Preliminary investigation of flow dynamics during the start-up of a bulb turbine model

M Coulaud, R Fraser, J Lemay, P Duquesne, V Aeschlimann, C Deschênes
Hydraulic Machine Laboratory (LAMH), Department of Mechanical Engineering, Laval University, 1065 Avenue de la médecine, G1V 0A6, Québec, Canada
E-mail: maxime.coulaud.1@ulaval.ca

Abstract. Nowadays, the electricity network undergoes more perturbations due to the market demand. Additionally, an increase of the production from alternative resources such as wind or solar also induces important variations on the grid. Hydraulic power plants are used to respond quickly to these variations to stabilize the network. Hydraulic turbines have to face more frequent start-up and stop sequences that might shorten significantly their life time. In this context, an experimental analysis of start-up sequences has been conducted on the bulb turbine model of the BulbT project at the Hydraulic Machines Laboratory (LAMH) of Laval University. Maintaining a constant head, guide vanes are opened from 0° to 30°. Three guide vanes opening speed have been chosen from 5°/s to 20°/s. Several repetitions were done for each guide vanes opening speed. During these sequences, synchronous time resolved measurements have been performed. Pressure signals were recorded at the runner inlet and outlet and along the draft tube. Also, 25 pressure measurements and strain measurements were obtained on the runner blades. Time resolved particle image velocimetry were used to evaluate flowrate during start-up for some repetitions. Torque fluctuations at shaft were also monitored. This paper presents the experimental set-up and start-up conditions chosen to simulate a prototype start-up. Transient flowrate methodology is explained and validation measurements are detailed. The preliminary results of global performances and runner pressure measurements are presented.

1. Introduction
Nowadays, the electricity network undergoes more perturbations due to the market demand. Additionally, an increase in the production from alternative resources such as wind or solar also induces important variations on the grid. Hydraulic power plants are used to respond quickly to these variations to stabilize the network. Hydraulic turbines have to face more frequent start-up and stop sequences that might shorten significantly their life time ([1],[2],[3]).

With the fast motion of the guide vanes and the high discharge gradient, the turbine undergoes complex transient flows. A better understanding of the hydraulic behaviour during these transient events is required in the early stage of the turbine design, in order to estimate the operational lifespan and to define transient sequences which are less destructive. The prediction of the forces during the transient is a major challenge both from the simulation and measurement perspectives. In this context, an experimental analysis of start-up sequences has been conducted on a bulb turbine model, which has already been studied under steady operating conditions ([4],[5]).
This paper presents a global overview of the experimental set-up used to gather data that will lead to the analysis and the understanding of the flow dynamics during start-up sequences. Various time-resolved measurements are performed along the model and on-board the rotor. Measurements of velocity, torque, pressure, flowrate, strain, runner speed and guide vane position are performed synchronously. The flowrate measurement is performed using Time-Resolved Particle Image Velocimetry (TR-PIV) coupled with water volume monitoring in the upstream tank. A detailed validation of these methods is also presented.

2. Experimental set-up

2.1. Model turbine and test rig

The model turbine under investigation on LAMH test bench is a bulb turbine with four runner blades and 16 guide vanes. It stands between two large tanks. In the short inlet conduit, a bulb is supported by two symmetrical piers (upper and lower). Inside, a compact eddy current break is used to control the runner angular velocity in steady state regime. During a start-up sequence, it is not powered but it accounts for 71% of the inertia of the rotating parts. The runner blade angle is held constant at 30°. The draft tube is composed in two parts: The first one is a conical part made of PMMA, with a half angle opening of 10.25°, and the second part is a transition from circular to rectangular cross section made of steel. At the end, a large rectangular cross section conduit allows to connect the model to the downstream tank.

Several experimental campaigns were previously performed in steady state regime. The flow behavior was analyzed at different part of the machine [6–10]. The present experiments study flow dynamics during start-up sequences. One of the main challenges is to keep a constant head between the two tanks during the transient regime in order to simulate a constant gross head. Also, emphasis is made on synchronization between measurements and sequences. Due to the leakage flow, the runner rotates even if the guide vanes are closed. But the beginning of guide vane opening starts exactly for the same position of the runner to ensure repeatability between experiments.

![Bulb model of BulbT project](image)

Figure 1: Bulb model of BulbT project

The test rig is set up to perform steady measurements according to the IEC 60193 standard. The methodology used to adapt the test rig to transient measurement is detailed in [11]. Thus, the modifications made to overcome the drop of head during the start-up allow sequences to be performed with a guide vane opening (GVO) speed up to 20°/s.

2.2. Start-up conditions

To take into account the scale factor between models and prototypes, a dimensionless analysis has been conducted. From this analysis, three coefficients are used in this paper: $N_{11}$ the
unitary runner speed, $T_{11}$ the unitary torque and $\varpi_0$ the dimensionless guide vane opening speed coefficient.

$$N_{11} = \frac{N_r D}{\sqrt{H}}, \quad T_{11} = \frac{T}{\sqrt{D^3 H}} \quad \text{and} \quad \varpi_0 = \frac{\omega_{geo} D \sqrt{\rho}}{\sqrt{\Delta P}} \quad (1)$$

Where:
- $N_r$ is the runner speed,
- $D$ is the runner diameter,
- $H$ is the head,
- $T$ is the runner torque,
- $\omega_{geo}$ is guide vane opening speed,
- $\rho$ is the density of fluid,
- $\Delta P$ is the pressure difference between upstream tank and downstream tank.

On bulb turbine prototype, $\varpi_0$ can reach 0.0205.

Even if a common start-up sequence on prototype is composed of a guide vane opening phase and a guide vane closure phase, the present study is simplified to a unique opening sequence from $0^\circ$ to $30^\circ$. $30^\circ$ guide vane opening allows to reach the synchronization speed of 175 RPM. Three guide vane opening speeds are chosen: $5^\circ/s$, $10^\circ/s$ and $20^\circ/s$. They correspond respectively to $\varpi_0$ of 0.0049, 0.0098 and 0.0197. The last one is close to the maximum $\varpi_0$ that could be reached on bulb turbine prototypes. The other dimensionless numbers that could be obtained from the variables used for dimensionless analysis like $T_{11}$ aren’t controlled and are results of the model. The inertia depends of the geometric characteristics of the model. Since no modulation system is used to control runner acceleration or torque, they are a result of the dynamic behaviour of the model as well.

### 2.3. Transient turbine measurements
A total of 64 sensors are used to obtain global and local information on the flow dynamics during the start-up sequence. All these measurements are obtained by three synchronized data acquisition boards PCI-6036E, PCI-6034E and PCI-6255. The sampling rate is set to 2.5 kHz and the measurements are performed during 30s. The sensors in the rotating part are connected to the data acquisition boards by a wireless technology device with a 5kHz bandwidth. The start-up sequence is divided in three parts. During the first 10s, guide vanes are closed. Then, guide vanes are opened from $0^\circ$ to $30^\circ$ according to a predefined opening speed. Finally, the runner is let at speed no load conditions until the 30s is reached.

![General view of LAMH Test rig. Dashed lines illustrate free surface in upstream and downstream tanks. Flowmeter meter measurements and air injection are shown.](image.png)

Figure 2: General view of LAMH Test rig. Dashed lines illustrate free surface in upstream and downstream tanks. Flowmeter meter measurements and air injection are shown.

Two omega PX409 differential pressure sensors with 1 kHz bandwidth are used. One of them measures the gross head between tanks and the other gives water level in the upstream tank. The net head, outlet pressure and the water level in the downstream tank are provided by Endress & Hauser PMD-230 pressure transducer. Runner speed is derived from an EL120
encoder and guide vane opening is provided by a QD145-05 encoder. The torque is directly obtained on the runner shaft [12]. A Magmaster ABB electromagnetic flowmeter (EFM) allows to measure flowrate at the initial and final states of the sequence. However, during the transient regime, the electromagnetic flowmeter is not reliable due to its low time response. So, some test cases are run with TR-PIV flowrate measurement as shown in figure 2. The details of this measurement are exposed in the section 3.1. Due to air injection in the upstream tank to maintain the gross head, the flowrate through the turbine is a combination of the amount of air injection and the inlet flowrate of the upstream tank (figure 2). To measure the amount of air injected in the upstream tank, the air flowrate is measured by an Endress & Hauser Promass 83 Coriolis flowmeter. To calculate air density in upstream tank, air temperature and air pressure in this tank are measured respectively by a B57540G0502F000 Epcos thermistor and a GP50 absolute pressure sensor.

Local pressure measurements are performed in both stationary and rotating parts of the machine. Only the rotating part are analyzed in this paper. Pressure sensors are Unisensor chips flush mounted on the runner blade 1 (figure 3).

Finally, to get a good average for the hydraulic behavior during start-up, 50 start-ups for each opening speed are performed. The global average $\bar{\chi}(t)$ of a physic quantity $\chi$ at $t$ is determined by:

$$\bar{\chi}(t) = \frac{1}{N} \sum_{i=1}^{N} \chi_i(t)$$

(2)

Where: - $\chi_i(t)$ is the value $\chi$ at $t$ for the $i^{th}$ test,
- $N$ is the total of test.

2.4. TR-PIV flowrate measurement

To obtain the flowrate during transient, two-component velocity fields in the pipe are measured with time-resolved particle image velocimetry (TR-PIV) (figure 2). To reduce the importance of image deformation resulting from the different refraction indexes in air, acrylic and water, the pipe surface on the outside is equipped with flat windows. But the image deformations created by the curved inside wall still need to be corrected with a cubic polynomial mapping function. The calibration is done by using a checker board target. To ensure two-dimensional measurement, the camera was mounted normal to the target.

The PIV system consists of a 2x30-mJ Nd:YLF pulsed laser (Litron Laser, LDY 300) generating a 527 nm laser sheet and a digital camera (Phantom V641 1600 × 2560 pixels CCD...
array size) mounted with 60 mm Nikkor lenses. The flow is seeded with 10 μm silver-coated glass spheres with relative density of 1.4. The laser sheet is evaluated to be 2 mm thick. The processing of the single-exposure dual-frame PIV images is done with Dantec Dynamics DynamicStudio software release 4.15. Image processing is done using iterative multigrid interrogation with window offset, cross-correlation with fast Fourier transform (FFT) and Gaussian sub-pixel interpolation. The iterative procedure comprises nine iterative steps with three interrogation window sizes. The final interrogation window size is 16x64 pixels, respectively in radial and axial directions. Interrogation windows are overlapped by 25% - 50%. At each iteration, peak validation and local neighbourhood validation are performed to detect and substitute false vectors. At the end of the iterative procedure, more rigorous vector validations are executed. Validations include N-sigma with a tolerance of four standard deviations (only for steady state measurements) and a local universal outlier validation [13]. The time between two successive laser flashes is 200 μs. To obtain a sufficient displacement at the lowest velocity in transient measurements, the two successive images used in the cross-correlation are separated by 4200 μs which corresponds to the time between the first frame of the previous acquisition and the second frame of the next acquisition.

Velocity is normalized with the reference velocity ($V_{ref}$) defined with mean core region velocity at the highest Reynolds number. All positions are normalized by $R_{ref}$ which is the pipe radius. Datasets for steady measurements contains 500 realizations and the acquisition rate is 500 Hz. For transient measurements, datasets and repeated 15 times and each of them contains between 3300 and 1750 realisations at 500 Hz. The measured area covers 96.6% of the total pipe diameter in the radial direction and the axial direction of the plane measures 0.76 $R_{ref}$.

3. Flowrate measurement

To determine the flowrate through the turbine during a start-up sequence, the water flowrate entering the upstream tank and the variation in time of the water volume in this tank must be evaluated. The inlet water flowrate in the upstream tank is provided by TR-PIV measurements. The variation in time of the water volume in the upstream tank is obtained from the balance of air injection in this tank.

3.1. TR-PIV flowrate analysis

TR-PIV measurements are conducted just upstream of the location of the electromagnetic flowmeter as shown in figure 2.

To estimate flowrate during start-up, TR-PIV flow profile are taken fifteen times for each opening. The instantaneous diametric velocity profile is so provided, and the flowrate is calculated by integration.

![Figure 4: Velocity profile in steady state for medium and high flowrates which are respectively cases II and III (symbols = measurements, lines = theoretical profiles).](image-url)
In a first step, three steady flow measurements (Test case I, II, III) are considered and the results are compared to the electromagnetic flowmeter. Test case I corresponds to the minimum flowrate, III is the maximum flowrate and II is a medium flowrate between I and III. As the TR-PIV cannot measure velocity near the wall, a theoretical profile is determined by using a power law equation valid under pressure gradient in turbulent boundary layers [14].

Figure 4 compares the measured velocity profile $U_{meas}$ to the theoretical velocity profile $U_{prof}$ for maximal and medium flowrates. For these two test cases, theoretical velocity profile corresponds well to the TR-PIV measurement. So, theoretical velocity profiles are good choices to determine flowrates.

Table 1 presents the ratios of TR-PIV flowrate $Q_{TR-PIV}$ and electromagnetic flowrate $Q_{EFM}$. Flowrates are determined with TR-PIV, within ±5% for the whole range. The largest error found for test case I is due to the low flowrate. The absolute error of TR-PIV compared to EFM is below 1 L/s.

| Test case | $Q_{TR-PIV}/Q_{EFM}$ |
|-----------|----------------------|
| I         | 1.045                |
| II        | 0.988                |
| III       | 1.019                |

Table 1: Comparison of EFM and TR-PIV in steady regime.

The methodology of TR-PIV in steady state regime is extended to transient regime. Figure 5 shows the evolution of the flowrate during start-up at $10^\circ/s$ and $20^\circ/s$. For each physical quantity presented, each of the fifteen different repetitions is represented by the light dots and their mean evolution is illustrated by coloured line. The black line corresponds to the guide vane opening angle. The flowrates are represented by blue and red lines. The blue line referred to TR-PIV measurements and the electromagnetic flowmeter are represented by the other. The two green dashed lines point out the initial and final flowrates estimated by EFM. First of all, TR-PIV measurements fit very well at the initial and final state, which give confidence in the method. The EFM has a high delay of response compared to TR-PIV, especially for an opening...
at 20°/s where the guide vanes reach their final state before a change on EFM. Clearly, EFM cannot follow the time evolution of flowrate compared to TR-PIV. Before the beginning of the guide vane opening, the flowrate rises a little. This phenomenon is explained because the test-bench pump has already begun to accelerate to avoid a drop of the gross head. On the other side, the steady state final flowrate is reached hundreds of milliseconds after guide vane opening.

Figure 6 compares velocity profiles in the pipe for an equivalent flowrate during steady state regime and transient regimes at 5°/s and 10°/s. There is a significant difference between steady regime and transient regimes, which shows that the steady state hypothesis is not applicable in this case. The change of profile is due to the difference between core and wall regions where inertial forces are greater in the first region than in the second one.

![Figure 6: Difference in velocity profiles for two guide vane opening speed sequences and steady state regime presenting the same instantaneous flowrate (symbols = measurements, lines = theoretical profiles).](image)

3.2. Flowrate through the turbine

The flowrate through the turbine is estimated using control volume analysis for water and for air in the upstream tank.

For water, the control volume analysis yields:

\[ \frac{dV_w}{dt} + Q_{w_{OUT}} - Q_{w_{IN}} = 0 \]  \hspace{1cm} \text{(3)}

Where:
- \( V_w \) is the water volume in the upstream tank \( (V_w = V_{tank} - V_{air}) \),
- \( Q_{w_{OUT}} \) is the water flowrate leaving the upstream tank,
- \( Q_{w_{IN}} \) is the water flowrate entering the upstream tank.

For air, the same analysis gives:

\[ V_{air} \frac{d\rho_{air}}{dt} + \rho_{air} \frac{dV_{air}}{dt} - \dot{m}_{air} = 0 \]  \hspace{1cm} \text{(4)}

Where:
- \( V_{air} \) is the air volume in the upstream tank \( (V_{air} = V_{tank} - V_w) \),
- \( \rho_{air} \) is air density in the upstream tank,
- \( \dot{m}_{air} \) is the mass flowrate injected in the upstream tank.

Considering air as an ideal gas and assuming an adiabatic expansion, the two above equations give (with \( \frac{dV_w}{dt} = -\frac{dV_{air}}{dt} \)):

\[ Q_{w_{OUT}} = Q_{w_{IN}} + \frac{r_{air} T_{air}}{P_{air}} \dot{m}_{air} - \left[ \left( \frac{P_{air_{out}}}{P_{air}} \right)^{1/\gamma} \frac{V_{air_{init}} T_{air}}{P_{air}} \left( \frac{1}{T_{air}} \frac{dP_{air}}{dt} - \frac{P_{air}}{T_{air}^2} \frac{dT_{air}}{dt} \right) \right] \]  \hspace{1cm} \text{(5)}
Where:
- \( T_{\text{air}} \) is the air temperature in the upstream tank,
- \( P_{\text{air}} \) is air pressure in the upstream tank,
- \( r_{\text{air}} \) is the air specific gas constant,
- \( P_{\text{air}, \text{init}} \) is the initial air pressure in the upstream tank,
- \( V_{\text{air}, \text{init}} \) is the initial air volume in the upstream tank.

Figure 7 shows the difference between the flowrate measured by the TR-PIV and the flowrate through the turbine. The guide vane opening is represented by the black line. The initial and final flowrates correspond to the two green dotted lines. The flowrate provided by the TR-PIV is illustrated by a red line and the turbine flowrate obtained by using equation 5 corresponds to the blue line. The difference between these two curves rises a little during the sequence but remains relatively small. The air injection in the upstream tank seems to have a small impact on the flowrate through the turbine.

![Figure 7: TR-PIV flowrate vs turbine flowrate for the 20°/s guide vane opening speed.](image)

4. Global performance
On the left of figure 8, the evolution of guide vane opening and normalized head for the three test cases are presented. \( H_b \) corresponds to the averaging head during measurement. The head between tanks is kept really close to a constant value for the whole study up to a guide vane opening speed of 20°/s. Besides, the sequence is rigorously repeatable as shown on figure 8 where four repetitions of each test case are represented. On the right hand side, unitary torque is shown for the same test case. The torque reaches a maximum value in the first moment independently of guide vane opening speed, before decreasing more or less rapidly depending on guide vane opening speed. Some fluctuations when the maximum of the torque is reached can be observed and are pointed out by an arrow on figure 8. Also, the subsequent decreasing evolution of the torque is characterized by two distinct stages. A first plateau (red ellipse) is observed at about half the value of the maximum torque, where large amplitude variations are recorded. The duration and the level of this state depend on guide vane opening speed. This behavior can be harmful for the runner. The second stage corresponds to the end of guide vane opening, where the torque drops rapidly to zero mean value, with still large amplitude variations.

5. Pressure measurements
The pressure contours illustrated on figure 9 correspond to pressure coefficient of blade #1 at the time identified on figure 8. The left hand side represents contours on the pressure side and the right hand side shows contours on the suction side. Pressure coefficient is normalized by the dynamic pressure obtained with the flowrate at the end of start-up and the runner diameter. The flow direction is from the left to the right for each side of the blade. Black points illustrate
Figure 8: Global performance evolution during the start-up sequence for a guide vane opening of $5^\circ/s$, $10^\circ/s$ and $20^\circ/s$. Guide vane opening and normalized head are shown on the left and the unitary torque $T_{11}$ are illustrated on the right. In each test case, 15 repetitions are shown. The dashed lines show the beginning and the end of guide vane opening. The letters for the test case at $5^\circ/s$ correspond to the timeline of figure 9.

positions of pressure measurements. During the beginning conditions, the pressure coefficient on blade is around 0 (figure 9a).

On the suction side, pressure coefficient shows that there is almost no suction effect during the first stages of the start-up. So, the dynamic behaviour during start-up is like an impulsive type machine. Near the blade tip, pressure coefficient can be greater than zero. This is probably due to the tip clearance where pressure can travel from the pressure side to the suction side. Also, high pressure zones appear also at the leading edge near the hub. Between these locations, the pressure is lower. Moreover, pressure contours seem to be unsteady. This particular behaviour could be linked with an interblade vortex. Indeed, during start-up a cavitating interblade vortex was observed.

On the pressure side, pressure contours are more stable with stratification from the hub to the tip blade. Near the hub, the pressure is surprisingly below zero which means there is suction at this zone.

6. Conclusion
It is well admitted that the flow dynamic effects during transient regime reduces lifetime of turbines. So, to improve knowledge during these regimes, a model test experiment has been conducted at LAMH for a start-up sequence. The methodology of the experimental study
during start-up was presented in this paper. In the experiment, the pressure drop between upstream and downstream tanks was kept constant to simulate prototype conditions. Besides, a dimensionless analysis was conducted to define a representative time scale of start-up. Three test cases have been chosen from $5^\circ/s$ to $20^\circ/s$. The latest one reaches the maximum value of dimensionless speed $\varpi_0$ observed on prototypes.

A large amount of measurements has been performed and synchronized with the start-up sequence. These measurements provide global and local performances of the turbine. Several repetitions of each test cases have been made to obtain ensemble average and envelope function of measurements. In this paper, the emphasis has been pointed out on flowrate and pressure measurements. TR-PIV measurements have been chosen to get an average flowrate evolution during transient regime. At first, comparison in steady state flow has been conducted between electromagnetic flowmeter and TR-PIV. The results show a good match between methods. Then, TR-PIV measurement has been extended to transient regime where EFM is not reliable. The measurements have been repeated ten times for each guide vane opening speed. From these preliminary results, the flowrate goes on rising after the guide vanes reach their final state.

Due to air injection, the real flowrate through the turbine is a combination of air injection and inlet water flowrate in the upstream tank. A procedure to obtain the outlet flowrate estimation has been presented. Comparison between inlet and outlet flowrate in the upstream tank has been done for fifteen repetitions. The influence of air injection in the upstream tank on the flowrate in the turbine is low. Several torque fluctuations have been observed during start-up. A few of them appear at the beginning of start-up when the torque reaches its maximum. Then, more fluctuations are present during the end of the guide vane opening. The amplitude and duration of these fluctuations depend on guide vane opening speed. Pressure measurements on one blade are shown. During start-up, the turbine is acting as impulse-type machine. Part of the high pressure from the blade pressure side goes to the suction side due to tip clearance. Also, suction zone appears near the hub on the pressure side of the blade.

The next step of the study will be to focus on the strain measurements on blades. Also, hydraulic phenomena which occur during start-up will be analysed using local pressure

![Figure 9: Qualitative pressure contour on the runner. The left part represents pressure side and the right corresponds to suction side. Each row illustrates pressure on runner at the specific time (see figure 8).](image-url)
measurements in the draft tube and on the runner and a stereoscopic-TR-PIV in vaneless space.

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