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# Performance tests of a new non-invasive sensor unit and ultrasound electronics

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ABSTRACT

Industrial applications involving pulsed ultrasound instrumentation require complete non-invasive setups due to high temperatures, pressures and possible abrasive fluids. Recently, new pulser-receiver electronics and a new sensor unit were developed by Flow-Viz. The complete sensor unit setup enables non-invasive Doppler measurements through high grade stainless steel. In this work a non-invasive sensor unit developed for one inch pipes (22.5 mm ID) and two inch pipes (48.4 mm ID) were evaluated. Performance tests were conducted using a Doppler string phantom setup and the Doppler velocity results were compared to the moving string target velocities. Eight different positions along the pipe internal diameter (22.5 mm) were investigated and at each position six speeds (0.1–0.6 m/s) were tested. Error differences ranged from 0.18 to 7.8% for the tested velocity range. The average accuracy of Doppler measurements for the 22.5 mm sensor unit decreased slightly from 1.3 to 2.3% across the ultrasound beam axis. Eleven positions were tested along the diameter of the 48.4 mm pipe (eight positions covered the pipe radius) and five speeds were tested (0.2–0.6 m/s). The average accuracy of Doppler measurements for the 48.4 mm sensor unit was between 2.4 and 5.9%, with the lowest accuracy at the point furthest away from the sensor unit. Error differences varied between 0.07 and 11.85% for the tested velocity range, where mostly overestimated velocities were recorded. This systematic error explains the higher average error difference percentage when comparing the 48.4 mm (2.4–5.9%) and 22.5 mm (1.3–2.3%) sensor unit performance. The overall performance of the combined Flow-Viz system (electronics, software, sensor) was excellent as similar or higher errors were typically reported in the medical field. This study has for the first time validated non-invasive Doppler measurements through high grade stainless steel pipes by using an advanced string phantom setup.

## 1. Introduction

Ultrasound instrumentation based on Doppler echography in the medical field has been of great interest to the fluid engineering industry since detailed information on the fluid flow can be measured in real-time [1–3]. This technology has already been applied in various complex geometries (valves, contractions) as well as complex industrial fluid suspensions such as chocolates, fiber flows, liquid metals, mineral suspensions and more [4–6]. Although good results were obtained in previous studies, the experimental setups were installed under laboratory conditions, for example, ultrasonic transducers are typically installed with direct contact with the fluid medium, which means that holes are drilled into pipe sections or spool pieces [4–7]. Industrial applications require complete non-invasive setups due to high temperatures, pressures and possible abrasive fluids. Moreover, non-invasive setups are mandatory for food and pharmaceutical industries where severe hygienic constraints prevent the possibility to drill through the stainless steel. Recently a new sensor unit was developed and commercialized by Flow-Viz™. The complete sensor unit setup enables, for the first time, non-invasive Doppler measurements through high grade stainless steel [8,9].

This work aims at the evaluation of the accuracy of this sensor unit through a complete acoustical characterization. For example, the knowledge of the sample volume size and beam geometry as a function of depth is important for the characterization of the lateral resolution and accuracy of velocity measurements that can vary across the ultrasound beam. Furthermore, the accuracy of pulsed Doppler measurements can be affected by installation angles (which affects the Doppler angle and thus the spectral

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**Notation**

| | |
|---|---|
| $c$ | velocity of sound (m/s) |
| $f_d$ | Doppler frequency (Hz) |
| $f_e$ | emitted frequency (Hz) |
| $v$ | velocity (m/s) |
| $I$ | intensity |
| $ID$ | inside diameter (m) |
| $IQ$ | in-phase/quadrature |
| $RPM$ | revolutions per minute |
| $t_b$ | electrical driving burst duration (s) |
| $T$ | temperature (°C) |
| $y$ | radial position across pipe diameter (m) |

*Greek letters*

| | |
|---|---|
| $\theta$ | Doppler angle, (deg) |
| $\omega$ | angular frequency |

broadening [10]), the velocity range being measured, as well as varying instrument settings such as the Pulse Repetition Frequency (PRF), amplification gain and gate widths (pulse lengths) [11–14].

Since the 1970s many studies have been conducted on investigating the performance of Doppler ultrasound systems by using different phantom test targets. However, very few studies (any) about performance testing of transducers for velocity profile measurements in industrial fluids have been published in the literature. Numerous methods have been previously described for assessing the accuracy of commercial Doppler systems, more particularly, the systems used in clinical applications. For example, moving string phantoms have been used for calibrating pulsed Doppler systems and evaluating the accuracy of velocity estimation [11–14]. The authors considered this approach well suited for quantitative Doppler velocity validation as well as for the assessment of the sample volume. Rotating discs made from tissue mimicking material were also recently used by Yang et al. [15] in order to assess the degree of over estimation of Doppler velocities caused by the Doppler angle. Prototype phantoms were developed for preclinical ultrasound scanners and it was found that this approach is capable of validating the performance of blood velocity measurements. Thin plastic tubes were previously designed by Eriksson et al. [16] and were used to carry blood mimicking particles (scatterers) through the ultrasound sample volume. The tubes were suspended in a surrounding liquid that was acoustically matched to the tube material in order to prevent stationary echoes from the walls. This setup was indeed satisfactory for mimicking blood perfusion, however, the tubes could be better arranged to achieve better homogeneity of the flow. Another method used in the 1970s by Jorgensen et al. [17] was small jet streams. A jet stream containing distilled water and 0.5% by volume silicon particles to act as sound scatterers was supplied from a 0.2 mm glass nozzle. The whole setup was submerged in distilled water and an exhaust tube was used to capture the stream before it could break into turbulence and mix with the distilled water in the tank. The ultrasound sensor was mounted above the jet stream so that the jet intersects the sound beam axis. This calibration effort was found to be applicable to blood flow as well as the silicon solution used, provided that certain parameters (e.g. focal point intensity, sample volume length at the noise floor) are defined for the scattering characteristics of blood.

After considering different methods, it was found that the moving string phantom test setup was best suitable for this study due to its relatively simple experimental setup [14] and the fact that 1-D measurements were tested with the aim of verifying Doppler velocity measurements. It must be noted that the previous studies discussed were based on assessing the accuracy of commercially available Doppler ultrasound systems for medical/clinical applications and not fluid engineering applications. In this work a non-invasive ultrasound transducer and pulsed ultrasound electronics were evaluated for pipe flow measurements for the first time. The results of the Doppler velocity measurements were compared to the moving string target velocities.

## 2. Methods and apparatus

### 2.1. Overview of the Flow-Viz electronics

The Flow-Viz™ system is a newly designed and fully integrated hardware platform comprising a total of four analog and digital electronics boards. The new Flow-Viz™ electronics has been developed by SP – Technical Research Institute of Sweden in collaboration with the University of Florence, Schmid Elektronik AG (Münchwilen, Switzerland), Sika Technology AG and Sika Services AG (Zurich, Switzerland) [9,19–20]. The electronics are controlled by an industrial PC unit (Beckhoff) comprising a $>2.5$ GHz Intel® Core™ i7 quad-core CPU with CFast and SSD memory cards, 8 GB RAM, 6 USB 3.0 ports and 2 independent Gbit Ethernet interfaces for remote control. The system also features a powerful Programmable Logic Controller (PLC) system for improved signal-processing capabilities.

#### 2.1.1. Motherboard

The Motherboard (Schmid Elektronik AG) provides filtering and stabilization of the power, 8 analog and digital input and output channels; 4–20 mA, 0–10 V, $\pm 5$ V; 16 bit, 4 PT100 circuits and serial ports. The Communications board is a National Instruments (NI) sbRIO-9606 module. The sbRIO board has a 400 MHz processor, a Field-Programmable Gate Array (FPGA), 96 DIO lines and provides Ethernet, RS232, CAN and USB connectivity. The IOs on the base board are controlled from the FPGA on the sbRIO. The electronics enable simultaneous UVP, pressure and temperature acquisition and signal-processing from multiple sensors. It also provides real-time communication capabilities to an industrial PC, see Fig. 1.

#### 2.1.2. Pulser-receiver electronics

The upgraded pulser-receiver electronics is based on a previous research board developed by the University of Florence [18]. It includes all the electronics needed for the acquisition and processing of ultrasound signals. It features 2 transmit/receive (TX/RX) channels that can work in stand-alone or pitch-catch configuration. The transmitters, based on an Arbitrary Waveform Generator (AWG), is capable of producing bursts (e.g. chirps, sinusoidal burst), typically at up to 80 $V_{\text{p-p}}$ with a frequency between 0.7 and 7 MHz. The FPGA (Cyclone family from Altera, San Jose, CA) includes coherent demodulators, filters and a Fast Fourier Transform (FFT) processor for spectral analysis. The boards are equipped with 64 MB of SDRAM where acquired raw samples or demodulated data can be buffered. The AWG can synthesize coded bursts for pulse compression. A high-performance Low Noise Amplifier (LNA) with a 0.74 nV/$\sqrt{\text{Hz}}$ noise level is used, the switching power