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Flow-Viz Pulsed Ultrasonic Doppler System with Auto Tuning of Analog-, Digital Gain and Threshold

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In all industrial applications and installations, it is important to have a robust system that is capable of performing accurate velocity profile measurements with minimum operator influence. Some critical measurement parameters need to be set and optimized prior to the measurement for the particular configuration. For example; acquisition depth, number of acquired samples, decimation, PRF, gain and velocity estimation parameters etc. The measurement accuracy will depend on how well the critical parameters are set. In this work, we present the latest revision of the developed Flow-Viz rheometric system that is equipped with a new firmware that allows the automatic tuning of some of the critical control parameters, and which is now optimized for real-time on-board data processing and onboard profile estimation. It is demonstrated that the auto tuning capabilities of the Flow-Viz system leads to improved measurement accuracy compared to the conventional instruments with manual, operator dependent setting of the critical measurement parameters.

Keywords: Ultrasound, Doppler, Pulsed Ultrasound Velocimetry (PUV), rheometry, industrial process monitoring

1. Introduction

Flow properties such as the shear rate dependent viscosity, are directly linked to product quality and therefore represent important control parameters. The continuous monitoring of these parameters of industrial fluids during production is of paramount importance for process and quality control. Typical industrial fluids are multiphase systems that are transported via pipes between process steps within a plant. For industries, understanding the fluid behavior and flow dynamics is also fundamental in optimizing such processes [1]. Until Flow-Viz was introduced, only time discrete laboratory measurements on fluids specimens were possible and no other practical in-line solution exists for non-Newtonian and opaque industrial fluid [1]. It has previously been demonstrated in the literature that measurement of the velocity profile of the flow moving in the pipe when combined with pressure measurements, allows an accurate rheological characterization according to the PUV+PD method [2-5]. The Flow-Viz, which is the only commercially available fully integrated ultrasound system for in-line fluid characterization, and its development has been presented in the literature, see e.g. [2-5]. In this work, the second generation of the Flow-Viz rheometric system is presented, which is now equipped with a new firmware that allows the automatic tuning of some of the critical control parameters and which is now also optimized for real-time on-board data processing and onboard profile estimation.

2. The Flow-Viz in-line rheometer system

The Flow-Viz system is based on the enhanced tube viscometry concept combining Pulsed Ultrasound Velocimetry + Pressure Difference (PUV+PD). The methodology has been described in numerous publications and will not be described here, see e.g. [3-7].

2.1 The operator's panel housing all electronics

The Flow-Viz system consists of an operator's panel and a remote sensor unit. The panel, shown in Figure 1, houses the proprietary electronics (see next section) and an industrial PC (Beckhoff Automation, Germany) that displays the user interface. In particular, the system embeds all of the electronics required for the conditioning, acquisition and processing of the ultrasonic and pressure signals. The Flow-Viz was presented in detail in [6].

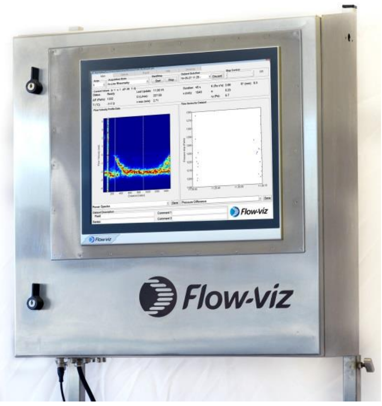

Figure 1: The Flow-Viz operator's panel.

2.2 Non-invasive sensor technology

The sensor unit holds all of the sensors and is installed in the process network and makes up the measuring section. Industrial applications require complete non-invasive ultrasound sensors due to high temperatures, pressures and possible abrasive fluids. Flow-Viz therefore developed a wide range of industrial sensors that consists of several components such as a high power ultrasound transducer, wedge, attenuator as well as different mounting designs for easy installation on pipes [6]. The complete sensor unit setup enables non-invasive Doppler measurements through high grade stainless steel and can be installed on pipes with diameters from 0.5 up to 6 inch with different pipe wall thickness (Flow-Viz, Sweden), see Figure 2.

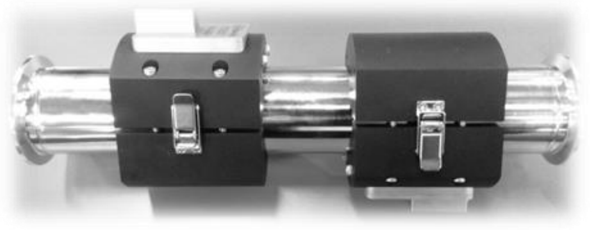

Figure 2: The Flow-Viz non-invasive sensors

The sensor unit typically comprises also a differential pressure sensor with remote seals (ABB Automation Technology Products AB, Sollentuna, Sweden) and a non-invasive PT-100 sensor (Pentronic, Gunnebo, Sweden).

2.3 Overview of the Flow-Viz electronics

The Flow-Viz system includes all the electronics necessary for processing and conditioning the ultrasound signal. The system measures the velocity profile of the fluid moving in a pipe through pulsed Doppler ultrasound, and combines it with the pressure drop. The electronics, featuring two ultrasound transmission/reception channels used alone or in pitch-catch configuration, includes powerful digital processing capabilities for real-time velocity profile calculation, and is fully programmable. It is very compact (10 × 12 cm total dimension), low power (5 W max.) and made up of two boards: The Analog Front-End and the Digital Board. The system is connected to a board of the sbRIO family (National Instruments, Austin, TX), which includes an Ethernet network connection. The details of the system are also presented elsewhere, for example in [7].

2.4 The analog front-end

The analog front-end is subdivided in two equivalent channels, shown in Figure 3. The transmission section (Tx) of each channel amplifies the transmission burst by a current feedback linear amplifier, which can reach 40 Vpp, and a transformer, that raises the signal up to 80 Vpp, and adapt the amplifier output to transducers impedance. The Tx devices are turned on only during the transmission to minimize the noise and optimize the power consumption. The receiving section (Rx) amplifies the backscattered echoes and consists of an impedance matching transformer and a single chip, which integrates a Low Noise Amplifier (LNA) and the Programmable Gain Amplifier (PGA), which, together, produce a gain from 7 to 55 dB with bandwidth between 0.8 and 7 MHz. The selection of the Rx and Tx channels is managed by suitable switches, controlled by the Field Programmable Gate Array (FPGA), located on the Digital board.

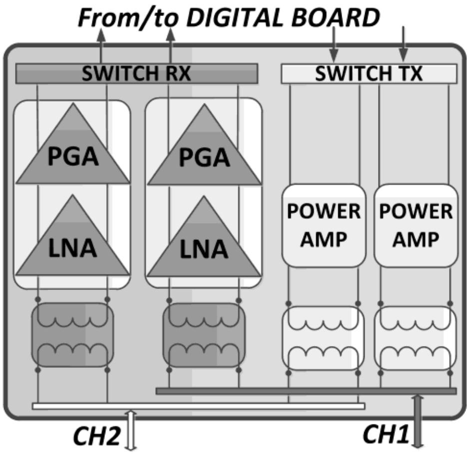

Figure 3: Analog Board with ultrasound front-end. Switches are used in TX/RX to manage 2 different transducers.

The Digital Board, shown in Figure 4, is based on the EP3C25F256 FPGA from the Cyclone family of Altera (San Jose, CA), which manages all of the digital devices present on the board. During the transmission, the burst is generated with programmable amplitude, frequency, number of cycles and tapering, by a Digital Direct Synthesizer (DDS) implemented on the FPGA. Transmission of coded excitations is possible as well. The burst is then converted by a 14-bit resolution, 100 MSPS Digital to Analog Converter (DAC) and sent to the analog front end. During the reception phase, the conditioned echoes are digital converted by an AD9265 (Analog Devices, Norwood, MA) at 100 MSPS with 16-bit resolution.

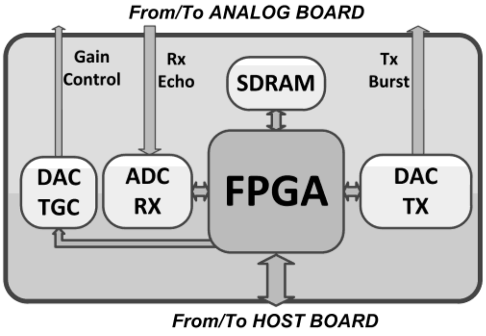

Figure 4: Digital Board. A FPGA manages all of the devices

The acquired data is then processed in the FPGA according to the flowchart presented in Figure 5. Samples are coherently demodulated by a multiplication to two, 16-bit resolution, quadrature-phase sinusoidal signals, which have the same frequency as the transmission burst. The resulting 32-bit, in-phase (I) and quadrature (Q) components are filtered by a Cascaded Integrator Comb (CIC) filter with a programmable cut off frequency and down-sampling factor. Each chain has 4 stages with input/output at 32 bit. The filtered samples are stored in the 64 MB SDRAM buffer at 32+32 bit per complex sample.

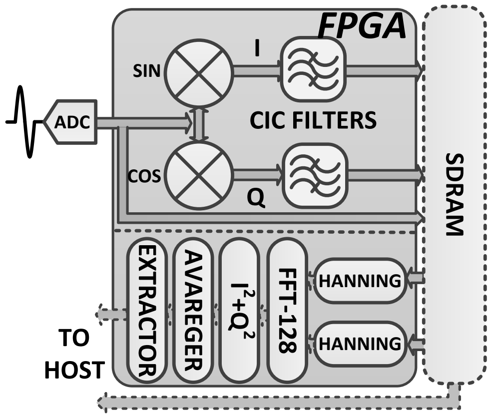

Figure 5: Signal processing chain for real-time profile calculation implemented in the FPGA.

3. Onboard data processing procedure

3.1 Velocity estimation methodology

In Pulsed Ultrasound Velocimetry (PUV) a burst is transmitted every Pulse Repetition Interval (PRI) into the medium. When moving particles are encountered, the burst produces an echo affected by a frequency shift that correlates to the particle axial velocity component, according to the Doppler effect. When a sufficient number of PRIs are stored, the velocity can be determined using methods described e.g. in [6].

3.2 Onboard data processing procedure

The latest revision is the first pulsed ultrasound system capable of automatically tuning the Analog and Digital gain parameters as well as the threshold applied to the FFT used for onboard profile estimation. When enough data has been stored in the SDRAM, the multi-gate spectral analysis starts, reading from the SDRAM to the FPGA blocks of 128 complex samples acquired from the same depth. The Hanning window is applied to each block and a block-floating point complex FFT processes the results. The sum of the square of the FFT output, converted to 32-bit floating-point format is used to determine the power spectrum. All the available depths are processed and the results are stored in the rows of a Doppler spectral matrix. A programmable number of matrices are averaged for improving the signal to noise ratio before the frequency profile is extracted. From each row of the denoised spectral matrix, the normalized frequency profile n_d is calculated with a discrete version of (5):

$$n_d = \frac{1}{N}\sum_{i=0}^{N-1} i \cdot \left|C_{d,i}\right|^2 \Big/ \sum_{i=0}^{N-1}\left|C_{d,i}\right|^2 \qquad (1)$$

Where $C_{d,i}$ is the matrix element corresponding to depth d and FFT bin i, and N is the FFT size. The frequency profile is obtained by dividing n_d to T_{PRI}, i.e. the temporal length of the PRI. The frequency profile is moved to the PC where the velocity profile is finally calculated by applying (1) and the rheological parameters are extracted and shown in real-time results. The Flow-Viz system offers the possibility to use both FFT and time domain (cross-correlation and auto-correlation) methods for velocity estimation. The autocorrelation method is robust and requires smaller footprint for its implementation but if the waveform is not perfectly repetitive due to noisy velocity signal, the autocorrelation peak will be shifted and inaccurate. Having access to the FFT power spectra provides "all" the velocity peaks, meaning that the correct velocity can be determined even from a noisy signal. With good data processing it is thus possible to obtain more accurate results but the estimation process is then slower.

3.3 Dynamic checks and auto-tuning capabilities

The tuning of the Analog and Digital gain parameters operation is based on a few RF acquisitions and the auto-tuning procedure is using an acquisition window corresponding to the internal diameter of the pipe. The automatic threshold tuning system evaluates all of the FFT lines that are calculated based on the current parameter settings and automatically adjusts the threshold value. If one or more parameters change, the tuning procedure is repeated to ensure optimal measurement accuracy. The system can check the dynamics used by the internal mathematics during the last acquisition. In particular this feature is useful to check if some saturation occurred and/or the signal was too weak in some point of the calculation chain. In case the risk of saturation is high, the number of bits used for velocity estimation is reduced. In this case, one or several bits are still available to accommodate larger signals. The automatic analog gain then tunes the gain to achieve so that the register value for the ADC range is set so that an optimal margin is left. If the signal is saturated in one of the stages of the CIC filter, resetting the dynamics of the filter to its default value is made since no digital saturation can occur (but the signal can be low and not optimized). The automatic tuning process is then repeated. The operation lasts, at maximum, 64 PRIs, which is fast enough to be used in a "real-time" application. The automatic tuning of the threshold that is applied to FFT for profile calculation is automatically estimated by the system by evaluating a sort of simplified average on all of the FFT lines that are calculated based on the current parameter setting. The threshold is set equal to the noise floor level and then corrected by a correction factor, calculated by the system or set by the operator. The threshold is tuned by over the depth range restricted by the dimensions of the pipe so that only data originating from within the fluid is used for the automatic tuning. The procedure takes longer time than the automatic tuning of the gain and is therefore made between actual measurements. The maximum time required, using 128 FFT_lines is:

$$\text{Time} = 38\mu\text{s} * \text{FFT\_lines} \qquad (2)$$

The auto-tuning procedure works on the configuration set by the user and if the parameter changes, the tuning procedure should be run again. The tuning procedure is based on the data acquired during the few PRIs. If something "strange" happens during such a period (e.g. a big air bubble) it is feasible that the found parameters are not optimal so one may have to repeat the procedure several times before the optimal threshold is found.

4. Results

The successful implementation of the velocity estimation on the FPGA of the processing chain is demonstrated in Figures 6 and 7. An application is presented where the system, coupled to a non-invasive ultrasound sensor unit, performs in-line velocity profile measurements through the wall of a high-grade stainless steel pipe. The presented velocity profiles were measured in a 1Pa.s industrial liquid containing tubular micelles. The inner pipe diameter was 22.6 mm, at a volumetric flow rate of 14-15 L/min. Figure 6 shows a comparison between a velocity profile calculated in the FPGA onboard with parameter auto tune switched on and the corresponding profiles calculated in Matlab® (The MathWorks Inc., Natick, MA) using demodulated I/Q and onboard spectra data downloaded from the SDRAM. If the threshold is set manually (and incorrectly) by the operator (IQ and onboard spectra case) it may lead to inaccurate velocities to be determined, especially if the data is noisy with several peaks in the spectra. The automatic optimization of the threshold and subsequent processing however allows the selection of the correct velocity peak. This is shown in Figure 6 where a difference in measured velocities is obtained, especially in the center of the pipe where the noise was the highest.

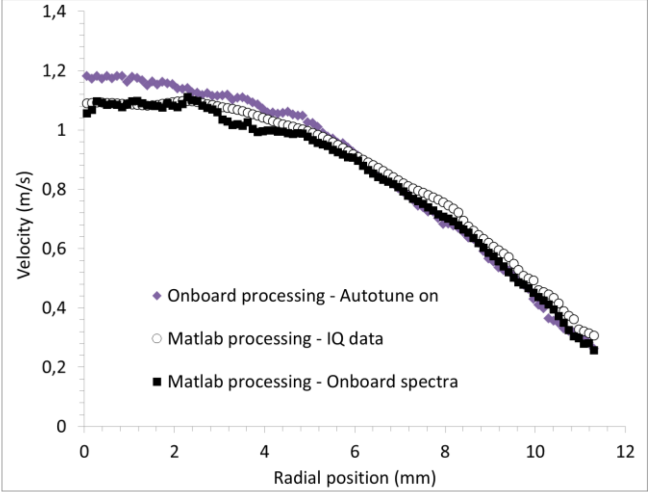

Figure 6: Velocity profiles calculated in the FPGA (diamonds) and in Matlab® using I/Q data (circles) and from onboard spectra data (squares).

The effect of the automatic tuning of the analog and digital gain in an attenuating industrial fluid is demonstrated in Figure 7. When the gain was set manually and too low by the user it is clear that the obtained velocity profile do not correspond with the expected theoretical profile. However, when the gain was automatically tuned to the optimal settings a realistic profile was obtained. It should however be noted that the same results are obtained if the parameters are set manually to the equivalent settings by the operator but this is often difficult to do, especially without a priori knowledge about the fluid and its properties. It should further be noted that if flow velocity changes so that aliasing occurs then the PRI must also be changed to a new value. The PRI parameter is however very difficult to tune automatically but does not influence the automatic gain or threshold settings.

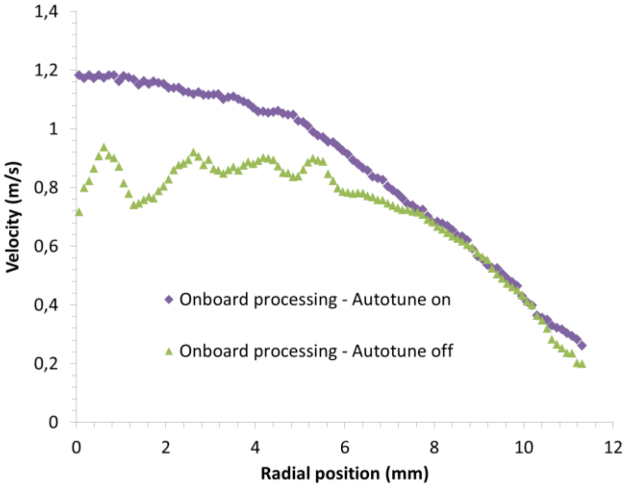

Figure 7: Velocity profile calculated in the FPGA (diamonds) with auto tune switched on and off (triangles).

5. Summary

This work presents the latest commercially available version of the Flow-Viz system featuring upgraded electronics and firmware features an Analog Front-End and a Digital Board that offers on-board processing and velocity estimation capabilities. It was demonstrated that the data processing can be performed directly in the FPGA and that automatic tuning of the analog-, digital gain and threshold results in more accurate velocity profiles in comparison with the traditional method were these parameters are set by the operator. Next step is the automatic tuning of the PRI acquisition parameter.

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