically expected, since the direct uncertainties propagation for the indirect uncertainties calculation results in a relative uncertainty increase. In Table 2, it was not possible to calculate the efficiency total uncertainty for operating point 1, since the respective values of both powers were null (turbine stopped and without flux) and the hydraulic power appears in the propagated equation denominator of efficiency uncertainty.

Efficiency, as well as shaft and hydraulic power, is an indirect parameter. However, unlike the two that are obtained through direct quantities, it is obtained through other indirect quantities. The greater uncertainties propagation explains the higher total uncertainties observed in the efficiency graph, in addition to the fact that the R^2 factor in this plot was worse than in the others ($R^2 = 0.9443$), however not invalidating the conclusions. As a general comment, it is noted that the Pelton turbine performance experimentally obtained is consistent with the theoretical expected performance, validating the use of the developed acquisition and control system.
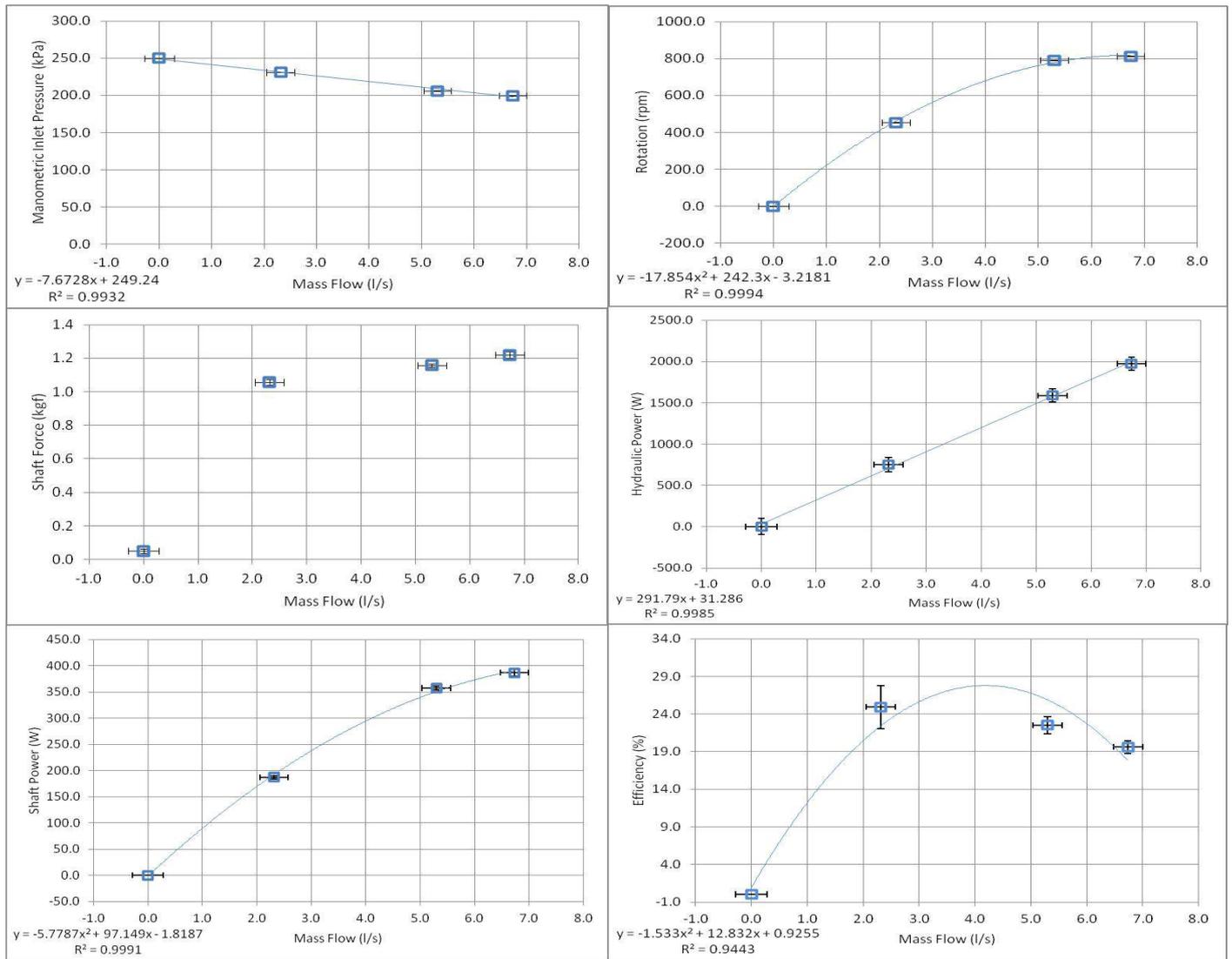
Figure 10. Variations as a function of the mass flow rate: manometric inlet pressure, rotation, shaft force, hydraulic power, shaft power, and efficiency.

4. CONCLUSIONS

Given the general context of recent improvements in ITA's LMH in recent years, the present research work was motivated to develop an automatic acquisition and control system with application in the laboratory's Pelton turbine, in order to obtain the machine performance curves under application of constant shaft force, for increasing mass flow rates. The system was developed using the same commercial software previously used in the test facility, the LabView from the National Instruments Company.

With the use of the developed system, initially a sensitivity study of the results was carried out in relation to the quantity of measurements of each turbine property, from where the total number of measurements to be used was defined. Then, the measurements necessary to determine the turbine performance curves were obtained and, with the use of the equations related to the performance of this machine type, its performance parameters were obtained, together with the respective total uncertainties. These parameters were organized in the form of tables and graphs, in order to allow the analysis of the results.

The variations of manometric inlet pressure, rotation, shaft force, shaft power, inlet hydraulic power and efficiency as a function of the flow rate had the theoretically expected behavior, according to the test conditions. The analysis of uncertainties confirmed the validity and quality of the results obtained. Thus, it is concluded that the developed system worked properly, reaching the objective of this work.

As future work, it is worth mentioning the exchange of the Prony mechanical braking system with an electromagnetic system, in order to eliminate (or at least mitigate) the problem of instability, especially for high loads and long operating times. Thus, it will be possible to determine the complete Pelton turbine operation map, as well as its

reception and operating curves. In addition, the success of this work in terms of actuator control started the interest in the development of control subroutines to be implemented in LabView; so that the system automatically and continuously performs the flow control according to the user configured value. Finally, the methodology employed can be replicated for other LMH machines, for example the Francis and Kaplan turbines.

5. ACKNOWLEDGEMENT

This work is being concluded in memory of André Neves de Almeida Prado. He was one of the co-authors but unfortunately died a few months ago. Awards winner, he was a worker at the Aeronautics and Space Institute, where he contributed enormously to numerous projects relevant to Brazil. He was also a collaborating professor at ITA, where he worked after hours to teach others. Thank you Professor André.

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