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MODELLING, CONTROL AND MEASUREMENT OF PELTON HYDRAULIC TURBINE: A LABORATORY CASE OF STUDY

Maycon Willian Mamoré dos Santos
Júlio Cezar Oliveira de Souza Lescano
Fernando Montanare Barbosa
Bruno de Paula Rosa
Daniel José Laporte
Universidade Católica Dom Bosco (UCDB) Av. Tamandaré 6000, Campo Grande, 79117-900, Brasil
maycon.mamore@gmail.com, julio.lescano@hotmail.com, montanare@gmail.com, probrunorosa@gmail.com, daniel.laporte@ucdb.br

Fabiano Pagliosa Branco
Universidade Católica Dom Bosco (UCDB) Av. Tamandaré 6000, Campo Grande, 79117-900, Brasil
Instituto Federal de Mato Grosso do Sul (IFMS) R. Taquari 381, Campo Grande, 79100-510, Brasil
fabiano@ucdb.br

Abstract: *The main objective of this work is to show the system dynamic modelling, simulation and control of Pelton hydraulic turbine in a laboratory scale. The linear modelling was based on physical laws and system parameters, linearized about an operating point in which the turbine efficiency was maximum, according to previous experiments. The model parameters identification was performed by means MatLab toolbox, which has measurement data and the 1st order model transfer function as routine inputs. Pelton control design was based on classical control theories and done by means PID tuner, another MatLab toolbox, reaching in a design of PI type and the most adequate control gains. Results of system simulation, performed on MatLab/Simulink, shows good correlation with measurement data.*

Keywords: *MatLab toolbox, Modelling, Simulation*

1. INTRODUCTION

Pelton turbines are machines which operates with tangential flow, usually applied on high falls and low flow rates, they have from one to six jets (Henn, 2012). The water injector changes its flow rate by means a hydraulic system actuator, for controlling turbine speed (Agudelo *et al*, 2013).

Pelton Turbines are largely applied in small hydraulic plants, operates with high angular velocities and are suitable for operating in falls up to 1100 m, very common in mountainous regions (Cardoso, 2016). This makes its study and understanding of physical concepts behind, allied with well-designed control system, important points for increasing the efficiency of energetic plants based on Pelton turbines.

Researches on Pelton turbine behavior under laboratory scale allows tests and evaluation of turbine-generator assembly based on basic concepts of fluid dynamics theory, such as characteristic curve determination, parameters variation to find better efficiency and mathematic model correlation needed for control design (Silva and Florêncio, 2014).

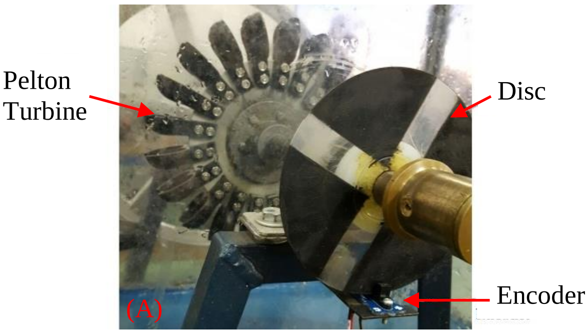
The objective of hydraulic turbines control is maximizing energy production, in such a way to generate more power with minimum possible of water flow in each power plant unit (Santander, 2014).

Hence, the objective of this work was the development of mathematic model which correlates with physical system behavior and responses in a laboratory scale. Pelton turbine model has as its operational points those tested previously and which results in better efficiency. This model allows the implementation of turbine speed control for future experiments on university laboratories of engineering.

2. METHODOLOGY

2.1 Experimental stand description

Physical plant is equipped with a 210 mm Pelton rotor, Fig. (1A), and 20 blades, and it is assembled on an experimental stand which allows the functioning simulation of a real system, Fig. (1B). Fall simulation is done by means hydraulic power supplied by a pump model CAM-W6-1.5CV.



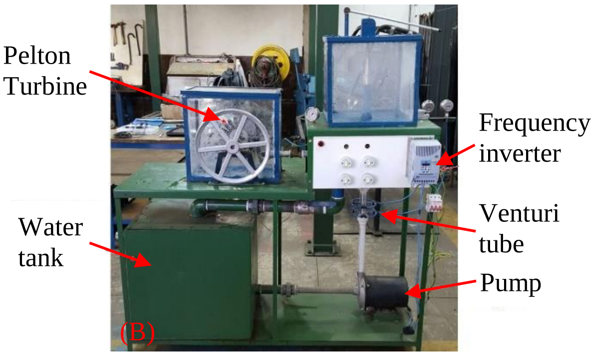


Figure 1. (A) Pelton turbine rotor and encoder for angular velocity measurement. (B) Turbine experimental stand.

Silva and Florêncio (2014) tested this same Pelton turbine by means dynamometer, in order to measure its efficiency (η) versus rotational speed (n) in converting hydraulic energy into mechanical, and reached to the results shown on Fig. (2). Efficiency was determined by the relation between mechanical power (W_m) measured at dynamometer and hydraulic power (W_h) calculated by means measured flow rate (Q) and experimental water fall height (H_t) by Eq. (1).

$$\eta_t = \frac{\dot{W}_m}{\dot{W}_h} = \frac{\dot{W}_m}{Q\gamma H_t} \tag{1}$$

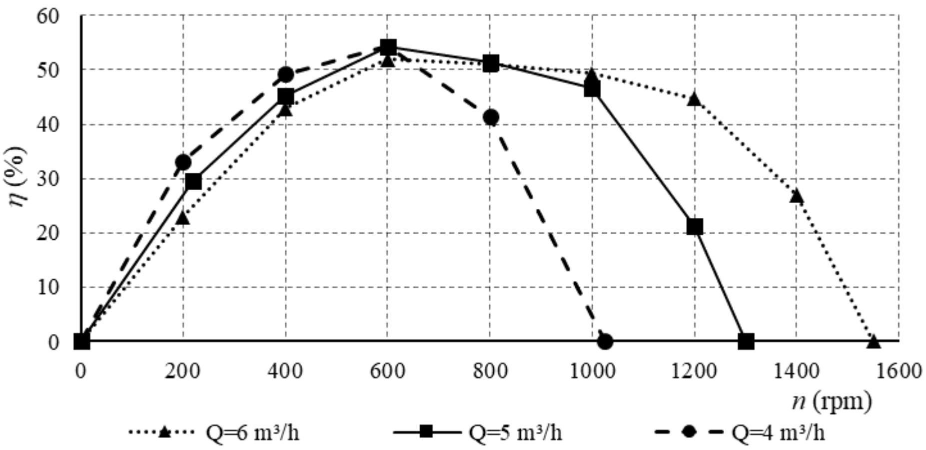


Figure 2. Pelton turbine efficiency curve.

According to these results, indicated in Fig. (2), system model operating point was defined as 600 rpm and volume flow rate equals to 5 m³/h, maximum efficiency point of 54 %.

2.2 Instrumentation and tests

Flow rate control, which propels the blades, has been done by means frequency inverter, actuating on pump motor rotational velocity. Flow rate measurement was done by means Venturi tube and digital piezo-resistive pressure sensors (MPX4250DP), and turbine rotation measurement by means encoder circuit, supplied data converted by Arduino Duemilanove. Figure (3) shows applied sensors connected to Arduino for data acquisition.

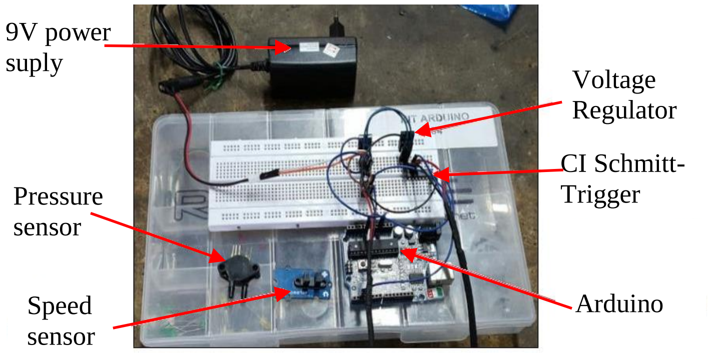


Figure 3. Circuit and sensors applied for data acquisition.

2.3 System modeling

System modeling was done based on classical theories and laws, such as Newton 2nd law and mass balance law, reaching in a 1st order system. System input was the flow rate, related to fall height, meanwhile the output was turbine rotational speed. Due to the complexity of estimating some physical parameters, such as damping and inertias, it was applied a MatLab routine for parameters estimation, given the transfer function, based on measured outputs and related inputs.

For this model correlation purposes, after data acquisition, they were inserted in toolbox System Identification (MATLAB, 2016a), which applies Kalman filter and state observation theories in order to find a set of parameters which gives the closest model response to physical measured one.

As the system plant model is correlated, it was developed a control system by means MatLab toolbox PID tuner, and simulated (plant and control system) by means MatLab Simulink.

3. RESULTS AND DISCUSSION

Data for each inverter frequency configuration, which is related to the pump power, are shown in Tab. (1). Highest rotational speed measured was 1504 rpm, related to volume flow rate of 6,65 m³/h which corresponds to the fall height of 18,5 m.

Table 1. Measured data for each inverter frequency applied to the pump.

Freq. (Hz)	*n* (rpm)	*Q* (m³/h)	H_t (m)
20	419	2,20	0,5
25	577	2,82	1,8
30	764	3,44	4,5
35	879	3,94	6,7
40	1018	4,61	9,6
45	1156	5,07	11,6
50	1268	5,69	14,3
55	1405	6,27	16,8
60	1504	6,65	18,5

These time history acquired data are shown in Fig. (4). It can be noted that stead state regime is reached from 3 to 10 seconds after flow rate step input was applied to the system. Moreover, it can be verified the first order system response behavior and system operational limits.

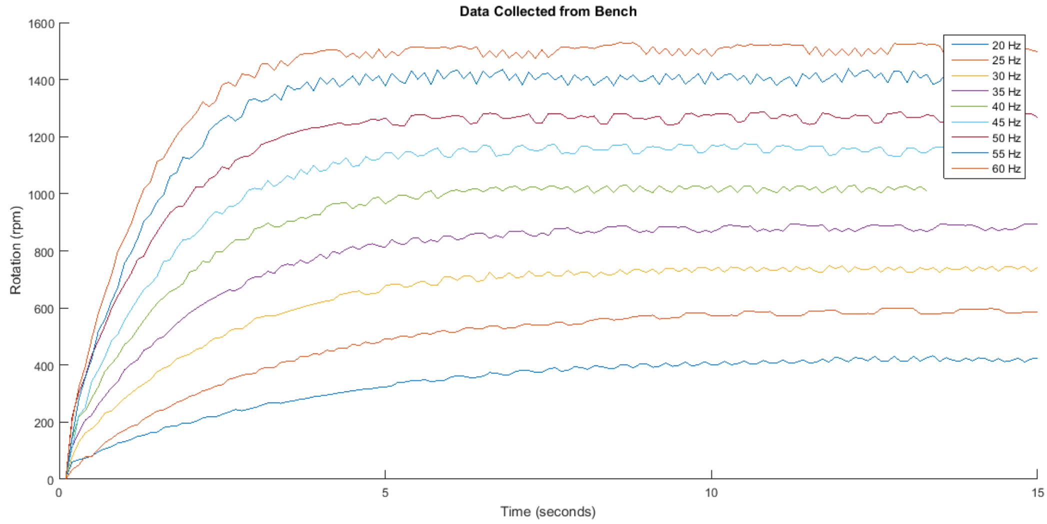


Figure 4. Measured rotational velocity to a flow rate step.

As explained before, these measured data were used for model correlation, and so, for determining model transfer function. In the Fig. (5) are shown the comparison between mathematical model response and physical system measurements, to the same steps as inputs. The found model represents well the dynamics of physical Pelton turbine.

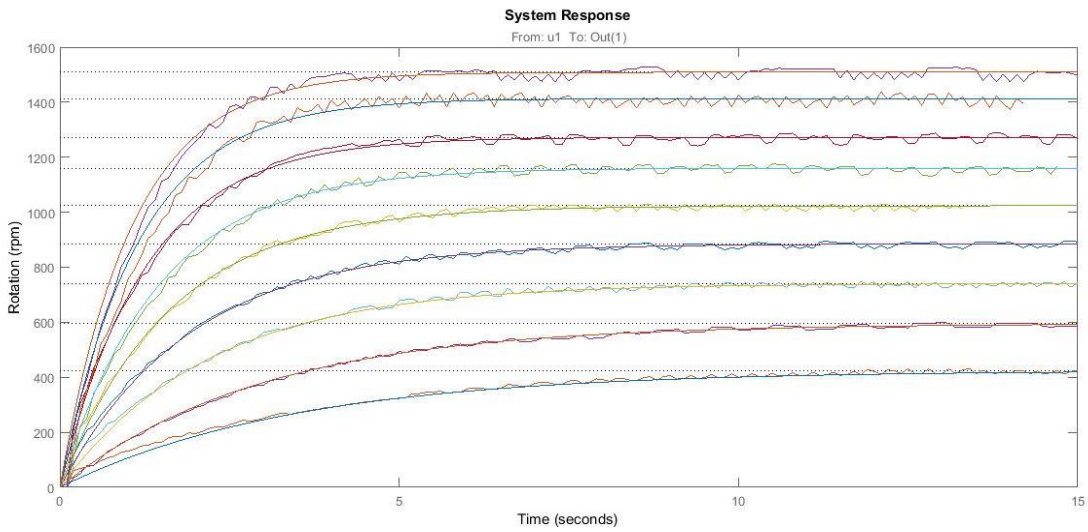


Figure 5. Rotational velocity response comparison, phisical and simulated system to a flow rate step.

Model transfer function for Pelton turbine, linearized at an operation point, was defined as a 1st order, given by Eq. (2).

$$G(s) = \frac{214{,}2}{2{,}743.s + 1} \tag{2}$$

A closed loop propotional and integral controller type was selected, for keeping turbine rotational speed as close as possible to a setting point, selected to be 600 rpm, equivalent to the best system efficiency, Fig. (2). A well designed controller is needed for guarantee that external disturbances, such as electric generator torque or hidraulic power reduction, will be compensated during turbine operation.

Control gains were defined by means PID tuner, form MatLab toolbox, such as proportional gain (k_p) equals to 0,01096 and integral gain (k_i) equals to 0,003995. These gains results in better response and system robustness.

Simulink was used for simulating closed loop system, by means block diagram, Fig. (6), with plant transfer function and designed controller. Disturbances were applied in the system in order to simulate generator charge variations during its operation.

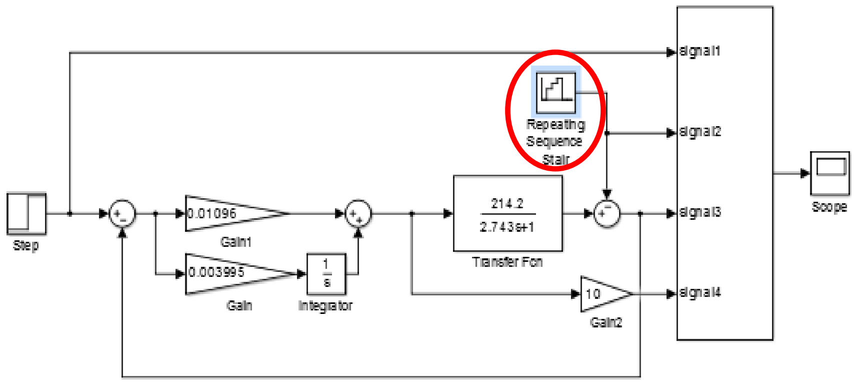


Figure 6. Block diagram of controller.

Control system simulation is shown in Fig. (7), in which was applied, as external disturbance, a breaking torque in turbine rotor, simulating electric generator charging, due to an increasing of power demand. In Fig. (5) it can be seen a repeating sequence stair, set for 200 and 400 rpm, over 6 and 12 seconds, respectively, these values are subtracted from plant rotation. Just after 21 seconds, the applied breaking torque is completely released. System response for this external excitation can be seem on Fig. (7A).

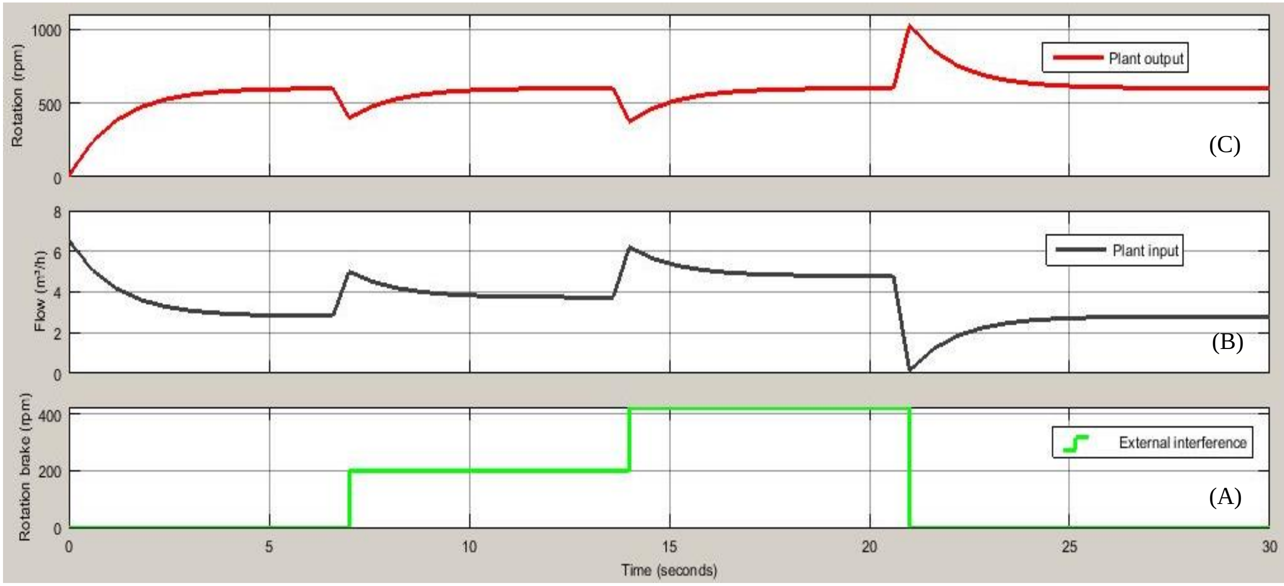


Figure 7. Control system simulation, in which (A) is the external disturbance, (B) is the inlet flow rate and (C) rotor speed toration.

Figure (7C) shows turbine rotation behavior for the closed loop system, considering as setting point 600 rpm, it can be noted 3 rotor speed transient responses, due to the disturbances applied to the system, hence, controller actuates on flow rate in order to compensate these variations and follow the reference rotation speed, established at 600 rpm. Flow rate behavior can be seen on Fig. (7B).

4. CONCLUSION

Pelton turbine experimental stand was used for mathematic model correlation, which was simulated by means Matlab/Simulink software and compared to measured results. These simulations results show that proposed 1st order model behavior is close to physical system, which allows parameters optimization studies in the future, besides of been suitable for using as controller plant on system control design, as demonstrated in this work.

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