Ultrasonic flow measurement under dynamic conditions (variation of flow speed) and geometrically unsteady conditions (after the elbow)

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Abstract

Flow monitoring in circuits for multiple regimes demands different measurement equipment for each regime that may be present in such circuit in order to acquire data within the range of the flow characteristics. This may add additional costs such as, equipment and data processing for the different regimes. Some of these multi-purpose circuits are proposedly built to held different regimes because they need to test different flow conditions for different applications. One example is the hydraulic circuits aimed to test models of hydraulic turbines under different conditions before the construction of the final protype. Non-invasive measurements as ultrasound represents a low cost alternative that offers high reliability to get a glimpse or more of the flow behavior at different regimes that may be present during the operation of the circuit without the need to switch to specialized measurement equipment for each regime. This paper addresses a current complex problem in using ultrasound measurements: while the this type of measurement has been proved efficient for stationary flow and in geometrical steady conditions, the measurement becomes complicate, even impossible, when these conditions are not satisfied. Our solution is to use the wide band ultrasound signal-based measurement and two ultrasound channels in order to adapt the acoustics paths to the arbitrary geometrical conditions. The results obtained in real configurations shows that the flow rate dynamics are accurately estimated using our two channel wide band ultrasound equipment.

Specific objectives

1-Measure flow rate during different regime conditions of the test bench, low flow circuit vs high flow circuit.

2- Detect flow rate variations during different regime conditions of the test bench, low flow circuit vs high flow circuit.

Keywords: Non-destructive testing, ultrasonic flow meter, matched filter, time-of-flight, multiple regimes, hydraulic turbine model.

1. Introduction - context

The purpose of our paper is to prove the feasibility of monitoring non-stationary flows in forced pipes by multi path ultrasonic sensing.

An important component of our methodology is ultrasonic transducer system and associated electronics, the installation principle of which is illustrated in Figure 1. The emission transducer (2) is connected to the AWG output (Arbitrary Waveform Generator) on the Tie Pie HS-5 board. The two scan channels on this board are used respectively for the acquisition of the ultrasound receive transducer at 1 MHz central frequency (3) and the optional pressure sensor (1). A laptop is in charge of controlling the operation of the system as well as the recording of data that is subsequently processed.

Figure 1 shows a simplified illustration of the ultrasonic system on a forced line

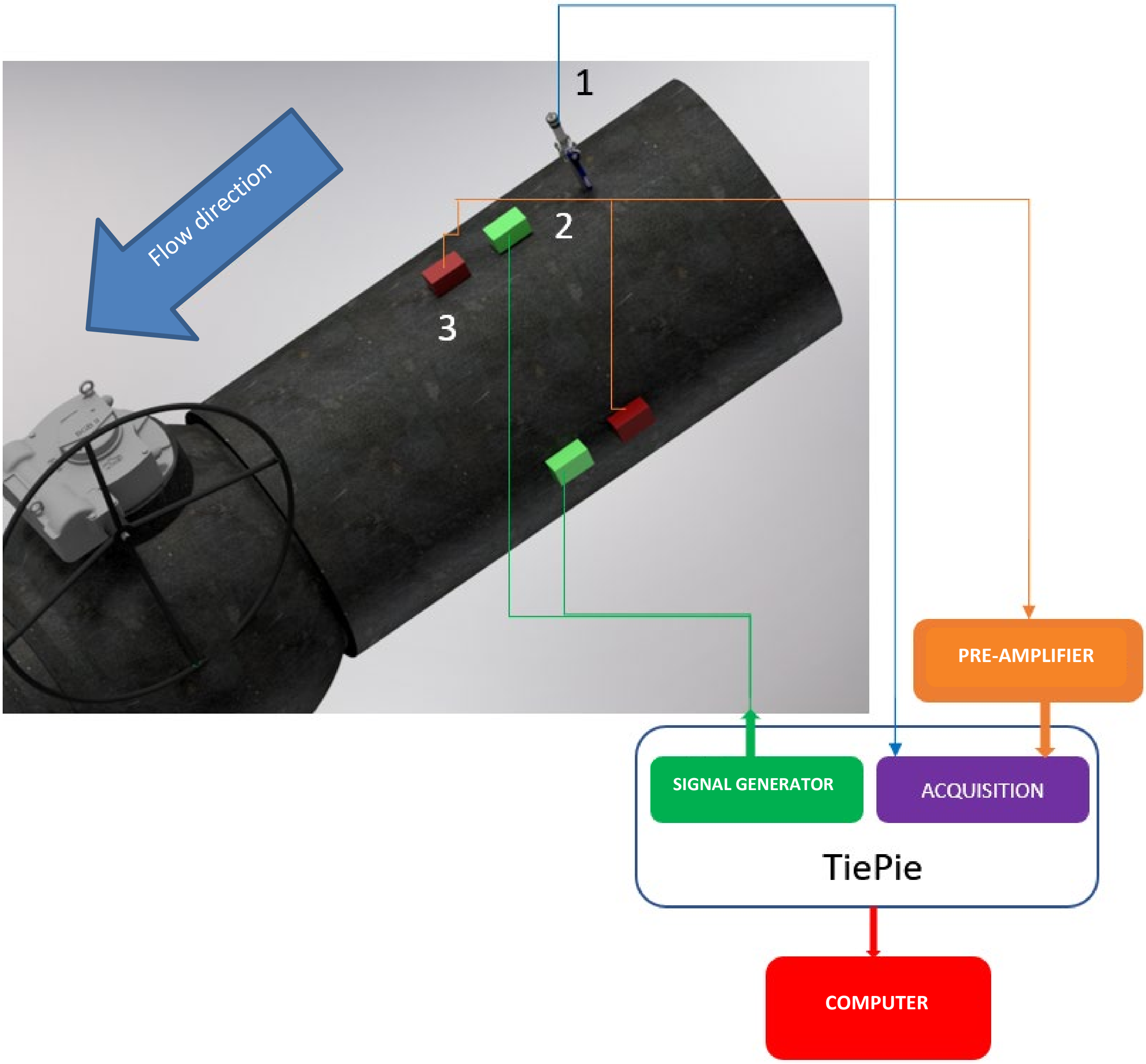

Figure 1: Block diagram of two paths ultrasound system

The experiments were performed at the turbine laboratories of General Electric Renewable Energy(Grenoble, France),where a test bench is used for testing different models of hydraulic turbines at different regimes.
The figure 2 shows few pictures with the two ultrasound paths installation as well as the electronic equipment used for these experiments. The ultrasound sensing composed by two paths is placed immediately after an elbow in the configuration illustrated by the figure 3.
The purpose of different flow regimes is to compare the dynamic flow rate estimated by our technique with the references values provided by an electromagnetic flow meter.

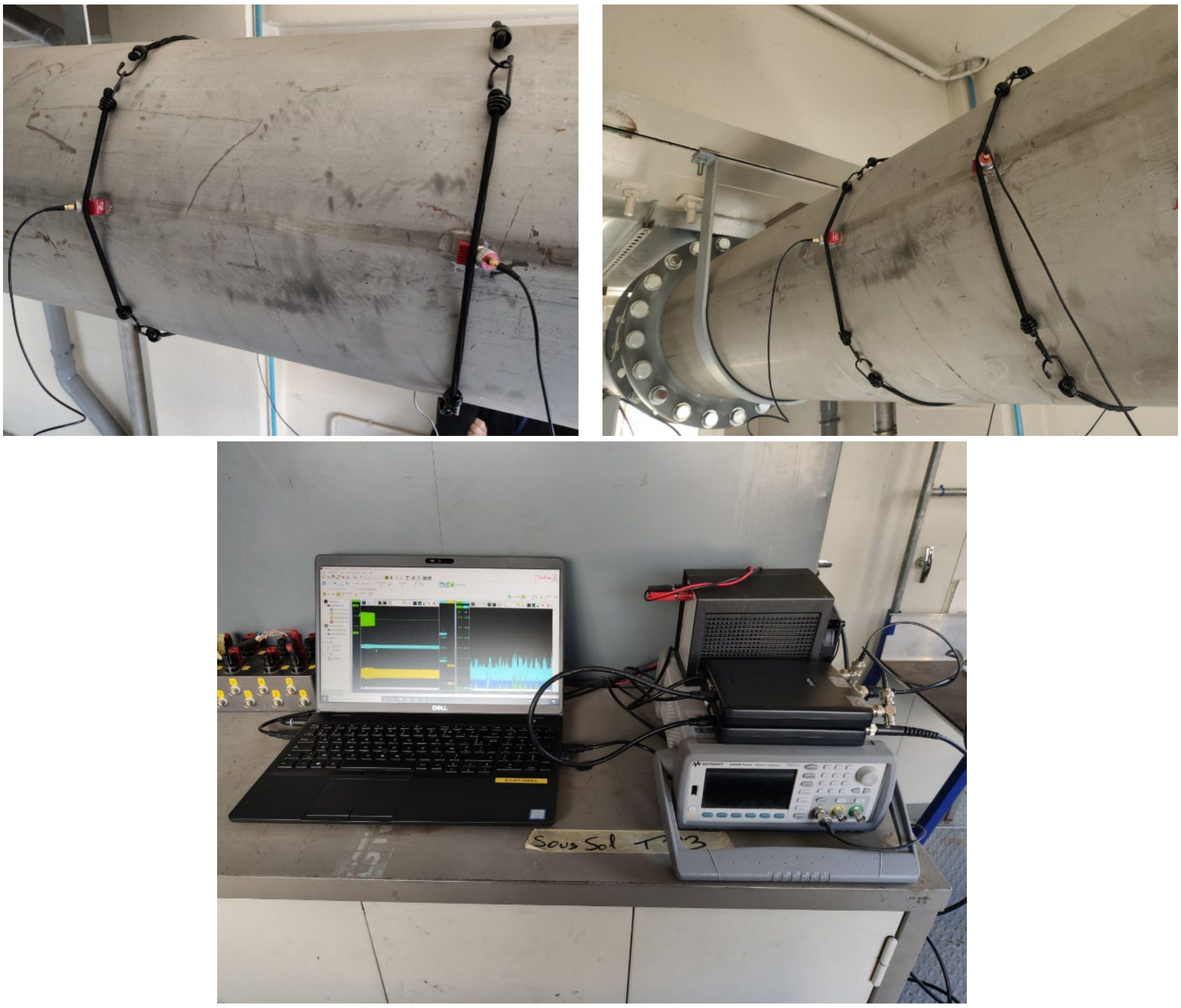

Figure 2: Illustration of ultrasound devices setup and the sensor configuration on the pipe under analysis

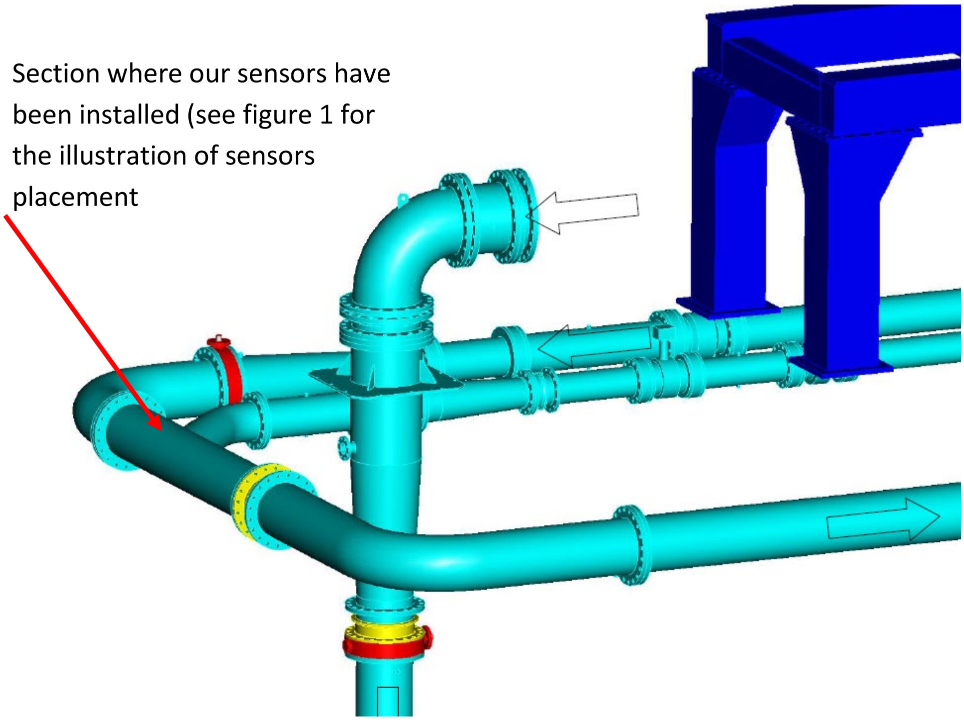

Figure 3: Illustration of General Electric Labs experimental facility and the section monitored by our system

2. Presentation of data processing algorithms

The HS-5 acquisition board is used to sample the ultrasonic signal acquired by the receiver transducer (the yellow transducer in Figure 2). The transmitted signal is a linearly frequency modulated signal in the band 0.7-1.200 MHz with a duration of 10 msec(milliseconds) and a period of 20 msec. That is, 50 ultrasound measurements per second are provided, allowing us to assess the flow rate dynamics.

At reception, the processing of ultrasonic signals consists first of correlating the signal received over each period in order to estimate the arrival time of the wave propagated in the pipe. Given the diameter of about 60 cm and the "V" emission configuration, the Time of Arrival - TOA corresponding to the zero velocity corresponds to 0.775 msec. In flow regime, the TOA will be estimated, for each period, as the time value corresponding to the maximum value of the correlation function in the search window (see Figure 2), defined around the TOA at zero velocity – TOA| v=0:

$$\boldsymbol{TOA_k = argmax_\tau \left[R_{ss}\left(k \cdot T_r + TOA|_{v=0} - \frac{D}{2} : k \cdot T_r + TOA|_{v=0} + \frac{D}{2}\right)\right]} \qquad (1)$$

where s is the received signal, Tr=10 msec is the repetition period, D=100 µsec – the size of the search window – see Figure4.

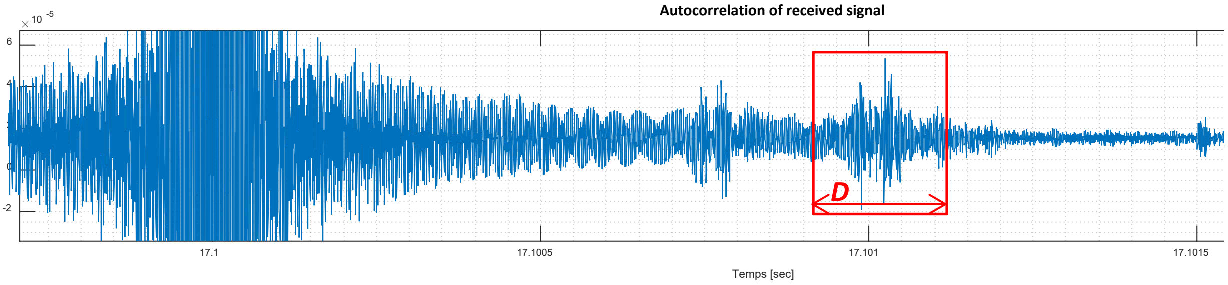

Figure 4: Illustration of the autocorrelation function of the received signal for period k and the definition of the TOAk estimation window

The average flow velocity in the measured section for period k is calculated using the formula:

$$v_k = \left(c - \frac{2 \cdot L}{TOA_k}\right) \frac{1}{cos\left(\frac{\pi}{4}\right)} \qquad (2)$$

where c=1480 m/sec is the velocity of the waves in the water, 2· L is the wave propagation distance and π/4 is the angle of transmission/reception of the sensors.

With this speed, we can estimate the instantaneous flow rate (corresponding to the period k) with the formula:

$$Q_k = v_k \cdot 1000 \cdot \frac{\pi d^2}{4} \qquad (3)$$

where d=80 cm is the internal diameter of the pipe.

3. Summary of experimental results

3.1 Low flow rate circuit

3.1.1 Q1, Non-stable speed before stabilizing at 0.290 m^3/s.
3.1.2 Q2, Steady RPM of 0.290 m^3/s.
3.1.3 Q3, Change of Regime to 0.2 m^3/s. (not stable).

3.2 High flow rate circuit

3.2.1 Q1, Transitional regime to 0.55 m3/s.
3.2.2 Q2, Transitional regime from 0.55 m3/s to 0.25 m3/s.

Measurement results

The results are presented in 3 graphs per test. TOF, time of flight, which shows the time that takes the ultrasonic beam by traveling the distance in "V", TOF1 is the time in the upstream-downstream direction and TOF2 in the downstream-upstream direction; U_{mean}/ U_{cordes}, the average speed calculated from the U components of each rope in the upstream-downstream and downstream-upstream directions. This speed is a difference between these two components, so the reference speed of the sound does not matter to calculate it, on the other hand, to know the approximate speeds in each string it is necessary to know the speed of sound in the propagation medium (water and its temperature), we chose t_{water} = 18 ° c. Finally, the last graph is U_{mean} vs Throughput. All graphs are accompanied by standard deviations for each 25 samples, which correspond to 0.5 seconds (the average values shown are also calculated with this time window), the observation times vary according to each test and the instructions to GE.

3.1 Low flow circuit tests.

3.1.1 Non-stable speed before stabilizing at 0.290 m3/s

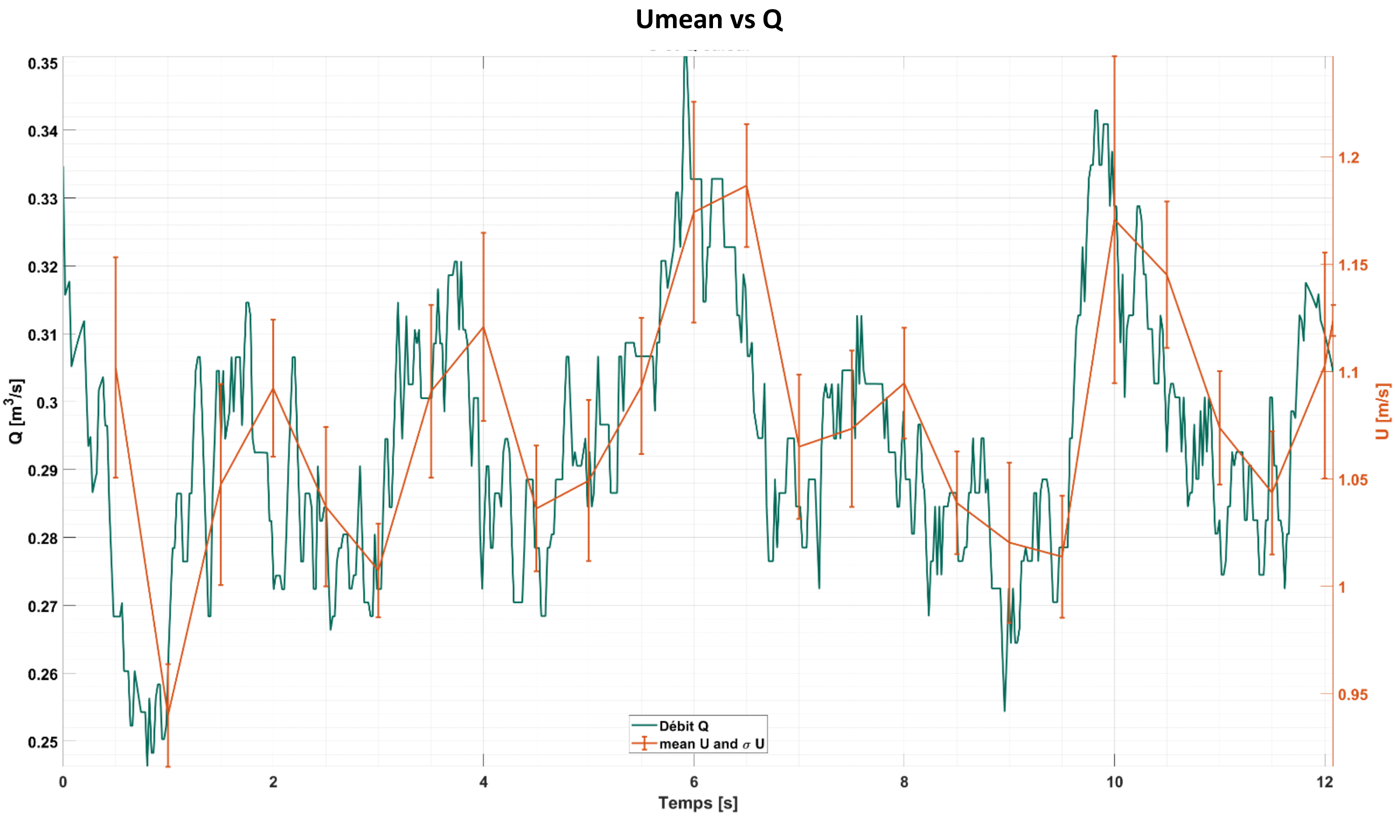

Figure 5: U mean an Q fluctuations before stabilizing at 0.290 m^3/s

3.1.2 Q2, Steady RPM of 0.290 m^3/s

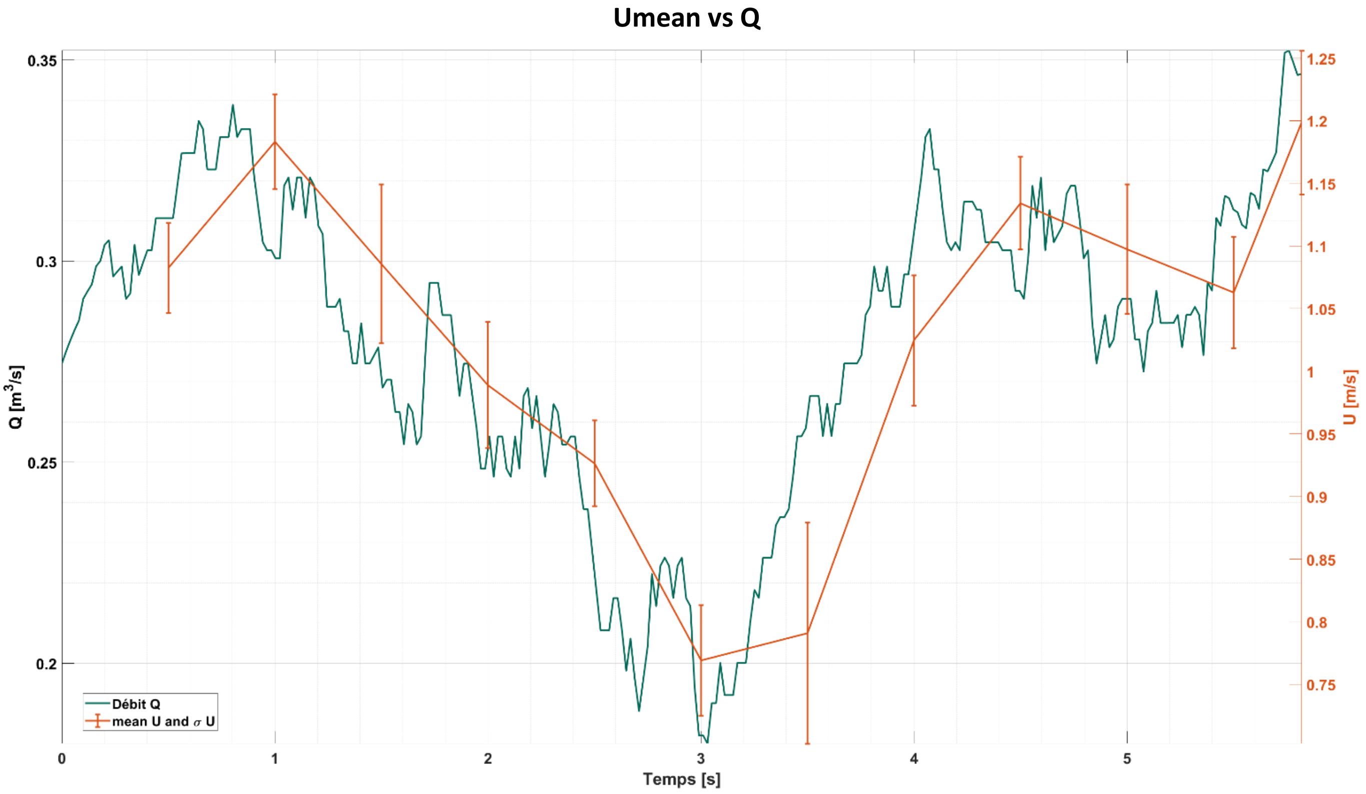

Figure 6: Stable flow regime at 0.290 m^3/s

3.1.3 Q3, Change of Regime to 0.2 m^3/s (not stable).

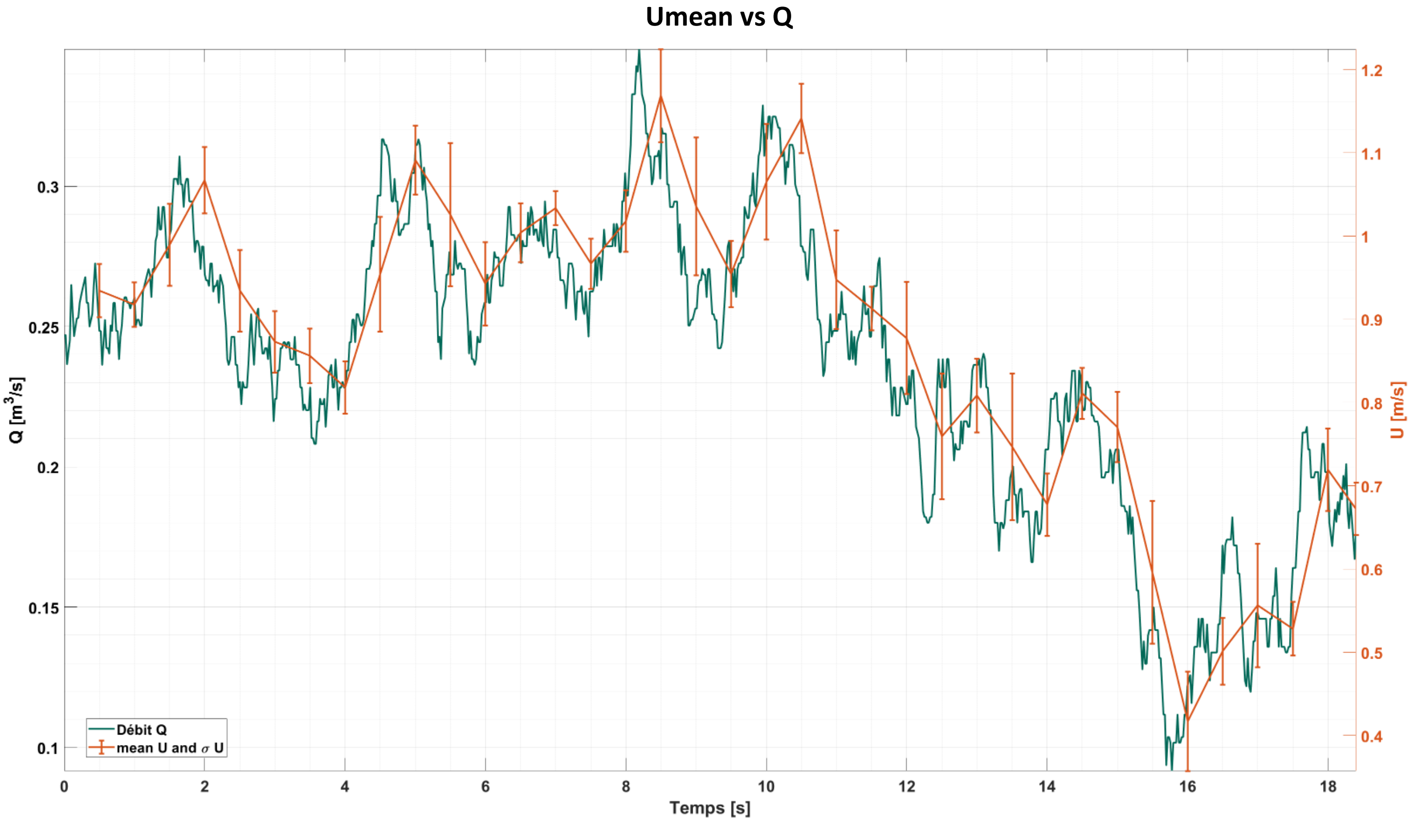

Figure 7: Flow variation towards a regime of 0.2 m^3/s

Figure 5 depicts how unstable the flow is when the flow rate circuit is reaching close to the maximum flow rate. Subsequently, at figure 6 the circuit reached a relatively stable condition of 0.29 m3/s. Although, it is evident there are important flow fluctuations, as these are shown by the standard deviation of the measurements.

Another change in the regime is depicted in figure 7, as the flow again starts a fluctuating behavior while going towards 0.2 m^3/s.

3.2 High flow rate circuit

3.2.1 Q1, Transitional regime to 0.55 m3/s.

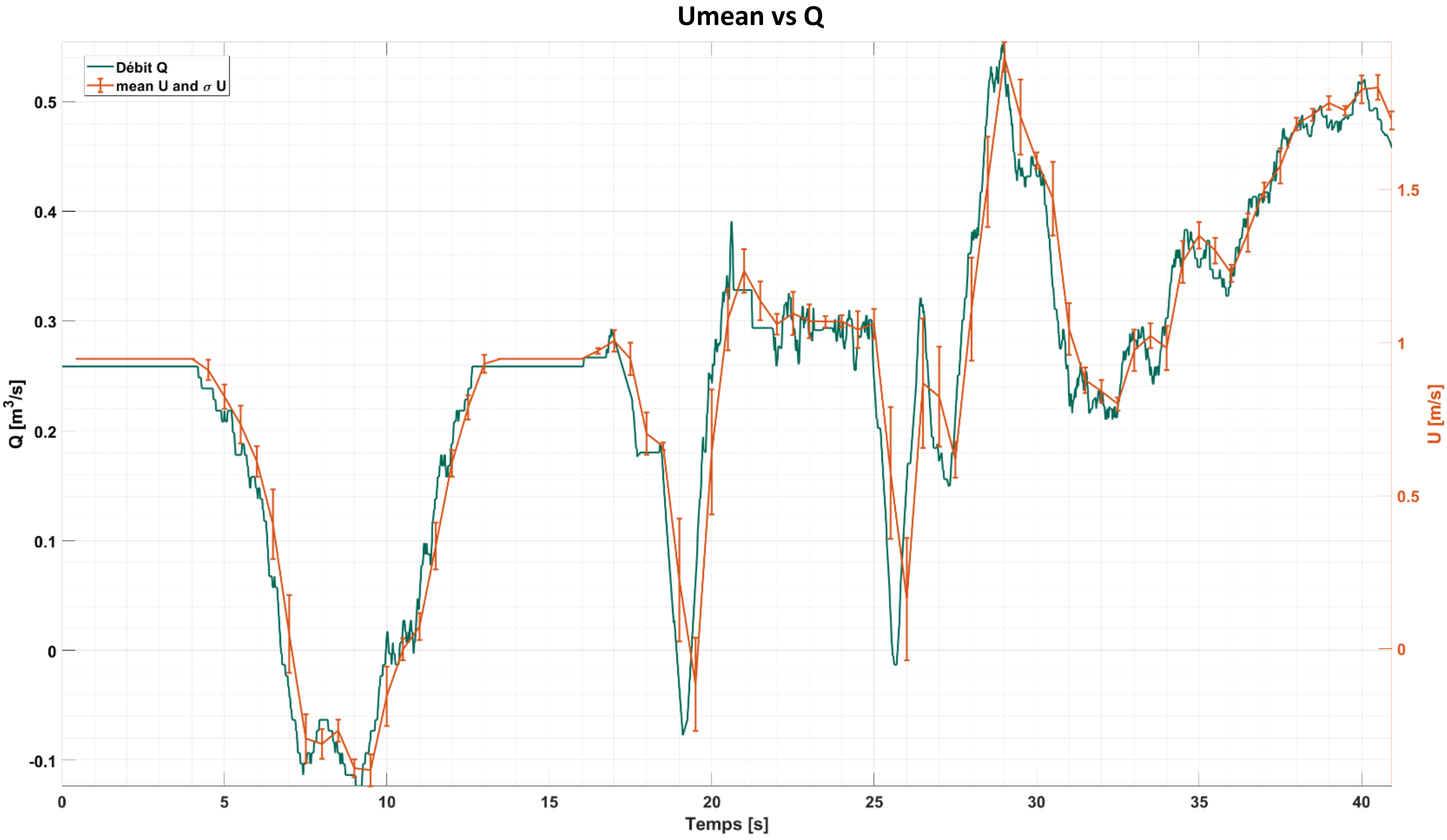

Figure 8: Flow variation towards a regime of 0.55 m^3/s

3.2.2 Q2, Transitional regime from 0.55 m3/s to 0.25 m3/s.

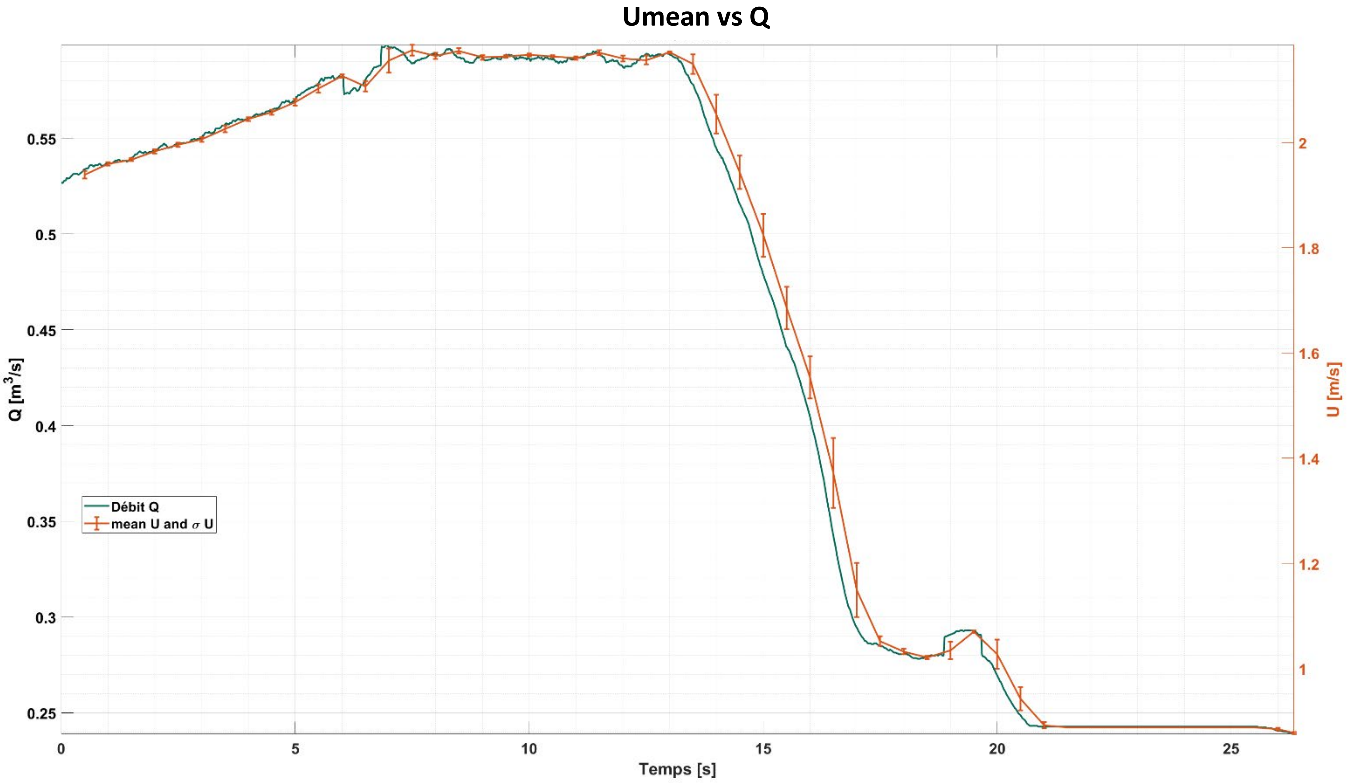

Figure 9: Flow transition from 0.55 m^3/s to 0.25 m^3/s.

For the high flow regime, at figure 8 we can observe fluctuations while it is on its way to 0.52 m3/s, the biggest fluctuations are due operation change in the circuit like change in load on the turbine. Upon arriving at the stabilized point of 0.55 m3/s (figure 9), Q shows an evolution from 0.53 m3/s to 0.597 m3/s, the average value after reaching the max (between t=7 s and t=14 s) is 0.593 m3/s. After the steep descent, Q arrives at 0.242 m3/s and is keep stable at such flow rates.

4 Conclusions and perspectives

After the analysis of the data, we can say that the measurement of flow fluctuations is very reliable with the method and equipment proposed in this paper, especially in the high flow regime, which may be related to a more stable zone of the turbine upstream. The low flow rate conditions may induce more turbulence at the output of the turbine, this may be related to load variation, which usually produce the famous rope at the nose of the turbines. The appearance of the rope may explain the low frequency flow fluctuations.

In the low flow circuit, the strings are not homogeneous enough, this indicates that the flow has a higher velocity U from one side of the forced duct than from the other. The most likely reason is the downstream elbow at 1 m (approximately) which forces the water to behave like this.

For the high-flow circuit, we have clearly seen the changes in speed in the two strings, which have remained homogeneous (or within the margin).

A consideration to improve the measurement in the low flow circuit is to use more than 2 transducers as receivers per string, this makes it possible to trace non-homogeneous variations with honeyed precision and in a new axis.

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