Program Digest, 2019 IEEE International Ultrasonics Symposium (IUS)
Glasgow, Scotland, October 6-9, 2019

Industrial Fluids Electronic Emulator for Rheological Doppler Tests

Stefano Ricci
Department of Information Engineering
University of Florence
Florence, Italy
stefano.ricci@unifi.it

Dario Russo
Department of Information Engineering
University of Florence
Florence, Italy
dario.russo@unifi.it

***Abstract*—Rheological measurements are widely employed for the monitoring of industrial production processes and for product quality certification. Recently, Doppler electronic systems are available that perform rheological fluid characterization in-line. Rheological fluid features are obtained from the velocity profile that the fluid develops when it flows in a pipe. Test, development, and performance assessment of these systems often involve the employment of cumbersome flow-rigs. Moreover, the exact profile the fluid develops in the flow-rigs is not perfectly known, making difficult an accurate performance evaluation of the connected system. In this work an electronic flow-rig emulator is presented. Connected to the transducer input of the system to be tested, it reproduces the echoes like they were originated from the fluid. Moreover, it reproduces a fluid with user-programmed, and thus well known, rheological and flow features. Tests of the proposed emulator connected to an industrial Doppler system are presented, where 2 fluids with different features are emulated.**

Keywords—Rheological characterization; flow emulator; velocity profile

I. INTRODUCTION

The monitoring of the rheology of fluids and suspensions involved in industrial processes is of paramount importance for product quality and industrial production monitoring. Until recently, rheological measurements were performed by manually analyzing fluid specimens in specialized laboratories by rheometers. Electronics systems are now available that characterize fluids by in-line measuring the profile that the fluid develops when flowing in a pipe through Doppler ultrasound [1][2][3]. The development, test and verification of such systems involve the employment of cumbersome flow-rigs where fluids with known rheology flow in controlled conditions. Unfortunately, unavoidable uncertainties in fluid features and flow conditions generate ambiguities in the tests.

In this work we propose a compact and programmable system that emulates a flow-rig in ultrasound Doppler tests. The emulator connects to the transducer input of the system under test (SUT), where it produces the radio-frequency (RF) signal that corresponds to a fluid with rheological parameters and flow conditions programmed by the user. The Doppler RF signal is synthetized off-line before the start of the emulation session, and the emulator produces a signal burst at every time the SUT issues a synchronism pulse, typically corresponding to the Pulse Repetition Interval (PRI).

Synchronism between the emulator and the SUT is critical: sub-ns random temporal variations between SUT synchronism and the effective start of echo generation produce an unbearable phase noise in the Doppler signal. This is the reason why most of the commercial function generators are not suitable for this task (for example, the modern function generator AFG3000C from Tektronix, Inc., Beaverton. OR, USA, features a too high 500 ps rms jitter on the trigger [4]). The proposed emulator includes a resynchronization circuit [5] that reduced the jitter below 100 ps rms, suitable for the applications.

The emulator was tested connected to a Doppler system for rheological applications [6]. Fluids with 2 different rheological characteristics were emulated. The profiles measured by the Doppler system were then compared to the references used for their generation.

II. MATERIALS AND METHOD

A. Emulator basic architecture

The proposed emulator is composed by an FPGA module implemented on a custom board [7], connected to a host PC through a Universal Serial Bus (USB) interface. The emulator is connected to the SUT as reported in Figure 1. A PRI synchronism is used to start the generation of each emulated echo burst, while the echo signal feeds the SUT input, replacing the transducer.

In the PC a software runs in Matlab (The Mathworks, Natick, MA). It includes a simple user interface where the user specifies the fluid rheological characteristics, the flow and acquisition conditions. These parameters are used by Matlab® to synthetize off-line the echo samples. It applys a rheological mathematical

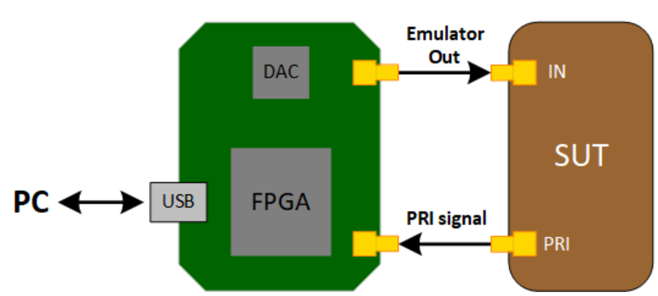

Figure 1. System architecture.

model to calculate the flows velocities, and then exploits Field II ultrasound simulator [8][9] for generating the RF echo samples. Simulated samples are then downloaded to the custom board, where, at user command, are reproduced towards the SUT like they originated from a real flow. Following sections detail each part of the emulator.

B. Custom board and FPGA module

The custom board is basically a signal synthesizer constituted (see Figure 2) by the FPGA module, the Digital-to-Analog (DA) converter, Flash and 64MB of SDRAM memories. The FPGA module is implemented in an Altera-Intel Cyclone III (Santa Clara, CA USA) FPGA; its architecture is sketched in Figure 2. It includes a Nios II® soft-processor that manages all the board operations. During the initialization, it loads from the PC the echo signal samples, previously generated off-line in Matlab®. Data are stored in the system flash memory or in the SDRAM. Samples are reproduced at 50Msps, 14 bit. For example, a 10mm diameter pipe is emulated with an echo burst of 13µs temporal length (sound velocity 1500m/s), corresponding to about 650 sample per PRI and 1200 bytes. In this example SDRAM can accommodate 53k PRIs.

After the board initialization, the first PRI is moved from the SDRAM to a FIFO memory in the FPGA, ready to be produced. Now the emulator waits for the PRI trigger from the SUT to start the echoes generation. At trigger, the FPGA waits a programmable time that accounts for the depth of the pipe, then starts the signal production. From now on, every next PRI trigger, the soft-processor starts the data transferring from the FIFO to the DA converter, and simultaneously, prepares the next PRI samples in the FIFO memory. These operations are repeated until the whole available signal is reproduced.

C. PRI Synchronization

The emulator works with a system clock that is totally unrelated to the clock of the System Under Test (SUT), and it synchronizes to the SUT through the PRI synchronism only. If the emulator would have simply resampled the PRI synchronism with its internal 100 MHz clock, a random variation (frame jitter [10]) of 10 ns in the start of the transmission would have been generated. This jitter sums directly to the emulated Doppler shift, destroying the useful velocity information. For this reason, an advanced synchronization circuit is added to the emulator to reduce the frame jitter. Details of the circuit can be found in [5], here a brief explanation is reported for reader convenience.

Like sketched in Figure 3, the PRI synchronism feeds a Tapped-Delay-Line (TDL). The TDL is constituted by an array of delay cells, typically realized by cascading logic elements in a FPGA. Each cell has an associated register that, at system clock edge, freezes the value of the cell. This way, the registers hold a screenshot of the delay elements crossed by the PRI synchronism before the system clock edge. An encoder translates this info in a binary code that is used, through a NIOS soft processor, to change the parameters of a Phase-Locked-Loop (PLL) so that its generated clock CLK_{ph} is phased to the PRI synchronism. CLK_{ph} is used in the emulator for the echo signal generation, which, thanks to this circuit, features a frame jitter below 100 ps rms [5].

D. Rheological signal model

In most industrial processes, the production involves fluids and/or suspensions that have non-Newtonian behavior. In a non-Newtonian fluid, the viscosity η is not constant, but depends on the shear rate $\dot{\gamma}$, i.e. the variation of the fluid velocity v evaluated along the radial direction of the pipe. Depending on the fluid characteristics, this relation can be quite complex. However, it is often approximated with a power low model [11]:

$$\eta = K\dot{\gamma}^{n-1} \tag{1}$$

Power low model describes the relationship between the viscosity η and the shear rate $\dot{\gamma}$ through the 2 indices K and n, that are the power law consistency index and the power low exponent, respectively. A fluid/suspension with rheological characteristic described by (1), flowing in a pipe of radius R with a volume flow Q, develops the velocity profile:

$$\mathrm{v(r)} = \frac{Q}{\pi R^2}\frac{3n+1}{n+1}\left(1-\left(\frac{r}{R}\right)^{n-1}\right) \tag{2}$$

Where v(r) is the velocity in the parallel direction to pipe axis at distance r from the pipe center. To complete the model, the consistency index K is related to the volume flow Q and the

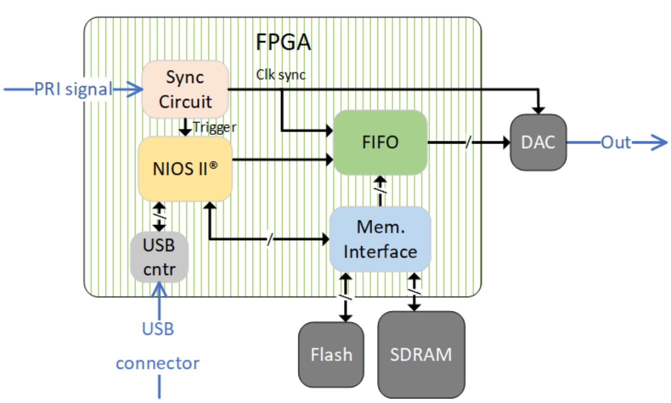

Figure 2. The custom board is composed by the FPGA module, a DA converter and memories.

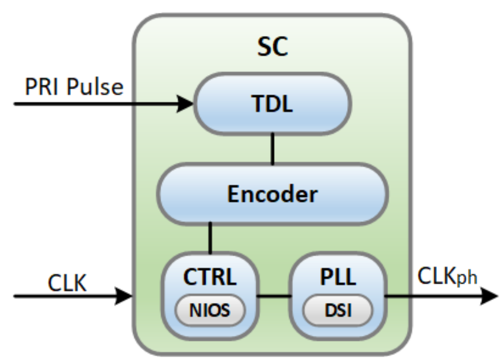

Figure 3. Architecture of the proposed Synchronization Circuit. It includes a Tap-Delay-Line (TDL), an Encoder, a controller (CTRL) and the Phase-Locked-Loop (PLL) units.

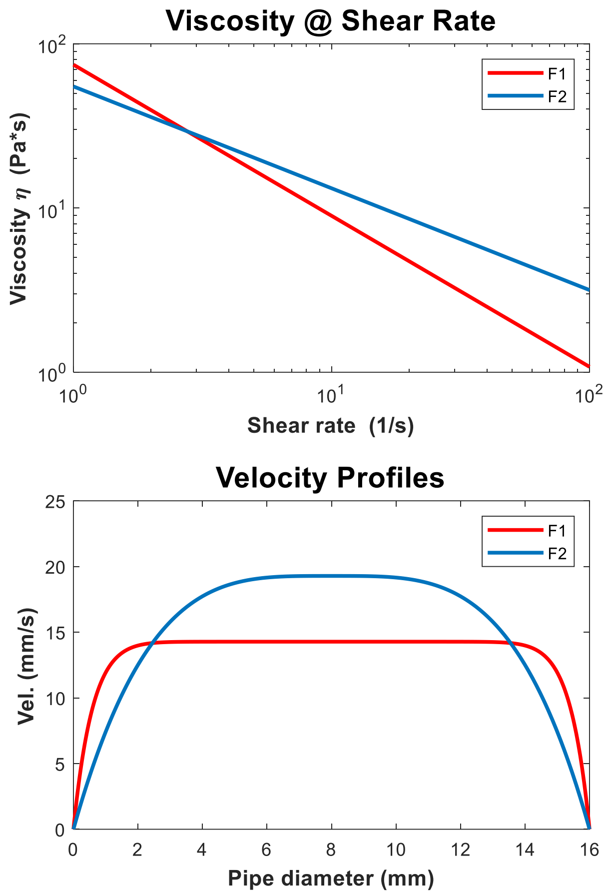

Figure 4. Relation between shear rate and viscosity (top), and velocity profile (bottom) of 2 fluids (F1 in red and F2 in blue) with the different rheological characteristics reported in Table I

pressure drop ΔP along the distance L in measured in pipe axis direction:

$$K = \frac{\Delta P}{2L}\left(\frac{3Q}{\pi} R^{\frac{-3n-1}{n}}\right)^{n} \quad (3)$$

Two examples of fluids/suspensions (labelled F_1 and F_2), whose rheological data are inspired to cosmetic emulsions, are reported in Figure 4. They have different rheological features, like reported in Table I. The top panel of Figure 4 shows the viscosity/shear rate trend (1). For both fluids the viscosity goes down for higher shear rates (shear thinning fluids), as expected for law-power exponent $n < 1$. The corresponding velocity profiles, plotted in the bottom of Figure 4 for a 16 mm diameter pipe and a Q = 2.5 ml/s volume flow, are flattened with respect to the parabolic profile of a Newtonian fluid.

TABLE I. RHEOLOGICAL AND FLOW PARAMETERS

Parameter	Symbol	Value	
		F_1	F_2
Flow rate	Q	2,5 ml/s	2,5 ml/s
Exponent	n	0,08	0,038
Consistency index	K	74,61	54,99
Velocity peaks	v_p	14 mm/s	19 mm/s
Shear rates	$\dot{\gamma}$	24,09 1/s	8,75 1/s
Viscosity	η	4 $Pa \cdot s$	14,3 $Pa \cdot s$

TABLE II. EMULATION PARAMETERS

Parameter	Value
Acquisition	
Number of PRI	1024
PRI length	0,7 ms
Samples per PRI	1500
SNR	30 dB
Transmission	
Transducer	Piston 7 mm
Frequency	5 MHz
Number of cycles	5
Apodization	Hanning
Pipe	
Diameter	16 mm
Doppler angle	60°

TABLE III. SUT PROCESSING PARAMETERS

Parameter	Value
Demodulation Frequency	5 MHz
Packet size	128 samples
Packet overlap	50%
Wall Filter	70 Hz
Spectral analysis	FFT
Data Apodization	Hanning Window

E. Echo Signals Synthesis

The user selects in the Matlab® interface the desired parameters so that the velocity profile corresponding to the fluid/suspension desired features are calculated by (2). Apart viscosity, flow velocity profile, pipe diameter, volumetric flow, etc. user should enter other parameters like: the excitation frequency, transduced feature, PRI length, desired Signal-to-Noise Ratio (SNR), and others. The radio-frequency echo signal are generated in Matlab® by Field II ultrasound simulation software [8][9]. The Doppler simulation is obtained like described, for example, in [12]: a set of scatterers is placed in the pipe lumen and moved among subsequent PRIs according to the velocities calculated by (2).

Since a complete Doppler simulation in a typical PC can last a relative long time, a set of pre-calculated signals are stored in a signal library that can be used at any moment. Library emulates fluids/suspensions with different rheological features and/or different flow conditions (pipe diameter, volume flow rates, etc.), or even acquisition condition, like signal-to-noise (SNR) ratios or other disturbs.

III. EXPERIMENTS AND RESULTS

Experiments were performed by employing as SUT the Doppler system for industrial applications described in [6][11]. This system acquires and processes the signal on board and produces the velocity profiles, which are streamed to a host computer in real-time. It applies coherent demodulation [13], wall filter, spectral analysis. Final velocity profile is obtained by detecting the centroid frequency of the Doppler spectrum in each depth, and converting the frequency through the Doppler equation [6].

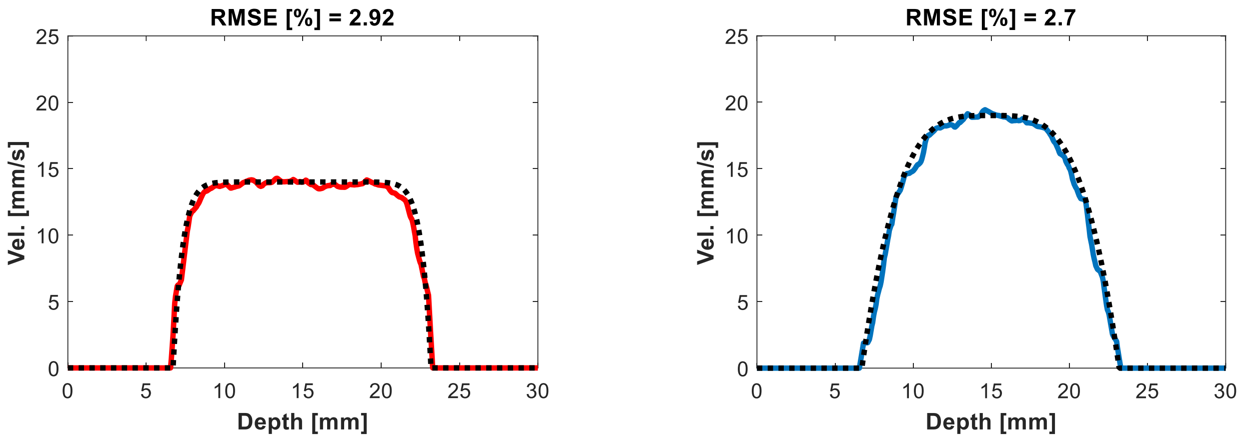

Figure. 5. Velocity profiles measured by the SUT from the data produced by the emulator for the 2 fluids F1 (red, left) and F2 (blue, right). Measured profiles are compared to reference profiles (black dotted curves); the error is 2.9% and 2.7% for F1 and F2, respectively

The emulator was connected to SUT like described in Figure 1: the emulator drove the transducer input of the SUT with the RF signal that corresponded to the emulated fluid. Each PRI was triggered by the corresponding SUT synchronism.

The 2 fluids with the rheological/flow parameters of Table I were emulated in Matlab®. A 7 mm piston transducer, excited by sinusoidal bursts composed by 5 cycles at 5 MHz was mimicked. It investigated a 16 mm pipe where the emulsions flowed with a flow rate of 2.5 ml/s (see Table II). 1024 PRIs were simulated and downloaded on the emulator board. SUT was programmed to process the acquired data according to the parameters reported in Table III.

Velocity profiles processed by the SUT from the emulated data were acquired in Matlab® and compared to the reference profiles calculated by (2). Results are shown in Figure 5. The black dotted profiles are the references while the red/blue solid lines represent the profiles detected by the SUT for the 2 fluids. The relative Root Mean Square Error (RMSE) between the curves is lower than 3%. The viscosity of the emulated emulsion was calculated back from the measured profiles by fitting to the model (2) [11]. The error on viscosity measurement was 4%.

IV. Discussion and Conclusion

A system capable of emulating the Doppler signal received during the investigation of a fluid/suspension with known rheological features is presented. Although the proposed emulator currently ignores the actual features of the transmitted burst, it can effectively replace a cumbersome flow-rig in quick laboratory tests of rheological Doppler instruments.

Acknowledgment

This work is partially funded from the Ministry of Education, Universities and Research (MIUR) of the Italian Government.

References

[1] B. Birkhofer, A. Debacker, S. Russo, S. Ricci, D. Lootens, "In-line rheometry based on ultrasonic velocity profiles: Comparison of data processing methods", *Appl. Rheol*, 22(4), 44701, 2012, DOI: 10.3933/ApplRheol-22-44701

[2] J. Wiklund, I. Shahram, M. Stading, "Methodology for in-line rheology by ultrasound Doppler velocity profiling and pressure difference techniques", *Chemical Engineering Science*, 62(16): 4277-4293, 2007, DOI:10.1016/j.ces.2007.05.007

[3] M. Muller, P.O. Brunn and C. Harder, "New Rheometric Technique: The Gradient-Ultrasound Pulse Doppler Method", *Appl. Rheol*, 7(5):204-210, 1997.

[4] AFG3000C Series Datasheet, Tektronics, [Online]. Available: https://sg.tek.com/datasheet/afg3000c-arbitrary-function-generator-datasheet

[5] D. Russo, S. Ricci, "Low-Jitter Systems Synchronization for Doppler Measurements", in print *in proc. of 2019 IEEE International Ultrasonics Symposium (IUS)*, Glasgow, Oct. 2019.

[6] S. Ricci, V. Meacci, B. Birkhofer, J. Wiklund, "FPGA-Based System for In-Line Measurement of Velocity Profiles of Fluids in Industrial Pipe Flow", *IEEE Trans on Ind. Electr.*, 64(5), 2017, DOI:10.1109/TIE.2016.2645503

[7] D. Russo, V. Meacci, S. Ricci, "Profile Generator for Ultrasound Doppler Systems", *proc. of 2018 IEEE New Generation of CAS (NGCAS) conference*, Valletta, Malta, Nov. 2018, DOI: 10.1109/NGCAS.2018.8572246

[8] J. A. Jensen and N. B. Svendsen, "Calculation of pressure fields from arbitrarily shaped, apodized, and excited ultrasound transducers," *IEEE Trans. Ultrason. Ferroelect.. Freq. Contr.*, 39(2):262–267, 1992, DOI:10.1109/58.139123

[9] J.A. Jensen: "Field: A Program for Simulating Ultrasound Systems", *Med. & Biol. Engin. & Comp.*, 34(1):351-353, 1996.

[10] A.N. Kalashnikov, R.E. Challis, M.E. Unwin, A.K. Holmes, "Effects of frame jitter in data acquisition systems", *IEEE Trans. Instrum. Meas.*, 54(6): 2177 – 2183, 2005, DOI: 10.1109/TIM.2005.858570

[11] S. Ricci, M. Liard, B. Birkhofer, D. Lootens, A. Brühwiler, and P. Tortoli. "Embedded Doppler system for industrial in-line rheometry". *IEEE Trans. Ultrason. Ferroelect.. Freq. Contr.*, 59(7):1395–1401, 2012, DOI:10.1109/TUFFC.2012.2340

[12] S. Ricci, A. Swillens, A. Ramalli, P. Segers, P. Tortoli, "Wall shear rate measurement: Validation of a new method through multiphysics simulations", *IEEE Trans. Ultrason. Ferroelect.. Freq. Contr*, 64(1):66-77, 2017, DOI:10.1109/TUFFC.2016.2608442

[13] S. Ricci, V. Meacci, "Data-Adaptive Coherent Demodulator for High Dynamics Pulse-Wave Ultrasound Applications", *Electronics*, 7(12), 434, 2018, DOI:10.3390/electronics7120434