

# Method for experimental investigation of transient operation on Laval test stand for model size turbines

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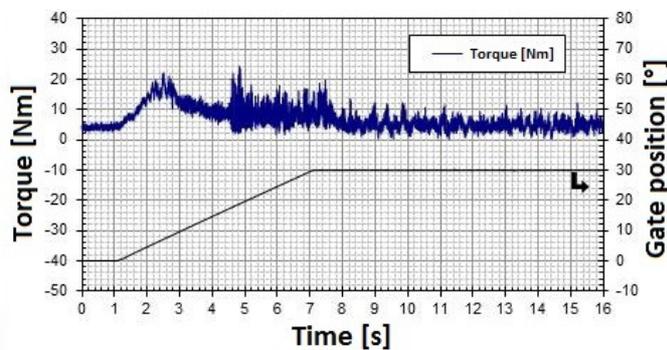
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**Abstract.** With the growing proportion of inconstant energy source as wind and solar, hydroelectricity becomes a first class source of peak energy in order to regularize the grid. The important increase of start – stop cycles may then cause a premature ageing of runners by both a higher number of cycles in stress fluctuations and by reaching a higher stress level in absolute. Aiming to sustain good quality development on fully homologous scale model turbines, the Hydraulic Machines Laboratory (LAMH) of Laval University has developed a methodology to operate model size turbines on transient regimes such as start-up, stop or load rejection on its test stand. This methodology allows maintaining a constant head while the wicket gates are opening or closing in a representative speed on the model scale of what is made on the prototype. This paper first presents the opening speed on model based on dimensionless numbers, the methodology itself and its application. Then both its limitation and the first results using a bulb turbine are detailed.

## 1. Introduction

The LAMH's team develops its expertise in transient operation since 2010 by acquisitioning data during a runaway event at the very end of the experimental program of Axial-T, the first project of the Consortium on Hydraulic Machines based at Laval University, which aims at achieving a better understanding of the hydraulic behaviours of low-head turbines [2, 3]. At that time, the objective behind those measurements was to pioneer the transient operation on model in preparation to Bulb-T, the second project of the consortium. Among numerous challenging measurements at different locations in the whole turbine [5, 6], it has been proposed to explore the dynamic behaviours of the flow in the turbine during transient operation. Start-up sequences were focused in this project since in today's world of partially deregulated utilities and grid systems where fish and water issues often eclipse energy issues, the operating flexibility of hydro machines has led turbines to become the load-follow units, bringing continuous load changes and partial load operation. In some cases, such machines are cycled on and off-line several times per day. As reported by Gagnon & al. [1] the shaft can experience important torque fluctuations during a start-up. Figure 1 shows a torque record of the studied turbine during a start-up sequence where the guide vanes move from 0° to 30°. Major torque fluctuations appear from about 18° of opening, showing that the studied turbine presents this characteristic on model, justifying the development of such a method.





**Figure 1:** Torque fluctuations during start-up

300 ms and has been stabilized about ten seconds later. Discharge measurement reacts after four seconds, damped due to the low frequency response of the flowmeter. Aiming getting good dynamic features, major improvements were then mandatory on both flow measurement and method to keep a constant head during the transient condition, either opening or closing distributor or acceleration stage for runaway. Both transient rotational speed and flow measurement issues are addressed by Coulaud & al. [4] while head and dynamic control of the test stand is the content of this paper. A torque meter allowing to measure torque due to the generator acceleration has been designed for the whole Bulb-T project [7]. This was mandatory to get the actual torque on shaft; information not provided by a brake mounted as a dynamometric balance as one can see in figure 2.

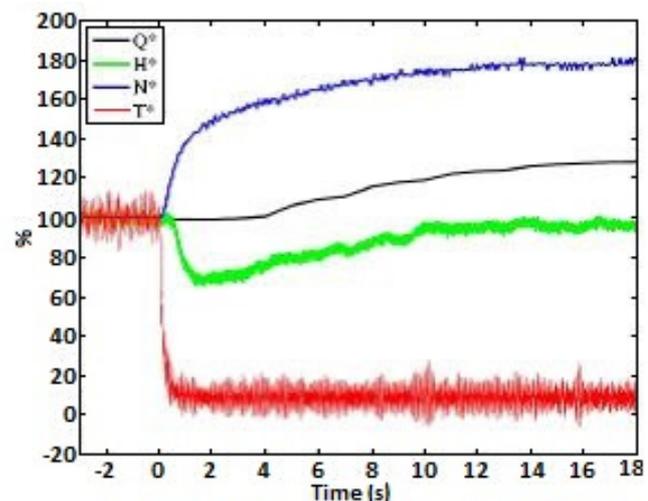
The turbine to be controlled in transient regime in the framework of this specific project is an adjustable blade bulb turbine presenting a specific speed  $N_s = 571$  at BEP. It has been used as a propeller for this case since there is no motorized mechanism for blade opening control on this model. For the whole Bulb-T program, the selected runner blade opening was 133% of rated blade angle and  $\Psi/\Psi_{opt} = 0.78$  was selected. With those initial conditions, the specific speed becomes  $N_s = 763$  and the synchronization speed occurs for a gate opening of  $30^\circ$ . Such a high  $N_s$  is considered a very challenging case since it represents a large volume of water to accelerate. This case then shows the possibility to successfully control the test stand in transient regimes for eventual future projects involving lower  $N_s$  turbines.

## 2. Expected performances

In order to target the guide vane opening speed to reach on a model size turbine, a dimensional analysis has been conducted. The variables governing the global time for a start-up are listed below:

- $t_o$	Opening time	[s]	- $Q$	Discharge	[m <sup>3</sup> /s]
- $\Delta P$	gross head	[Pa]	- $a$	Sound speed	[m/s]
- $\rho$	Density	[kg/m <sup>3</sup> ]	- $\mu$	Viscosity	[N s/m <sup>2</sup> ]
- $D$	Runner reference diameter	[m]	- $\omega_r$	Runner speed	[rad/s]

From the early beginning of LAMH's activities in the nineties, head is maintained constant through a PID regulating the pump speed. Very low gains were used getting stable and safe operation for both model and test stand installation. In the pioneering stage of dynamic control of the test stand, measurements were recorded during a runaway event of a propeller turbine [2, 3]. One can see in figure 2 the evolution of the different parameters during this event. Torque dropped almost instantaneously, head dropped after around



**Figure 2:** Parameters evolution during a runaway event at the pioneering stage

- $\dot{\omega}_r$	Runner acceleration	[rad/s <sup>2</sup> ]	- $\omega_{gvc}$	Guide vane closing speed	[rad/s]
- $J$	Inertia	[kg m <sup>2</sup> ]	- $g$	Gravitational acceleration	[m/s <sup>2</sup> ]
- $T$	Torque	[Nm]			
- $\omega_{gvo}$	Guide vane opening speed	[rad/s]			

However, since the project presented in this paper focuses on a constant guide vane opening speed  $\omega_{gvo}$ ,  $\Delta P$ ,  $D$  and  $\rho$  have been chosen as repeated variables for analysis since they are commonly used in reduced values for hydraulic machines which allow comparing turbine of unit diameter (1m) working on unit head (1m).

$$\Pi_1 = t_o \rho^a D^b \Delta P^c$$

$$[T][ML^{-3}]^a [L]^b [ML^{-1}T^{-2}]^c = [M]^0 [L]^0 [T]^0$$

$$\begin{array}{l} [M] \quad a + c = 0 \\ [L] \quad -3a + b - c = 0 \\ [T] \quad 1 - 2c = 0 \end{array} \Rightarrow \begin{array}{l} a = -\frac{1}{2} \\ b = -1 \\ c = \frac{1}{2} \end{array}$$

$$\Pi_1 = \frac{t_o \Delta P^{1/2}}{D \rho^{1/2}}$$

Keeping this dimensionless number constant while replacing  $\Delta P/\rho$  by  $E = gH$ , one can then deduce time factor, then reduced time

$$t_{ED} = \frac{t\sqrt{E}}{D}$$

$$t_{11} = \frac{t\sqrt{H}}{D}$$

Time relationship between model and prototype then becomes

$$\frac{t_m}{t_p} = \frac{D_m \sqrt{H_p}}{D_p \sqrt{H_m}}$$

Based on a homologous bulb turbine having scale factors  $\lambda_D=10.588$  and  $\lambda_H=2.662$ , its opening time of 10 s on prototype then become 1.54 s on model. Considering a constant opening speed for this project, a velocity of 20°/s is required to reach the guide vane angle of 30°, which is corresponding to the opening required to get synchronous speed for this turbine, in 1.5 s.

### 3. Hardware modifications

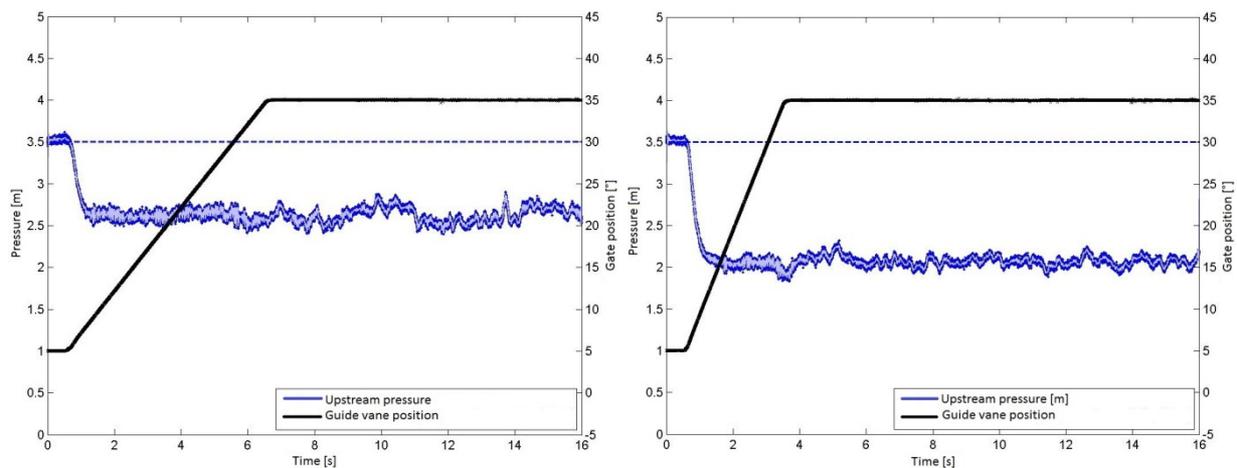
On its main test stand, LAMH has a Vertiline 28SKKS-1 pump driven by a GE 444-5011 asynchronous motor. This vertical induction motor is connected to a Relcon AFR-8000 drive. Head is measured and controlled by an Endress & Hauser PMD-230 pressure transducer. Discharge is measured with an ABB Taylor-Kent MagMaster electro-magnetic flowmeter.

Aiming to achieve dynamical response of the system, some changes were mandatory in the hardware of the test stand.

- The existing head transducer has been replaced for a dynamic one having a response within 1ms avoiding first the 300 ms lag at the very beginning of the event and allowing giving the actual pressure information to the controller during transient regime.
- The acceleration parameter of the frequency modulator driving the main pump's motor has been set to maximum.
- The scan time of the PID controller has been reduced.
- The electro-magnetic flowmeter has been discarded since its minimal time constant is 2 s. Pressure-time method has been settled and calibrated. [4]

#### 4. Methodology

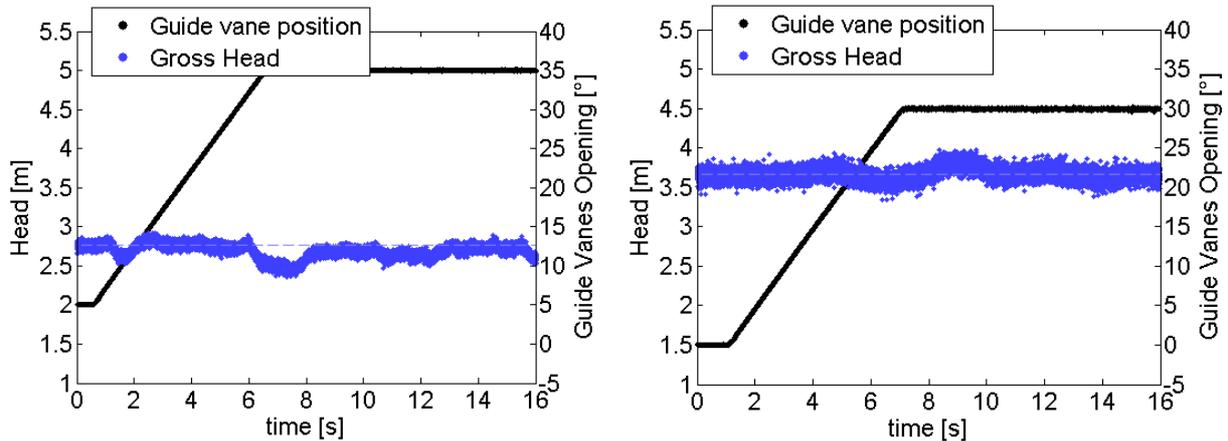
The first step consists in finding rules for compensating flow increase while the distributor is opening according to the specific characteristic of the LAMH's pumping installation. This step has been investigated starting with a minimal opening allowing an initial flow. This has been achieved mainly by controlling the time resolution of the device giving the analog command to the drive. As one can see on figure 3, it was possible to maintain head constant for different opening speed. Head fluctuations observed after opening ramp is characteristic of the studied turbine at this particular runaway condition.



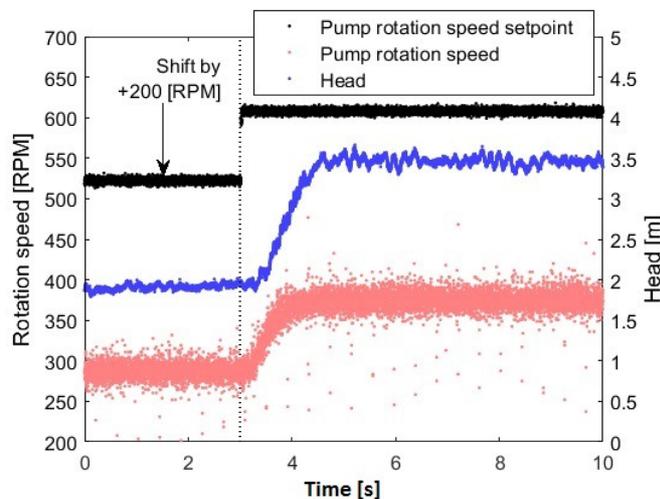
**Figure 3:** Gross head measured during distributor opening for two different opening speeds.  
Left: 5°/s, Right: 10°/s

The second step consists in controlling the head drop from the very beginning of the distributor's movement. For this step, after a few attempts, it has been chosen to withdraw the control with a PID which is necessary leading to a lag since it is not possible to react prior to the effective head drop. A preprogrammed analog command was sent to the drive synchronised with the beginning of the distributor movement. Due to both pump and whole hydraulic circuit time constants, it has been necessary to anticipate the beginning of the distributor's movement by few hundredths of second and to begin the command by a step, the ramp coming afterward.

As one can see in figure 4a), method has contributed to reduce head fluctuations at the initiation of distributor movement for low opening speed, (0 – 5°/s). From this point it has not been possible to get a perfectly flat head characteristic due to the dynamic characteristic of the whole test stand. This characteristic has been measured and is presented in figure 5. Either a small and short head drop occurs, either a small and short over pressure occurs by anticipating the movement a little more.



**Figure 4:** Gross head measured during distributor opening for a) 5°/s b) 10°/s



**Figure 5:** Test stand’s time constant

These head fluctuations at the beginning of the distributor movement have been overcome by inserting an important damping in the system by a free surface in the upstream tank, which allowed keeping head constant over whole opening as one can see in figure 4b).

Since intake submergence had to be conserved, the free surface has been kept above 90% of the tank diameter. Due to the cylindrical shape of the upstream tank, level variation, then pressure, is important

on the top of the tank, even for a small volume. So from 10°/s, free surface in the upstream tank is not sufficient. This then leads to the third step which was to control air pressure over this free surface through a very fast pneumatic proportional valve connected to both compressed air and a vacuum pump as shown in figure 6.

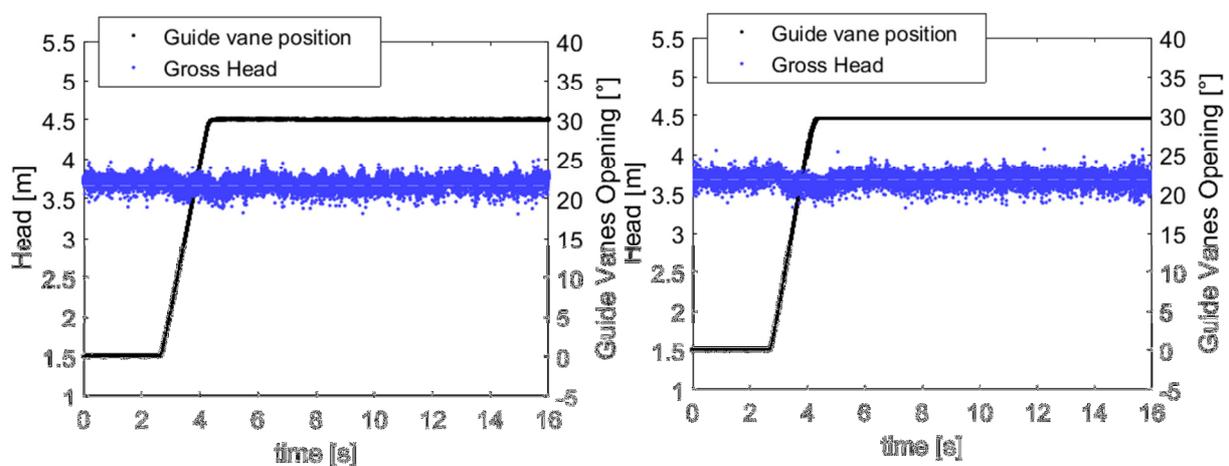
This third step obviously led to an additional difficulty for flowrate measurement. The water level is then recorded to know its variation over time. Knowing the characteristic shape of the upstream tank, it is possible to know the flow



**Figure 6:** Pressure control apparatus on the upstream tank

variation over time. Anticipating the possibility of a non-uniform free surface, the volume of injected air is also measured with a mass flowmeter; along with both pressure and temperature to get the injected volume. Both methods can then be compared for a suitable compensation of the flow variation. This important consideration is addressed by Coulaud & al. [4] in combination with a method to measure the discharge dynamically replacing the electro-magnetic flowmeter.

This air injection allows reaching higher opening velocities. Figure 7 shows the head over time characteristic for opening speeds of a) 18 °/s and b) 20°/s, which is the final achievement reached under a 3.6 m head. One can see in this figure that 20°/s is the limit for keeping a constant gross head with the available equipment on LAMH's test stand since the record presents a slight head variation during gate movement from this opening velocity.



**Figure 7:** Head over time for a) 18°/s and b) 20°/s

## 5. Conclusion

In the framework of Bulb-T project, LAMH has developed the expertise to dynamically run its test stand in transient regimes. It has been achieved by establishing the relation between pump rotation speed and gross head for a specific turbine and by running with a controlled free surface in upstream tank. The objective here was to maintain a constant gross head during a start-up; by extension it would be possible to impose head changing as a function of time  $H=f(t)$  in order to be in perfect similitude with a given prototype. A similar procedure could be applied to control head as function of time during either a load rejection or while stopping a unit.

This first transient control of a test stand for model size turbines has been successfully performed for a dual regulation bulb turbine used as a propeller with a specific speed of ( $N_S=571$ ). One may consider this as a worst case scenario since it should theoretically be easier to achieve with lower  $N_S$  turbines requiring lower flow gradient during transient stage. The possibility to impose a head function could be especially interesting for turbine presenting much longer penstocks than bulbs.

Next step will be to properly represent the rotor inertia. This will be feasible by controlling runner acceleration instead of the runner rotation speed. This could be done by modulating the excitation of the eddy current brake's inducer [7] since one will have to brake due to dynamometer inertia which is much lower than generator's one. To represent a stopping unit, one would have to motorize the dynamometer to control runner deceleration.

## 6. Acknowledgement

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