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

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Industrial applications require complete non-invasive setups due to high temperatures, pressures and possible abrasive fluids. Recently a new sensor unit was developed by Flow-Viz™ that consists of several components such as a high power ultrasound transducer, wedge, attenuator as well as different couplant materials. The complete sensor unit setup enables non-invasive Doppler measurements through high grade stainless steel. However, the sensor unit still needs to be acoustically characterised and evaluated. In this work a non-invasive sensor unit for one inch pipes (22.5 mm ID) was 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 were investigated and at each position six speeds (0.1 – 0.6 m/s) were tested. Error differences ranged between 0.18 to 7.8% for the tested velocity range. The average accuracy of Doppler measurements decreased slightly from 1.3 to 2.3% close to the pipe wall towards the opposite pipe wall and was expected. 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 validates the high performance and accuracy of non-invasive measurements through high grade stainless steel pipes using the Flow-Viz system.

Keywords: Ultrasonic transducer, acoustic characterisation, Doppler string phantom, Ultrasonic Velocity Profiling (UVP)

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 [1-2]. This technology has already been applied in various complex geometries (valves, contractions) as well as complex industrial fluid suspensions ranging from chocolates, fibre flows, liquid metals, mineral suspensions and more [3-5]. 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 [3-6]. Industrial applications require complete non-invasive setups due to high temperatures, pressures and possible abrasive fluids. Recently a new sensor unit was developed by Flow-Viz™ and is currently being marketed and sold. The complete sensor unit setup enables non-invasive Doppler measurements through high grade stainless steel [7-8].

However, the sensor unit needs to be acoustically characterised and evaluated. For example, knowledge of the sample volume size as a function of depth is important when parameters such as lateral resolution and accuracy are considered. Since the ultrasound beam is not constant with propagation distance the accuracy of velocity measurements across the ultrasound beam may vary. Furthermore, the accuracy of pulsed Doppler measurements can be affected by installation angles (Doppler angle), 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) [9-12]. Since the 1970's many studies have been conducted on investigating the performance of Doppler ultrasound systems by using different phantom test targets e.g. moving strings [9-12], rotating discs [13], thin plastic tubes [14] and small jet streams [15]. However, these studies were based on assessing the accuracy of commercially available Doppler ultrasound systems for medical applications.

In this work a non-invasive ultrasound transducer were evaluated and compared. Performance tests were conducted using a Doppler string phantom setup and the Doppler velocity results were compared to the moving string target velocities.

2 METHODS AND APPARATUS

2.1 Non-invasive ultrasound transducers

A non-invasive sensor unit was developed [7-8] that consists of several components such as a high power ultrasound transducer, wedge, attenuator as well as different couplant materials.

The configuration provides optimum acoustic beam properties, such as, beam forming, focusing and coupling, and impedance matching. It further provides optimum beam path through material layers and into the fluid medium as well as sensor protection. The configuration is designed to generate or eliminate different types of waves in any solid or semi-solid materials that could be used for non-invasive measurements. The sensor "block" can either be an integral part of the material wall layer (e.g. pipe wall) or used as a clamp-on device. A non-invasive sensor unit (Flow-Viz^{TM}, Sweden) made for 1" stainless steel pipes was evaluated and compared. The sensor has an emission frequency of 2 MHz.

2.2 Doppler string phantom setup

A moving Doppler string test target was specially designed and developed at SIK – The Swedish Institute for Food and Biotechnology, Sweden. It contains a high precision DC motor (Maxon Motor AG, Switzerland), pulleys, and a string loop (0.45 mm thickness) all mounted on a stable PVC frame. The setup can be adjusted so that the string target (or Doppler angle) can be varied from 0 to 90 degrees. Movement of the string was controlled by adjusting the motor RPM using a high precision positioning controller and software (EPOS Studio 2, Maxon Motor AG, Switzerland). This enabled the user to control the speed of the string using a PC connected to the DC motor via an USB interface. The target was placed in a water tank lined with absorbing rubber to minimise undesirable acoustic reflections from the walls. Figure 1 shows the Doppler string setup at SIK. The sensor unit was mounted using a steel plate onto a caliper (accuracy 0.05 mm) in order to provide precision movement in the vertical direction (y-axis). The unit was lowered into the water so that the pipe section was submerged in the water, while the string target moved through the pipe.

Figure 1: Doppler string phantom setup at SIK, Sweden.

A string setup was chosen because it is relatively easy to implement and can be used to evaluate several different properties of an ultrasound system. Similar string phantom designs have been used by many investigators, e.g. see [9-11]. The temperature was continuously monitored using a thermometer (Testo AG, model 735, 0.5° accuracy). The temperature was constant (21°) and corresponds to a velocity of sound of 1485.4 m/s.

2.3 Experimental methodology

The Flow-Viz^{TM} system including the ultrasound electronics and software was used during this project. Table 1 shows the parameter settings used.

Table 1: Flow-Viz^{TM} parameter settings used for Doppler string study.

Voltage (V_{p-p})	Gain (dB)	Cycles (#)	Pulse (#)
80	12	5	128

The Pulse Repetition Frequency (PRF) was varied and optimised for each string velocity setting so that the maximum measureable velocity was close to the actual flow velocity in the pipe. The number of cycles was set to five, which seems large for this study. However, the emission pulse length was reduced by implementing a windowing function. A linear gain setting was chosen. These values typically represent settings chosen for industrial applications. The string phantom was tested at seven different positions along the internal pipe diameter (22.5 mm), see Figure 2.

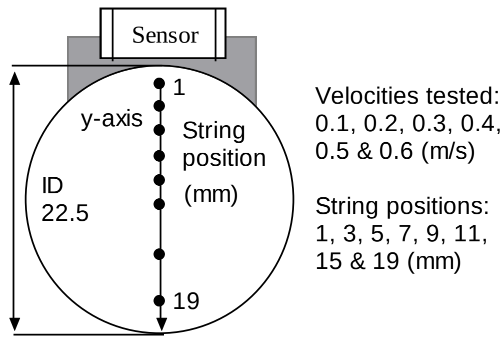

Figure 2: String positions and velocity range tested.

Seven depth positions along the pipe radius were chosen as this is the important region for velocity profile measurements, two depth points close to the opposite wall was selected in order to evaluate any accuracy decrease. Six velocities were tested at each depth position ranging from 0.1 to 0.6 m/s. The velocity estimator used for the measurements was based on the Fast Fourier Transform method (frequency domain) and an average of three velocity measurements was used. The string speed was set as the reference value and an error difference percentage was calculated for each velocity measurement (128 pulses per measurement). Lastly, an average percentage difference value of each velocity range was calculated and presented as a function of depth position along the y-axis (radial position). The velocity range chosen represents an industrial application where highly viscous materials are pumped at low flow rates.

3 RESULTS AND DISCUSSION

3.1 Sample volume shape and spectra

Figure 3 shows the magnitude of I/Q baseband echo data for the measurement at 11 mm depth (pipe radius) and 0.4 m/s string speed. Between channels 700 and 1000 the received echo from the moving string can be observed. The shape of the sample volume can be described by an exponential rise followed by an exponential decay when the envelope is considered. This is also observed elsewhere [6, 11, 14]. The large echoes before channel 500 are due to the wave passing through the coupling material and pipe wall, and the echo at channel 1400 is due to the reflection from the opposite pipe wall.

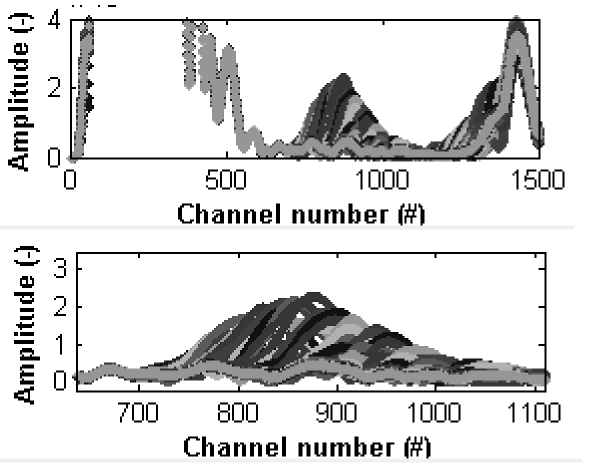

Figure 3: Magnitude of complex signal showing sampling volume axial extension. The bottom panel is a zoom between gates 600 and 1100. Each line is a received echo from an emiited pulse.

Figure 4 shows the corresponding Doppler spectra and velocity estimation (FFT). A constant velocity is present (0.4 m/s) between channels 780 and 950. This corresponds to the two points where the maximum energy drops to ±50%. Using the sampling frequency (100 MHz) and velocity of sound (1485.4 m/s), a sample volume length of approximately 5 mm (170 channels) was calculated. This seems realistic when taking the number of cycles, Doppler angle, string size and wavelength into account. By using 50% energy points the effect of channel overlapping is compensated for when calculating the sample volume length.

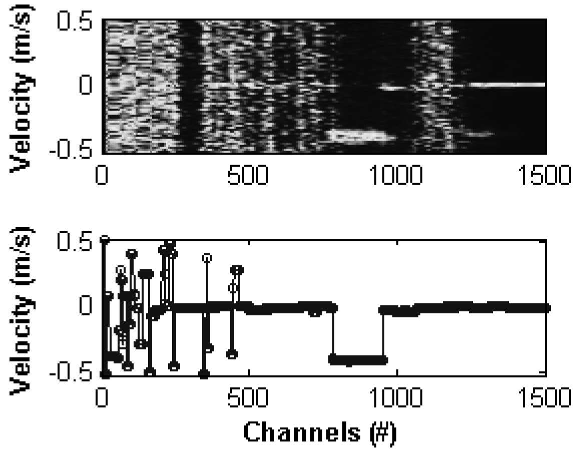

Figure 4: Doppler spectra and corresponding velocity measurement for 11 mm depth and 0.4 m/s string speed.

In this work the velocity at the highest energy point was chosen as the measured result. In this particular case channel 860 corresponded to 0.402 m/s. Three more measurements were taken and the average was used.

3.2 Velocity error vs. depth position

The deviation between measured velocities and string velocities vs. depth positions is shown in Figure 5. The maximum and minimum deviation was 7.8% and 0.18%, respectively. Higher deviation was observed for the lower velocities (0.1 and 0.2 m/s). This may be because the string jumped very slightly at lower velocities due to the string tension.

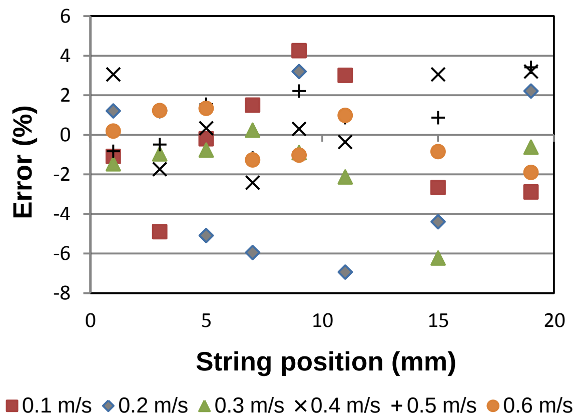

Figure 5: Devation of measured velocity from string velocity vs. depth positions.

Figure 6 shows the final summary of the average error between the measured and string velocities as a function of sample volume depth positions. A power-law fit was used and shows that the error slightly increases from 1.3% (1 mm) to 2.3% (19 mm). This was expected as the ultrasound energy decreases with increasing distance.

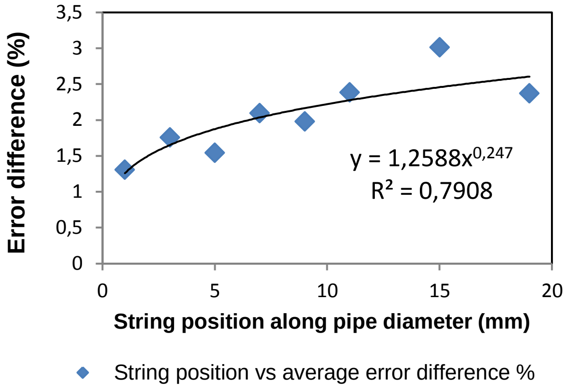

Figure 6: Average velocity error vs. depth positions (absolute error).

4 SUMMARY

The purpose of the presented test methods and investigations has been to evaluate the performance and accuracy of the Flow-Viz system. Errors ranged between 0.18 to 7.8% for the tested velocity range. The average accuracy of Doppler measurements decreased slightly from 1.3 to 2.3% close to the pipe wall towards the opposite pipe wall and was expected. Similar or higher errors were typically reported in the medical field, see e.g. [9-10,12]. The total uncertainty of the test system consists of uncertainties in the diameter of the drive pulley, speed of rotation, Doppler angle, and speed of sound (ultrasound velocity) in water. The new transducer technology was demonstrated to have high accuracy for complete non-invasive measurements through high grade stainless steel.

5 FUTURE WORK

By using only one transducer different ultrasound systems can be evaluated and compared. Sample volume dimensions can also be characterized for different transducers and/or ultrasound electronics. Furthermore, if raw echo data is captured the accuracy of different velocity estimation algorithms can be investigated and assessed. The second phase of the project will include tests using an advanced XY-scanner and hydrophone setup at SIK, Sweden.

6 ACKKNOWLEDGEMENTS

The NRF of South Africa and the CPUT Innovation Fund for funding. SIK is gratefully acknowledged for scientific collaboration.

REFERENCES

[1] Takeda Y: Measurement of velocity profile of mercury flow by ultrasound Doppler shift method, Nucl. Technol. 79 (1987), 120-124.

[2] Wiklund J, Shahram I, Stading M: Methodology for in-line rheology by ultrasound Doppler velocity profiling and pressure difference techniques, Chem. Eng. Sci. 62 (2007) 4159-4500.

[3] Wiklund J, Stading M: Application of in-line ultrasound Doppler based UVP-PD method to concentrated model and industrial suspensions, Flow Meas. Instrum. 19 (2008) 171-179.

[4] Kotzé R, Haldenwang R, Slatter P: Rheological characterization of highly concentrated mineral suspensions using an Ultrasonic Velocity Profiling with combined Pressure Difference method, Appl. Rheol. 18(6) (2008) 62114-62124.

[5] Kotzé R, Wiklund J, Haldenwang R, Fester V: Measurement and analysis of flow behaviour in complex geometries using the Ultrasonic Velocity Profiling (UVP) technique, Flow Meas. Instrum. 22 (2011) 110-119.

[6] Kotzé R, Wiklund J, Haldenwang R: Optimisation of Pulsed Ultrasonic Velocimetry and Transducer Technology for Industrial Applications, Ultrasonics 53 (2013) 459-469.

[7] Wiklund J, Kotzé R, Haldenwang R, Stading M: Development of an industrial UVP+PD based rheometer - optimisation of UVP system and transducer technology, Proceedings of the 8th International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering (2012) 49-52.

[8] Wiklund J, Kotzé R, Birkhofer B, Ricci S, Haldenwang R, Stading, M: Flow-Viz™ – A fully integrated and commercial in-line fluid characterization system for industrial applications, Proceedings of the 9th International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering (2014).

[9] Stewart, S.F.C: Effects of transducer, velocity, Doppler angle, and instrument settings on the accuracy of color Doppler ultrasound, Ultrasound in Med. & Biol. 27(4) (2001) 551-564.

[10] Thijssen JM, Wijk MC, Cuypers MHM: Performance testing of medical echo/Doppler equipment. European Journal of Ultrasound, 15 (2002) 151-164.

[11] Holland WPJ, Buyruk HM, Hoorn E, Stam HJ: Tendon displacement assessment by pulsed Doppler tissue imaging: Validation with a reciprocating string test target, Ultrasound in Med. & Biol. 25(8) (1999) 1229-1239.

[12] Walker AR, Phillips DJ, Powers JE: Evaluating Doppler Devices Using a Moving String Test Target, J. Clin. Ultrasound, 10 (1982) 25-30.

[13] Yang X, Sun C, Anderson T, Moran CM, Hadoke PWF, Gray GA, Hoskins PR: Assessment of spectral Doppler in preclinical ultrasound using a small-size rotating phantom, Ultrasound in Med. & Biol 39(8) (2013) 1491-1499.

[14] Eriksson R, Persson HW, Dymling SO, Lindstrom K: A microcirculation phantom for performance testing of blood perfusion measurement equipment. European Journal of Ultrasound, 2 (1995) 65-75.

[15] Jorgensen JE, Campau DN, Baker DW: Physical characteristics and mathematical modelling of the pulsed ultrasonic flowmeter, Med. & Biol. Eng. 11(4) (1973) 404-421.