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MODELING AND EXPERIMENTAL EVALUATION IN THE NEW HYDRAULIC TURBINE USED IN THE AMAZON REGION

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KEYWORDS: Hydropower, Renewable energy, Turbine testing, Hill charts, Bond Graph, Indalma turbine.

ABSTRACT
The use of a new water turbine to meet the needs of electrification in isolated places in the Amazon region has been successful. It is highlighted that this technology was designed by empirical development and its use also is based on such techniques. This paper pro-poses a mathematical model using the theory of Bond Graph, and an experimental evaluation in reduced model of the hydraulic turbine, to characterize their operating limits. The dynamic control techniques are adopted in applied mathematical model and a bench was developed for experimental trials in hydraulic pico-turbines. They are reported as result: the mathematical model and hill charts containing a total of 4200 points, with power and efficiency values depending on the speed. The simulation results support the conclusion that the model has as answer a quick stabilization that happens as a damped form, another conclusion is that this turbine has a comprehensive use of potential because there were no significant variations in the values of their income, remained at approximately 79 %.

INTRODUCTION
In the Amazon region, long distances, natural obstacles, difficulties of access and low population density make it difficult to care much of the population by the conventional distribution system, on the other hand, the alternative service, with thermal diesel systems, too used in the region, present high cost of operation and maintenance and fuel distribution logistics [1]. There are many areas in Brazil that do not have access to electricity as seen in large urban centres, as evidenced last Census, in the northern region 24.1% of rural households had no electricity.

The potential available for the construction of large hydro power plants in Brazil is nearly exhausted. There remain the great exploitations of the Amazon region, with a high cost for the installed kilowatt and flood large forest or agricultural areas, as well as social and ecological consequences, the very core of the metal components can be affected by corrosive gases from the de-composition of plant material flooded [2, 3].

In this context, the use of small and micro hydro power plants earn high relevance, because the viability of small hydropower utilizations, low cost, low environmental impact (in isolated or interconnected systems), can be highly advantageous especially for the development of the countryside.

The hydraulic turbines are drive machines which per-form the conversion of hydraulic energy of a fluid into energy in the form of torque and rotational speed. Conventional turbines require, in general, a directional electromechanical control of the flow in the rotor blades so that their performance is satisfactory, this control system has high cost of installation and operation hampered its use for small energy uses [4].

The turbine of this work was developed to fill this gap and can be classified as an unconventional turbine and has the advantage of simple construction, simplicity of operation and maintenance, fitness for standardization, low cost and good behavior in isolated systems; this turbine has been installed in various locations in northern Brazil, in 2010 was responsible for the electricity supply to more than two thousand two hundred families who are not served by the electric utility [5, 6].

Turbines evaluations are performed mainly by numerical simulations, bench testing or modelling. Numerical simulations have the primary goal of reducing the costs of experimental testing and optimizing geometries without the need for physical construction of a prototype [7, 8]. Worktops tests are conducted usually in scale models and aim to validate the theoretical and computational predictions, although the results are more reliable, have high implementation costs compared with the numerical simulation [9.10]. A simple and representative model is necessary both to computer simulation and to theoretical predictions; in [11] one Modelling is presented using Bond Graph technique and presents convergent results with simulations performed by the author. An essential part of this type of analysis is its applicability in the concept of similarity, because the variation yields in similar turbines operating in similar conditions, is quite small and can be assumed, in most cases, their equality

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Among the general modelling techniques, it is necessary to find mechanisms for building models using concepts of the theoretical modelling and empirical model-ling [12]. This paper proposes the use of Bond Graph Theory (BG) in the representation of hydraulic systems. The challenges inherent in the proposal directs us to obtain a mathematical model intended to focus with representation system in the turbine rotor. In this sense, we will concentrate an alternative method to the classical practices of existing modelling, which provides the state-space representation of these nonlinear systems called BG tool. As a graphical representation of dynamic physical system, BG facilitates the understanding of the influence of each element and the visualization of the energy flow (gain and loss) throughout the system under study, to our understanding a difference in relation to the modelling techniques general.

BG theory is a unified representation of dynamic systems in which elements interact with each other via ports allocated within the system where the energy exchange occurs [13-16]. The methodology of obtaining the model via BG tool can be set in three steps: Specify the analogy system based on the actual physical model, deter-mine the energy fields and set the simplification of assumptions and input variables and system output [17, 18]. Represent key aspects and parameters of the turbine system through mathematical modelling, aims to understand its operation due to some important variables such as income and mechanical power.

Results available in [19] show that the guaranteed in-come turbine was 70%, in the optimum operating point. In 2014 this turbine was optimized using empirical techniques in order to improve their performance. After these changes were not determined its characteristic curves. This work has the hypothesis that the change in geometry of the turbine Indalma improved their income.

This study aims to present a mathematical model of this new turbine and carry out their experimental evaluation in reduced model. The significance of this work is justified by the contribution to the characterization of the turbine and determine its limits of operation, helping to the use of small hydropower utilizations, one of viable solutions to meet rural communities in the Amazon region.

MATERIALS AND METHODS

About the turbine

The hydraulic turbine, Fig. 1 - A, on which this work is anchored, is a turbine invented, patented and developed by Indalma company located in Santarém, Pará - Brazil. It was developed to meet the segment of existing turbines in small hydro power plants.

This turbine is a centripetal turbine-axial reaction, empirical development, designed by analysis of a Francis turbine. It is composed of a spiral triangular box section devoid of blades guidelines. Because it has no distributor or sophisticated mechanical system to control flow and power, facilitates its use in small hydrological exploitations. The water is directed to a compound rotor two sections, the first section of the blades is constant and arranged in the radial direction in the center of the rotor, the section changes to a longitudinal arrangement [20].

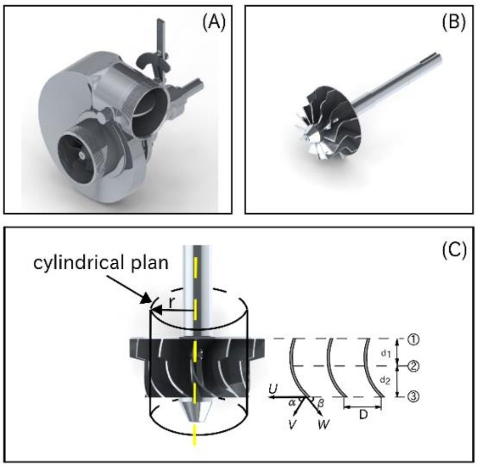

Fig. 1. Turbine Indalma. (A) Isometric view of the turbine with the intake valve with maximum opening, (B) rotor inner detail, (C) cylindrical cut in the rotor to highlight the profile of the blades and the velocity profile.

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In Fig. 1-A has the isometric view, where the inlet and outlet diameters are equal to *0.1m*, in Fig. 1-B was removed from all over the snail and external details to expose the rotor geometry, which has external diameter of 0.1m.

In Fig. 1-C centred in southern rotor shaft was created a cylindrical plane at a distance r equal to *0.041 m*. On this plan was performed a cylindrical cut, by the planning of this section, a plane containing the pro-files of the rotor blades is shown, this profile is called both grid and are shown three profiles of Fig. 1-C.

The distance between the blades of *D* profiles equals $0.018m$, $d_1 = 0.020m$ is the distance between the axis (1) and (2) and $d_2 = 0.031m$ equivalent to the distance between the axles (2) and (3).

In a point of the rotor profile, Fig. 1-C, the fluid particle velocity assumes the following parameters:

- U - Linear blade velocity;
- V- Absolute fluid velocity;
- W- Relative fluid velocity;
- α - Guide vane angle;

The turbine efficiency, Eq. (1), defined by the International Code for Model Acceptance Tests (IEC) 60193:1999 [21] and the Brazilian Association of Technical Standards (ABNT) [22], can be determined by the ratio between the mechanical power supplied by turbine shaft, Eq. (2), divided by the hydraulic power Eq. (3),

$$\eta = P_m \cdot P_h^{-1} \qquad (1)$$

where η is the guaranteed efficiency of the turbine, P_m is the mechanical power [W], P_h is the hydraulic power [W],

$$P_m = \omega \cdot \tau \qquad (2)$$

where ω is the rotational axis of the turbine speed [rad/s], τ is the torque provided by the turbine shaft [N.m],

$$P_h = \gamma \cdot Q \cdot H \qquad (3)$$

Where γ is the specific weight [N.m3], Q is the volumetric flow rate and H is the net pressure head. The net pressure head can be calculated using the difference between the trinomials Bernoulli's equation, Eq. (4) and Eq. (5).

$$H_{in} = z_1 + P_1 \cdot \gamma^{-1} + v_1^2 \cdot (2g)^{-1} \qquad (4)$$
$$H_{out} = z_2 + P_2 \cdot \gamma^{-1} + v_2^2 \cdot (2g)^{-1} \qquad (5)$$

And g gravitational acceleration, the indices *1* and *2* indicate the input positions and turbine output, the terms (P_1 e P_2), (v_1 e v_2) and (z_1 e z_2) represent the pressure, average speed and the topographic level respectively.

Modeling via Bond Graph tool

A graph of links is intended to represent the energy exchange between components of a physical system [13]. In the physical junction where the energy transfer takes place between components of a system, formed in the link, the instantaneous power is represented by two dynamic variables, the variable stress (e) and the variable flow(f). The variable power is characterized by the variables integrated accumulated effort (p) and accumulated flow(q).

The power factors, effort and flow, have different interpretations in different physical domains. In mechanical systems, such as hydraulic turbine system similar built variable effort (e) is the strength and the variable flow (f) is the speed.

The basic components are classified by their energy behavior (store or dissipate energy) and its function within the system (flow sensor, etc.).

The element of a capacitor door (C) stores energy without losses, and has a constitutive relation that relates stress and displacement, for example, springs and capacitors. The element of a resistive door R dissipates energy, as the resistors. The inertia elements (I) also store energy, where the time is related to the flow of a static law.
To model the turbine, the above elements were used; to this end, it is necessary to develop a representative system similar. The door elements are ad-dressed by a single power port and there is only one pair of stress variables (e) and flow (f).

The analogy system, Fig. 2, will be given by an initial mass M which is a parameter that characterizes the weight of the blades, and this will suffer a speed (Se). The influence of the angle β will be referred to in this scenario by a spring K_1 with a rigidity coefficient, was also adopted, the Voigt Kelvin model, having a spring with elasticity K_2 arranged in parallel with a viscosity damper B_1.

The model shown in Fig. 2 is representative of one of the blades, 12 analogous models were placed in series to shape around the rotor. The joints are numbered from the a-z and 1-11, the variables $X_1, X_2, \ldots, X_{36}$ represent the position. So it follows that in K_1 acts $(X_2 - X_1)$, in K_2 acts $(X_3 - X_2)$ and in B_1 acts derived speeds, so $(dX_3 - dX_2)$.

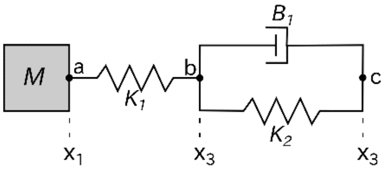

Fig. 2. Hydraulic analogy model of the turbine, where M is the original mass, K_1 the stiffness coefficient, B_2 and K_2 represents the Kelvin Voigt model.

Combining the above results in [28] and relating it to the relationships present in Fig. 1-C, we have the stiffness coefficient can be calculated by Eq. (6). The term dx, Eq. (7), is the difference of positions. Eq. (8) is the product between the angle β and the differences of positionsd_X.

$$K^1 = K_1(1 - \beta d_X) \quad (6)$$
$$d_X = X_1(t) - X_2(t) \quad (7)$$
$$\beta d_X = d_1^{-1}(1 + sgn\ d_X)(1 - sgn(d_X + d_2 - D)) \quad (8)$$

Experimental Procedure
The tests were carried out in installation for hydraulic turbines assays, Fig. 3, Terms of Sciences Laboratory of Gama Faculty – FGA, from the University of Brasilia. This facility can be treated as a small-scale model of a real power plant, and is designed to test action and reaction turbines.

In the design and development, standards have been adopted in IEC 60193:1999 [21] and ABNT [22 - 26]. Fig. 3 represents the plant for testing peak-hydraulic turbines (up to 20 kW), consisting of:
[1] Frequency Inverter;
[2] Three-phase motor 183 [rad/s], 18.4 [kW];
[3] Water Pump 0 – 0.05 [m³/s];
[4] Indalma turbine;
[5] Water Reservoir 2 [m³];
[6] Pressure Gauges;
[7] Electromagnetic meter volumetric flow;
[8] Triangular Spillway with 90º central angle;
[9] Force sensor 0-392 [N];
[10] Inductive sensor for rotation measurement;
[11] Manual valves for auxiliary pressure control.

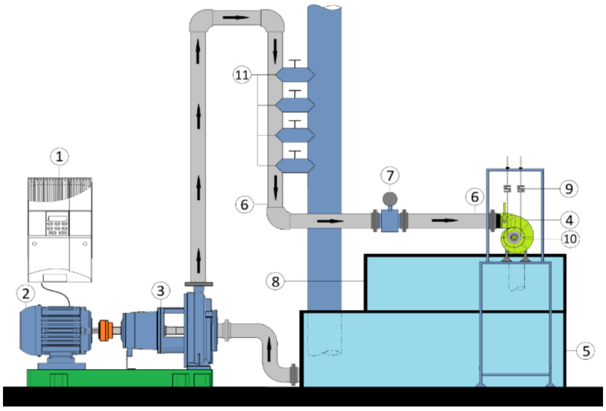

Fig. 3. Installation for testing of hydraulic turbines. 1, 2 and are together responsible for controlling the installation, 6, 7, 8, 9 and 10 are sensors of physical parameters and 4 is the turbine.

The drop height available for the turbine was set at 2m, 4m and 6mThis operation was possible due to the frequency variation using the inverter by changing the speed of the motor-pump assembly and, consequently, the pressure and flow at the turbine inlet.

It is used to setup the turbine outlet with straight cylindrical suction tube, therefore, by using this, the flow velocity in the turbine outlet is equal around the suction tube and the amount of energy represented by this gap between the output of the turbine and the downstream level is utilized, and also for being the most common usage situation in the Amazon region. The turbine inlet valve is maintained at the maximum opening.

Experimental tests have an average duration of two hours each time. Three different drop heights shall be adopted: 2m, 4m and 6m, totalling six hours of testing.

RESULTS AND DISCUSSION

As the results are presented the mathematical model and the characteristics curves of experimental performance.

Mathematical Modelling

Some considerations were taken in system model-ling:

- Flow in steady state, in order to characterize experimental parameters;
- Incompressible flow;
- Valid flow along a current row;
- Turbulent flow;
- The module of the vortices present is not significant;
- Lack of external pressure gradients - state that the external pressure gradient is equal to zero does not imply that the pressure cannot vary, but if it occurs, will be hydrostatic form;
- The diffusive effects, arising shear, are not significant.

Following the steps shown by [27] for transforming the analog turbine system, Fig. 2, for a graph of links containing the blades 12, the following procedures were performed:

1. Identification of the physical domain represented by the identification system and the capacitive elements (C), resistive (R), inertia (I), flux sources (Sf) or effort (Se) present in the system;
2. Identification of other energy variables such as the speed of the mass elements, naming them and assigning the joints of the type *1*;
3. Identification of differences efforts, in this case the speed differences, and assignment of the junction type *0* these speed differences;
4. Connection of the elements found in step *1* with their efforts or differences efforts, represented by joint type *1*. Allocation of causalities, done automatically by the simulation software 20-Sim.

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The formulation of BG diagram and the system of equations followed the algorithm for construction of the connection graph, based on use of the software 20-sim. The system link graph of the energy and causal directions is shown in Fig. 4.

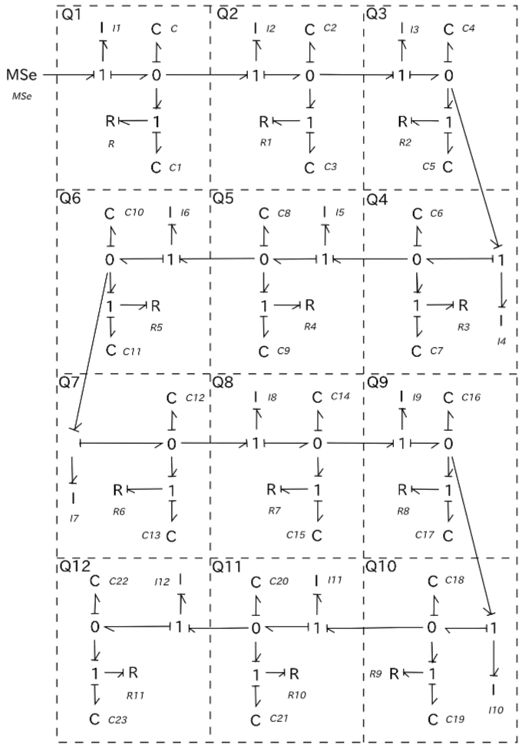

Fig. 4. Bond Graph representation of the hydraulic turbine, been Q1, Q2, ..., Q12 the turbine blades.

Should be analysed each junction, applying their proper rules of continuity and compatibility and use these relationships to get the vector elements$X$.
To remove the equations of the model shown in Fig. 3, the following steps were adopted:

- Format the links;
- Name the joints;
- Number the efforts and flows of each connection.

Defining state variables, for example, accumulated flow q and cumulative effort p the stores (capacitive and inductive elements), representing integral causality already set.

Note q' and p' links in the graph, the appropriate connections to represent effort and flow corresponding to each variable p and q. Also note the effort variable and each capacitor, and the variable f flow in each inductor.

Making use of matrix-vector notation, a differential equation of order n can be represented by a matrix-vector equation of the first order. Table 1 shows the classification obtained from the state space analysis, Eq. (9) the modelled system.

Table 1. State space for the modelled system classification.

Input Vector	MSe
Matrix A	Dimension 36 x 36
Matrix B	Dimension 36 x 1
Matrix C	Dimension 1 x 36
Matrix D	Null

After the simplified model Bond Graph, the equations were obtained for the construction of state-space matrix, Eq. 9.

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$$\dot{x} = Ax + Bu \quad (9)$$

In Eq. (10-13) the first and last ratios of equation are provided$\dot{x} = Ax + Bu$, for $x \in \Re^{36}$.

$$\dot{x} = [\dot{x_1} \quad \dot{x_2} \quad \dot{x_3} \quad \cdots \quad \dot{x_{35}} \quad \dot{x_{36}}]^T \quad (10)$$
$$x = [x_1 \quad x_2 \quad x_3 \quad \cdots \quad x_{35} \quad x_{36}]^T \quad (11)$$
$$B = [1 \quad 0 \quad 0 \quad \cdots \quad 0 \quad 0]^T \quad (12)$$

$$A = \begin{bmatrix} 0 & \frac{-1}{C} & \cdots & 0 & 0 & 0 \\ \frac{1}{C} & 0 & \cdots & 0 & 0 & 0 \\ 0 & 0 & \cdots & 0 & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & \frac{1}{I_{12}} & \frac{-1}{R_{11}C_{22}} & \frac{1}{R_{11}C_{23}} \\ 0 & 0 & \cdots & 0 & \frac{1}{R_{11}C_{22}} & \frac{-1}{R_{11}C_{23}} \end{bmatrix} \quad (13)$$

The simulation model was analysed applying two situations characteristics:

- Step energy input - operating situation in a steady state without significant variations in operating conditions;
- A pulse energy input - a situation characterized by rapid change of energy and can simulate a mechanical failure or change in operating conditions.

The system response when stimulated with step input, Fig. 5-A, indicates a stable behaviour characteristics of the first order system as shown in Eq. 5, the same happens in the system response when stimulated with pulse entry, Fig. 5-B.

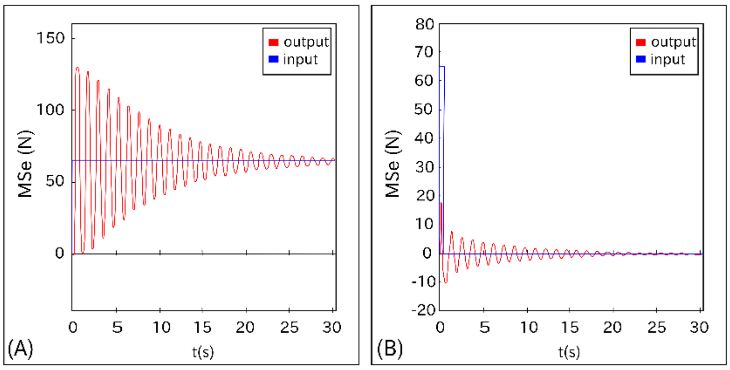

Fig. 5 – Model temporal response with a step excitement and a pulse excitation. (A) Patterned system response to the input step, and (B) response of the modelled system for pulse input.

EXPERIMENTAL RESULTS

The adopted experimental methodology generates a database containing a total of 4200 points. After proper treatment, these data show the income, the rotation and the mechanical power of the turbine, valued at net drop heights of 2m, 4m and 6m.

Experimental results, Fig. (6) Demonstrate that the performance of the turbine in the optimum operating point was approximately 79 $\pm$ 4.5% for all heights of liquid taken down.

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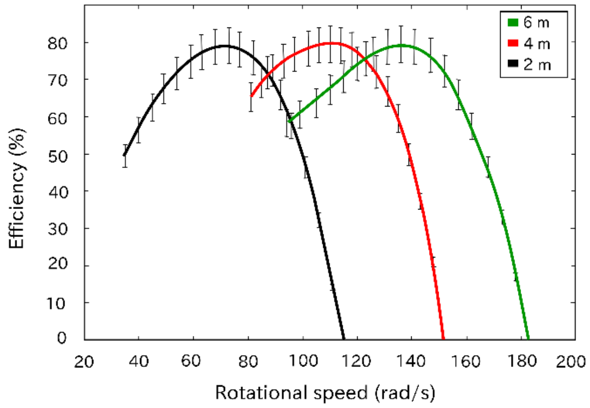

Fig. 6. Characteristic curve of income depending on the speed.

One form of representation of the hydraulic turbine characteristic curves is choline diagram, characterized by representing three dimensions on a two-dimensional graph, similar to what is done in a topographical representation. For hydraulic turbines are analyzed parameters in the hill diagram using the iso-yield curves.

In Fig. (7) is exposed to the diagram of the hydraulic turbine Indalma, in his analysis, we can extract crucial information to determine and characterize its operation, generating minimal and favorable conditions of use. For a 6m drop height, the optimum operating point occurs around 130rad/s to 4m occurs 110rad/s to 2m occurs 70rad/s. The small-scale model showed a maximum mechanical power of 735W.

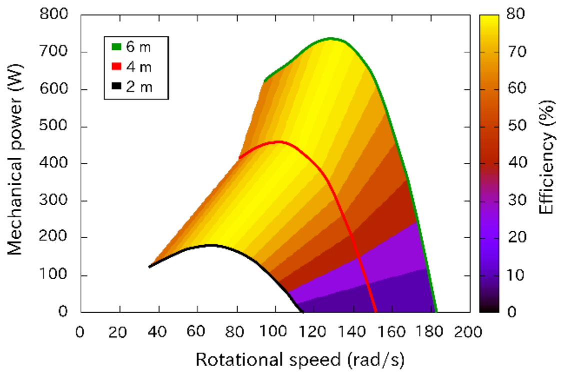

Fig. 7 - Diagram hill to power values, assessed income and rotation drop heights of 2m, 4m and 6m.

The described technique for turbine testing can be very useful in further developing hydropower technologies. It can reduce the duration of initial research and development phase by enabling quick testing of new prototype designs. The hill charts can then be used in research and development to evaluate and compare the performance of the Indalma turbine.

The results presented provides the conditions of use for a better utilization of the hydropower potential available in the Amazon region.

CONCLUSION

The initial hypothesis that the change in the geometry of the turbine Indalma improved its performance has been confirmed, as there was an improvement in their income by approximately 13%.

The model presented the characteristic response in Fig. 5 is a damped rapid stabilization and it is a peculiar feature of the model and positive, it indicates that abrupt changes of force, such as variations in flow or pressure difference is rapidly stabilized, indicating that the turbine has a tendency to regular self, when operating in situations outside the conditions operating standards. This feature was also investigated experimentally.

It is expected that the continued use of this new turbine is not based solely on empirical parameters and that the data will serve as facilitator for the population of the Amazon region. It is expected that future impacts of the presented results are positive, contributing to a better use of small hydropower utilizations.

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