Applicability of Ultrasonic Pulsed Doppler for Fast Flow-Metering

Stéphane Fischer(1), Claude Rebattet(2), Thibault Lalande(2), Damien Dufour(1), Nicolas Bachellier(1)
(1) Ubertone SAS, Strasbourg, France, www.ubertone.com
(2) CREMHyG Lab, INP, Grenoble, France

Measurement of fluctuating flows in hydraulic machines is an ongoing challenge for which classical flow meter technologies (Differential pressure, Magnetic, Turbine and Propeller) are not well adapted. The ultrasonic pulsed Doppler technique allows to measure instantaneous velocity profiles in a very short time. This paper presents the performances of the ultrasonic velocity profiler UB-Lab to achieve faster velocity flow measurement through hydraulic pipes. The system has been optimized (transducer frequency, beam angle, parameters of sequencing) in order to reduce effect of wall echoes, to keep a good velocity range and to minimize the effect of secondary currents. The paper presents the measurement system with UB-lab's software module dedicated to fast flow-metering, the velocity profile measurement in a mixing tank, the bench demonstrator, the results and the perspectives of development of such solutions.

Keywords: hydraulic machines, fast measurement, velocity, flow modulation.

1 INTRODUCTION

Measurement of fluctuating flows in hydraulic machines is an ongoing challenge because of the need to study, quantify, and improve their performances and reliabilities. Indeed, unsteady flows have an impact on the machine working. Moreover, these effects often appear with a high frequency with possible circuit coupling effects. Therefore, to study them correctly, a high frequency flow measurement system is necessary.

Classical flow meter technologies (Differential pressure, Magnetic, Turbine and Propeller) are not well adapted for such kind of measurements. The ultrasonic pulsed Doppler technique allows to measure velocity profile in a more acceptable time range. It has been particularly used to observe coherent structures at high frequency in costal [1] and river flows [2]. This technique has also shown excellent performances to measure flow rate, especially on transient flows [3].

The ultrasonic profiler UB-Lab, developed by Ubertone, measures velocity profiles at high resolution in laboratory and industrial flows. This application-oriented instrument has a flexible architecture, it is compact and adapted to industrial conditions. In order to allow fast measurement of velocity profiles we have rewrite the core of the driver of UB-Lab. This has been done by using multi-threading and TCP-IP transfer optimization.

This paper presents the collaborative development of Ubertone SAS and Cremhyg Lab of Grenoble University, to develop and improve the performances of the ultrasonic velocity profiler data acquisition system to achieve faster velocity flow measurement through hydraulic pipes and turbomachineries.

2 INSTRUMENT SETUP

2.1 Specification

This technology will be tested on bench, at Cremhyg Lab, which enables to create high frequency flow modulation through several hydraulic components. Thanks to an oscillating piston, this bench can produce discharge and pressure fluctuations with a frequency range from 5 and 50Hz. The velocity oscillations are presently measured in a straight DN40 pipe with indirect 3-pressure method. The main velocity is about 2 m/s. Results may be available at the end of a PhD program and may be analyzed and published within next year.

As an example of typical modulation, the figure 1 shows the modulation of pressure signals measured by 3-pressure piezoelectric sensor (A1, A2, A3) located on pipe closed to exciter piston.

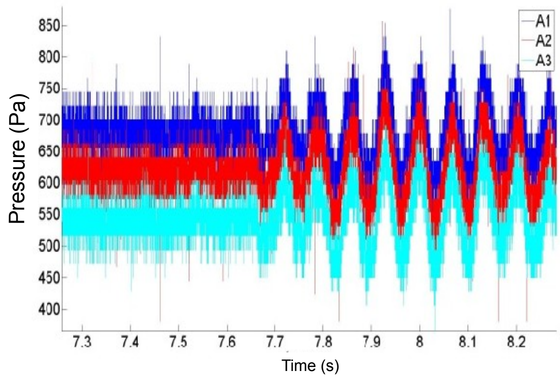

Figure 1 : modulation of pressure signals near the piston.

Fluctuations of discharge flow are represented on figure 2, the different curves demonstrate the influence of location of the section of measurement on pipe and distance to piston.

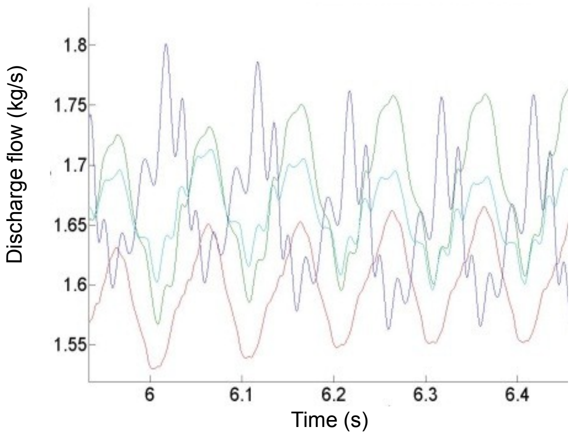

Figure 2 : Fluctuations of discharge flow at different locations.

The final objective is to measure the amplitude modulation of flow along any section on the main axis of pipe. The ultrasonic flow must be sufficiently fast to capture information of propagative flow waves. The measurement accuracy is a secondary endpoint and will be evaluated on this experimental test bench with reference to other flow measurement methods.

2.2 Technological constraints

The use of pulsed ultrasounds allows to observe a velocity profile along an acoustic beam sliced in many measurement cells. With the coherent pulse Doppler method used in the UB-Lab, the estimation of the velocity [4] is obtained with a low variance. This estimation is done, after sending N_{pp} ultrasonic pulses at a specific PRF (pulse repetition frequency), by computing the autocorrelation of the signal. Thus, the measurement frequency of the velocities is given by :

$$f_s = \frac{N_{pp}}{PRF} \quad (1)$$

This gives two parameters that can be changed to set this sampling frequency f_s. On the other side, the variance of the estimation is proportional to the signal to noise ratio [5] and inversely proportional to N_{pp}.

The coherent pulse Doppler method induce a velocity range limitation [6] expressed by :

$$\left[0 .. \frac{c^2 \tan\beta}{4 f_0 d}\right] \quad (2)$$

For the given pipe diameter d and a sound velocity c, this range limitation will influence the set of the parameters : the PRF, the beam angle β and the emitting frequency f_0.

2.3 Geometry sizing

Only one transducer is used in order to get the maximum sampling rate on velocity measurement by avoiding channel switch time. In order to reduce effects of parasite echoes, the spatial range will integrate two wall reflections (see figure 3). We also set the beam angle (β) to 60° in order to minimize the influence of radial velocity component (average and fluctuating) but still keeping a comfortable velocity-depth range. This sets the spatial range to 115 mm along the acoustic beam.

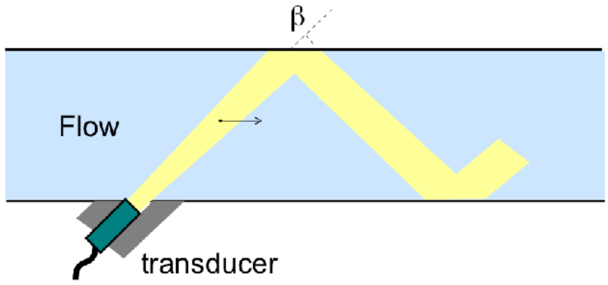

Figure 3: Transducer insertion in the pipe. The spatial range will integrate two wall reflections.

2.3 Transducer Sizing

The velocity range is set to [0..3m/s] in order to take account of the turbulence of the flow. The velocity-depth constraint imposes a maximum frequency of 3.2 MHz (obtained from the equation 2).

We choose a transducer centered on 3 MHz with a 6 dB bandwidth ranging from 2 to 4 MHz. This will allow, for maximum flexibility, to improve sensitivity (with higher frequencies) or to increase the velocity-depth range (with lower frequencies).

2.4 Ultrasonic pulses sequencing

The minimum spatial range for the ultrasonic velocity profile is 115 mm. This corresponds to a maximum PRF of 6435 Hz and to a range of theoretical instantaneous velocity of [0 .. 3.15 m/s].

3 HARDWARE IMPROVEMENTS

3.1 Data transmission

On the first version of the UB-Lab, the maximum frequency acquisition of velocity profile was about 1Hz. To reduce the response time, we choose a multi-thread approach allowing the management of different tasks and the optimization of computing resources. These improvements allow the device to measure and transfer a velocity profile each 5ms (200Hz, limited to 30 cells) or each 10ms at full capacity (100Hz, 62 cells). Moreover, to reduce the size of data flow, the new TCP-IP protocol does not transfer raw Doppler signal; conversely, it only transfers velocity profiles, variances and correlations.

3.2 Operating modes

There are two operating modes implemented in the driver :

- The "continuous mode" is able to measure and transfer up to 200 profiles per second. It is designed to study high frequency flows and to observe evolutions of the flow in real time. Moreover it is possible to record and post-process the data for further study.
- The "bloc mode" measures several profiles like the continuous mode but will only transfer the average profile of these data. Duration and period of these measurements are specified by the user. Mostly designed for long-term studies, the device can be installed for several days or weeks.

These operating modes allow acquiring a large range of velocity profiles in different conditions.

3.3 Communication protocol

To improve data exchange and automated measurement routines with homemade or licensed software like Matlab or Labview, a TCP-IP communication protocol with the driver was created. Once the client software is connected to the device, the user can load a configuration and start measurement with one of the two operating modes described above (continuous or bloc).

When the continuous mode is started, the driver sends the desired number of instantaneous profiles in a data-stream. An "end flag" is send to close the data-stream.

In the bloc mode, the driver computes the average on the number of asked profiles. During the processing of the bloc mode, the user can ask for an instantaneous profile or a moving average. If this profile is available, it is sent to the user; otherwise an empty profile is sent. The device does not send the same profile twice.

Routines can be stopped at any time by a "stop command".

4 FIRST TECHNICAL RESULTS

Experiments were carried out in a mixing tank that contains about 20 liters of water and few grams of corn farina. The tank has a diameter of 36 cm. A vortex is created inside the tank by a mixer rotating with an adjustable speed. The transducer connected to the UB-Lab device is set to measure the velocities along the diameter of the mixing tank.

The velocity profiles are measured continuously during several minutes. We used a frequency f_0 of 4.17 MHz, a PRF of 3 kHz and 128 samples (N_{pp}) are used for each profile. This lead to a velocity sampling frequency f_s of 23.4 Hz (23 velocity profiles measured per second). Cells size and intervals are set to 4 mm.

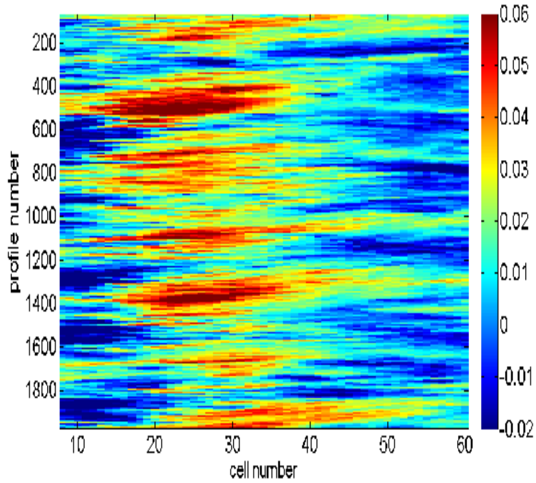

Figure 4: spatio-temporal view of the velocities in the vortex of the mixing tank (23.4 Hz sampling frequency) .

Figure 4 shows the velocity values according to the cell number (X axis, referring to the depth) and the profile number (Y axis, referring to time). The blues zones correspond to negative velocities and the red ones to positive velocities. The evolution of velocities across time and depth shows the turbulence due to the mixer.

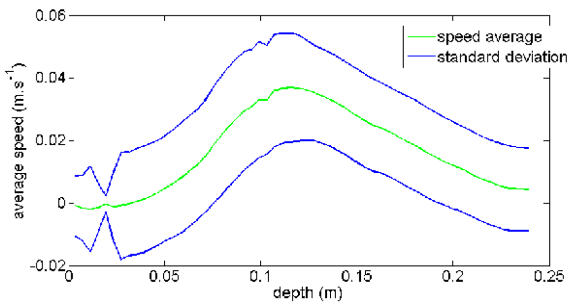

Figure 5: Mean velocity profile through the vortex.

The temporal average of the velocities (Figure 5) shows a smooth variation of the mean velocity along the depth as the transducer axis did not cross the center of the vortex. This graph shows that the standard deviation is constant except for one point at a depth of 0.019. This breakdown of the standard deviation is due to a parasite echo that leads to a low SNR (signal-to-noise ratio).

Figure 6 compares the evolution of velocities during time in cells located at 0.092 m, 0.119 m and 0.139 m of the transducer. Depending on the position of the vortex relatively to the cells, the velocities in these cells follow sometimes the same variations.

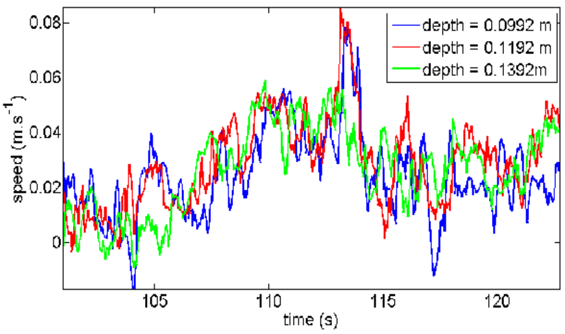

Figure 6: evolution of the velocity in three different cells.

The spectral analysis of the velocities shows the distribution of the turbulent energy (figure 7). Two cells in the same area (homogeneous turbulence is assumed) but with different SNR are compared.

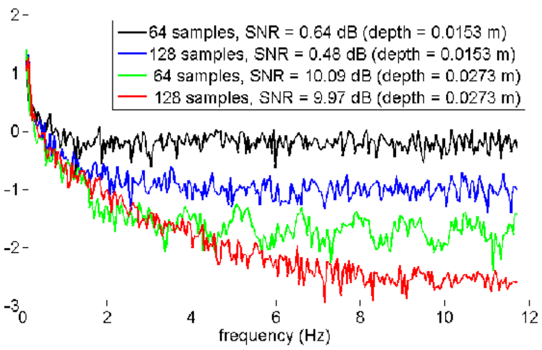

Figure 7: power spectrum of velocities (in dB).

The turbulent energy is present at low frequencies and decrease progressively. The variance of the velocity estimation appears as white noise. The level of this noise depends on the signal-to-noise ratio and on the number of samples used for one velocity estimation.

These results shows that while increasing the sampling frequency from 23.4 to 46.9 Hz (with N_{pp}=64), the noise level grows of about 1.2dB. On the other side, the SNR decreases the noise level, allowing to see the turbulent energy on a wider frequency range.

5 BENCH DEMONSTRATOR

The aim of the test bench is to permit measurement with monitored flow oscillation at different amplitude and frequency ranges. This bench has been designed initially to study the impact of flow fluctuation on several hydraulic components such as cavitating pumps and cavitating radial chamber systems, both with impedance influence coupled with pipe arrangement circuit. The possibility to equip the pipes with different instrumentations and to modulate the flow through variable hydraulic components offer a possibility to characterize the speed, the accuracy and the flexibility of US high speed methods.

6 CONCLUSION AND PERSPECTIVES

The presented system of high speed flow measurement has been developed for further hydraulic applications on hydraulic circuit and turbo-machineries. Because of high speed oscillation due to acoustic propagation in water channel, it is necessary to improve both the methodology and the instrument technology to access the flow modulation. Coupled with pressure measurement, it is possible to quantify the unsteady flow in pipes of circuit and access to the transfer function of hydraulic components. During this year, the Cremhyg test bench had been developed to generate such calibrated oscillation with an exciter piston. In the same time, Ubertone had developed new functionality and improved the acquisition system to measure fluctuation of discharge flow. The combination of R&D and availability of operational test circuit may permit to achieve test validation during next year to demonstrate the capability of Ubertone's profiler in fast flow metering.

ACKNOWLEDGEMENT

Ubertone is supported by the French Ministry of Research through the "*Concours National d'Aide à la Création d'Entreprises de Technologies Innovantes*".

REFERENCES

[1] Hurther D., Thorne P.D.: Suspension and near bed load sediment transport processes above a migrating, sand rippled bed under shoaling waves, journal of geophysical research 116 (2011)
[2] Bagherimiyab F.: Coherent structure and particle turbulence interaction in suspended sediment-laden laboratory open-channel flows, 34th IAHR World Congress (2011) 3354-3361
[3] Mori M., Tezuka K., Tezuka H., Furuichi N., Kikura H., and Takeda Y.: Industrial application experiences of new type flowmetering system based on ultrasonic doppler flow profile measurement, 3th International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering (2002)
[4] Miller, K.S., Rochwarger, M.M.: A covariance approach to spectral moment estimation, IEEE Transactions on Information Theory, 18 (1972) 588-596.
[5] Abeysekera S.: Performance of pulse-pair method of Doppler estimation. Aerospace and Electronic Systems, IEEE Transactions, 34 (1998) 520-531.
[6] Takeda Y.: Velocity profile measurement by ultrasonic Doppler method, Experimental Thermal and Fluid Science 10 (1995) 444–453.