Acoustic characterization of pulsed ultrasound sensors for improved non-invasive Pulsed Ultrasound Velocimetry through high-grade stainless steel pipes

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The newly developed Flow-Viz rheometric system is capable of performing detailed non-invasive velocimetry measurements through industrial stainless steel pipes. In order to advance the current non-invasive ultrasound sensor technology; acoustic characterization tests are required. The primary purpose of this work was to evaluate the effect of different non-invasive ultrasound sensor coupling configurations, for Doppler velocimetry in stainless steel pipes. The experiments involved measuring the ultrasound beam propagation through stainless steel (316L) pipe walls. A high-precision robotic XYZ-scanner and needle hydrophone setup was utilized to measure the beam propagation after the pipe wall; using a planar measuring technique along the beam's focal axis. The output for each test was a two dimensional acoustic color map, detailing the acoustic intensity of the ultrasound beam. Critical parameters such as the: focal zone start distance, focal zone length, Doppler angle and peak focal zone intensity are presented as part of the measurement results. It was noted that variations in the measured beam properties were highly dependent on the acoustic couplants. The Flow-Viz sensor technology was for the first time acoustically characterized, through stainless steel pipes. This information will now be used to further optimise the sensor technology for advanced industrial applications.

Keywords: Non-invasive ultrasound sensor, velocimetry, acoustic characterization, PUV, PUV+PD

1. Introduction and background

Pulsed Ultrasound Velocimetry (PUV) in industrial pipe flow has now reached a high level of development, since its first application to general fluids [1]. Non-invasive PUV is an appealing flow measurement technique for several industrial applications, especially in the food processing plants where hygienic requirements impose, clean, non-intrusive and non-destructive instrumentation [2]. By using the Doppler technique as described in [1] in conjunction with pressure difference measurement, the PUV+PD technique for determining the flow properties (rheology) of fluids was developed [3]. PUV+PD is mainly used as an in-line rheometric technique for quality control purposes. Over the past 15-20 years, the PUV+PD technique has been continually optimised and evaluated for a wide range of complex industrial fluids [4]–[7]; however, no commercial in-line rheometric system was developed for industrial implementation. Most of the in-line measurement data from earlier systems was post-processed off-line in order to determine the in-line rheological properties. Recently, Flow-Viz a non-invasive industrial rheometric system based on the PUV+PD methodology was developed under collaborative research between SP – Technical Research Institute of Sweden (SP), Gothenburg and Flow Process and Rheology Center (FPRC) at Cape Peninsula University of Technology (CPUT), Cape Town. The commercially available Flow-Viz system which is able to provide rheometric data in-line, consists of three integral parts, which are the operator's panel, system software and the non-invasive sensor unit [8], [9]. The main problem which still persists, and requires more attention is related to the development of more advanced non-invasive ultrasound sensor technology for measurements in complex industrial fluids [10]. The ideal ultrasound beam required for accurate measurements should be able to penetrate across the entire measurement depth especially in highly attenuating industrial fluids. The beam should also be as narrow as possible throughout the measurement axis, in order to achieve a higher spatial and lateral resolution [7].

Effective and efficient transmission of the pulsed ultrasound beam into the fluid under test at a predetermined Doppler angle, requires that there be an effective mechanical construction in place to hold the transducer in position, together with a suitable coupling medium to facilitate the transmission of acoustic energy [11]. The most common mounting fixtures which have been used thus far, are invasive flow adaptor designs [12]. A completely non-invasive ultrasound sensor solution which is capable of measuring through stainless steel (SS316L), was developed by Flow-Viz [10]. With the new sensors, the beam geometry is influenced by different material boundaries such as the coupling material and pipe walls, before it propagates into the fluid medium. The new non-invasive sensors require a coupling material between the sensor wedge surface and the outer pipe wall in order to maximize the acoustic energy propagating between the two material layers. The improved coupling corresponds to an increase in ultrasound transmission [11]. The resulting beam after the coupling material needs to also have a focal zone which starts at the inner pipe wall interface. This work was aimed at the acoustic characterization and evaluation of Flow-Viz ultrasound sensors for non-invasive velocity profile measurements through stainless steel pipes. None of the new sensor configurations were previously acoustically characterized. These tests investigated the propagation of the pulsed ultrasound beam from sensors, using different couplants, wedge and transducer technologies. The focus was on comparing the effectiveness of different couplants and sensor configurations; in order to develop the next generation non-invasive ultrasound sensor technology and to maximise the effectiveness of coupling configurations for existing sensors.

2. Experimental methods

2.1 XYZ-scanning system

To determine the sensors', beam properties, acoustic characterization tests were carried out using a high-precision (1 mm) needle hydrophone *(www.precision-acoustics.com/)* and an advanced XYZ-scanner setup. The submersible needle hydrophone and the different acoustic sensors were immersed in the water tank at room temperature. The XYZ-scanner was used to navigate the needle hydrophone probe across a predefined scanning grid i.e., to cover the focal area where the beam was located with a spatial resolution of 1 micrometer. In this work, only two spatial dimensions were used to map out a complete acoustic map i.e., vertical (Z-axis) and lateral (Y-axis) for the tests through stainless steel. The pulser-receiver was controlled from the host computer via RS232 serial (9600 baud-rate, 8-bit data) communications. The digitizer acquired the hydrophone measurement signal for each point within the scanning grid at set times, which were determined by the Matlab® based application.

2.2 Sensors and coupling configurations

Two types of sensors were tested: (i) the new commercial black Flow-Viz sensor and (ii) the prototype sensor with separate wedge and transducer, which allows detachment of the transducer from the wedge. The new commercial Flow-Viz sensor design only requires a coupling material between the sensor unit (with wedge) and stainless steel pipe, since it contains an integrated transducer-to-wedge couplant. The new design with integrated wedge is more convenient than the prototype wedge, as it reduces the complexity of couplant installation and the uncertainities associated with determining critical measurement parameters such as the Doppler angle (θ). Three solid (solid-X, solid-Y and solid-Z) and one liquid couplant were used in different configurations: at each sensor's transducer-to-wedge (TX) and wedge-to-pipe boundaries. The thicknesses of the couplants were: solid-X is ~1 mm, solid-Y is ~2 mm and solid-Z is ~2.5 mm. The liquid couplant was applied as a thin film of < 1mm. A sampling frequency of 100 MHz was used with the digitizer. Figure 1 illustatres the vertical scanning area along the beams focal axis after propagating through the half-cut stainless steel pipe spool piece. The beam propagation angle within the wedge with reference to the horizontal is α, whereas that after the inner pipe wall interface is θ. Transducers used for the tests were rated at (1.8-2.2) MHz central frequency. A pulse length of 250 ns with an excitation voltage of 100 V were applied.

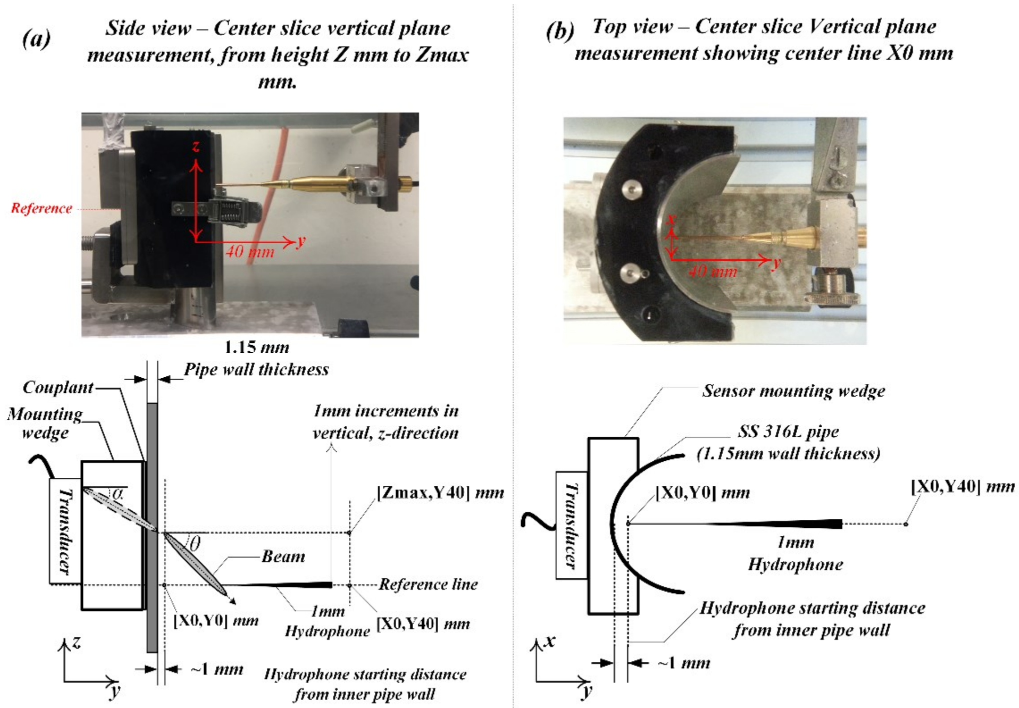


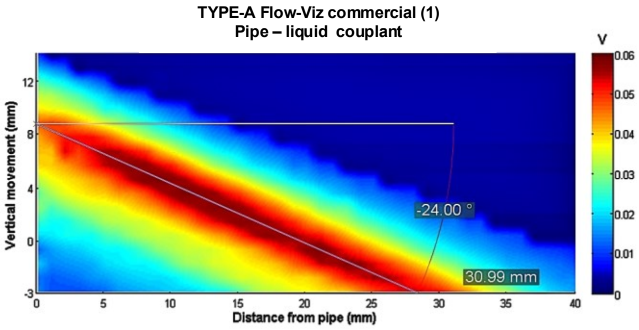
Figure 1: (a) Side view image and schematic of the vertical distance covered in the vertical direction (Z0 to Zmax). (b) top-view schematic of the lateral distance covered (Y0-Y40) along beam center line (X0) (adapted from [9]).

3. Results and Discussion

3.1 Flow-Viz Commercial –sensor configuration for 47.8 mm pipe

Acoustic color maps are oriented with respect to the sensor; i.e., for all pipe tests the sensor unit is positioned at the left of the acoustic map; and the 0 mm marking on the vertical movement axis is the reference position on the physical sensor unit (see Figure 1). Four Flow-Viz transducers numbered 78, 79, 80 and 81 were used. Detailed information on these transducers can be found in [9]. Figure 2 shows the acoustic map obtained from the Flow-Viz 47.8 mm commercial sensor, pipe tests.

(a)



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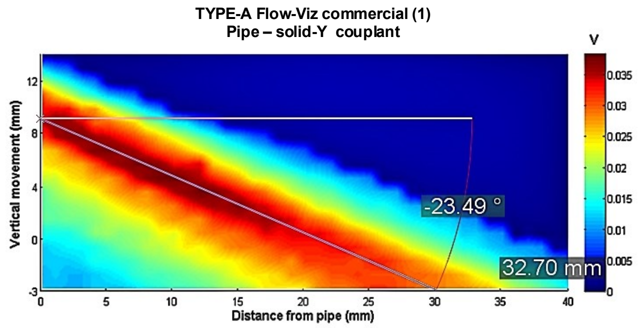


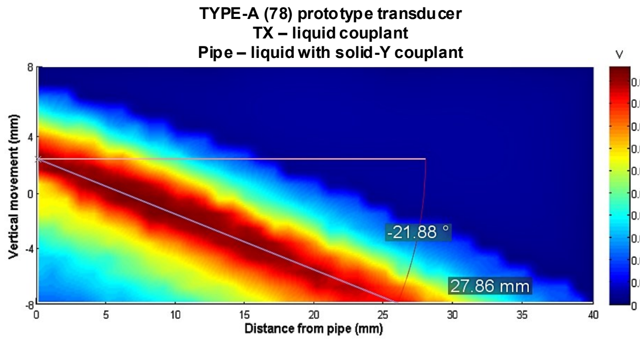
Figure 2: Acoustic maps for Flow-Viz 47.8 mm commercial sensor with (a) liquid couplant (b) liquid and solid-Y couplant at wedge-to-pipe interface [9].

In order to test the quality and consistency of the Flow-Viz manufacturing process, two identical sensors with liquid couplant at the wedge-to-pipe boundary were tested, and similar results were obtained. One result from the sensor tests with liquid couplant is illustrated in Figure 2(a). The start of the focal zone was at a distance of ~5 mm away from the inner pipe wall with the liquid only couplant; however, with the solid-Y couplant the focal zone is situated close to the inner pipe wall. A focal zone starting at the pipe wall improves the near wall measurements. This is important for accurate in-line rheology as it reduces the near wall fluctuations which have been reported in literature [6]. The liquid couplant is a more effective couplant than the solid couplant when using the commercial Flow-Viz sensor unit. The solid-Y couplant in Figure 2(b), seemed to have more attenuating effects on the beam propagation. The peak focal zone voltage with the liquid couplant was 60.3 mV whereas with the solid-Y couplant it was 38.5 mV.

3.2 Prototype wedge sensor configuration for 47.8 mm pipe

Figure 3 confirmed that for the 47.8 mm prototype sensor, solid-Z resulted in the most undesirable beam of the configurations which were tested, since the focal zone length (~20 mm) is less than the pipe radius (23.9 mm). The most preferable beam with regards to the length and location of the focal zone is that measured from the combined liquid and solid-Y couplant. The focal zone is both close the pipe wall and extends over half the pipe radius, similarly to the liquid only configuration in Figure 2(a), despite less focal zone peak voltages than the latter.

(a)



(b)

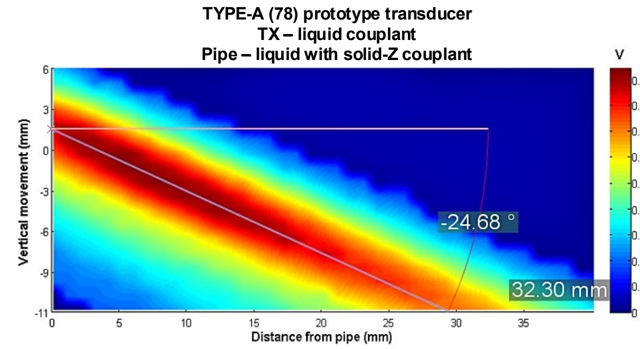


Figure 3: Acoustic maps for 47.8 mm prototype (78) sensor with liquid transducer-to-wedge couplant (TX); (a) liquid and solid-Y couplant (b) liquid and solid-Z couplant at wedge-to-pipe interface [9].

A third setup (not illustrated in Figure 3) i.e., with liquid couplant at the wedge-to-pipe interface resulted in similar beam properties to those obtained with the Flow-Viz commercial sensor in Figure 2(a). The critical Doppler angle from Figure 3 was seen to change by ~3° after changing the wedge-to-pipe couplants. This has to be taken note of since it directly affects the calculated axial velocity vectors along the pipe radius; and consequently the rheology of the fluid due to the changes in the velocity profile dependent shear rates.

3.3 Prototype wedge sensor configuration for 22.4 mm pipe

For the test in Figure 4, a different transducer-to-wedge (TX) couplant in the form of solid-X (described in Section 3) was used. The significant increase in energy observed for this test (Figure 4) is mainly attributed to the thin solid-X couplant between the transducer and wedge interface. With a solid-X couplant, the maximum voltages within the focal zone for Figure 4 (a) and (b) were ~127 mV and ~93 mV, respectively, whereas those from Figure 5 with a liquid couplant at the transducer-to-wedge were in the range of (53-55) mV. Since the high energy (peak voltage) output with solid-X was an exception, it must be pointed out that the transducer (79) with the thin solid-X couplant had a different design compared to transducer 80, which could also be another contributing factor for the increased energy output.

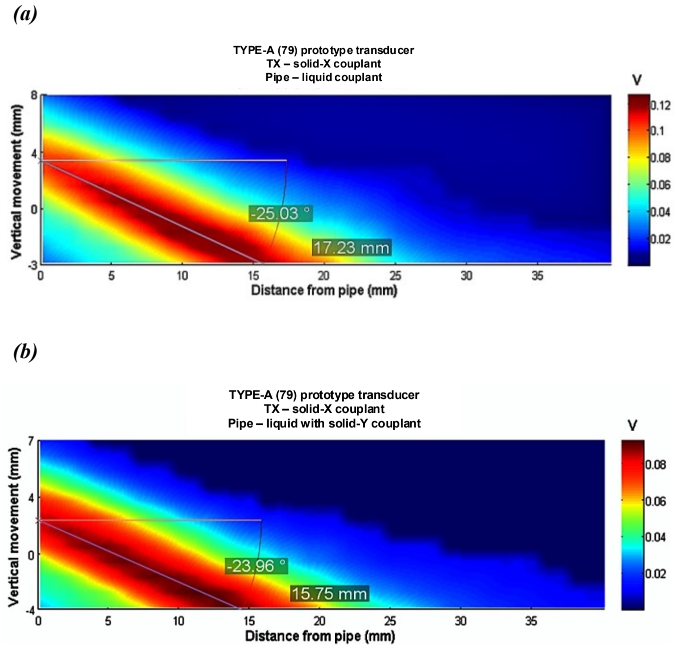


Figure 4: Acoustic maps for 22.4 mm pipe (79) sensor attached to prototype wedge with (a) only liquid couplant (b) liquid and solid-Y couplant between pipe and wedge [9].

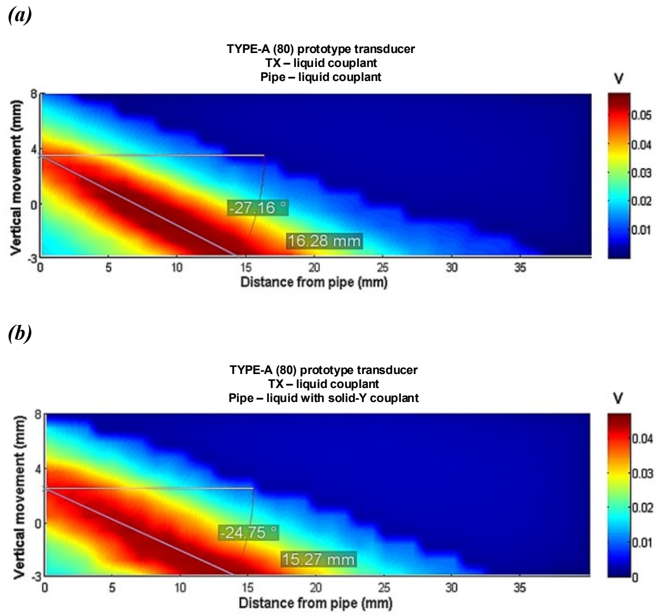


Figure 5. Acoustic maps for 22.4 mm pipe (80) sensor attached to prototype wedge with (a) only liquid couplant (b) liquid and solid-Y couplant between pipe and wedge [9].

The Doppler angle when using liquid couplant (Figure 5(a)) is reduced (~63.0°) compared to that obtained when using solid-Y couplant (~65.0°) at the wedge-to-pipe interface. This observation in Doppler angle changes is similar to that observed in Figure 4.

4. Conclusion

In this work, detailed acoustic characterization maps of the Flow-Viz non-invasive ultrasound sensors were obtained. The tests revealed that correct selection of solid and liquid couplants at different sensor interfaces is important in order to improve the overall transmitted beam properties and consequently PUV and PUV+PD measurements. As a general guideline, combining the solid-Y and liquid couplant at the wedge-to-pipe interface produced the most optimal beam properties i.e., focal zone starting distance and overall focal zone length. The next step is to conduct detailed 3-dimensional (3-D) acoustic measurements to gain more information on the entire beam geometry and to advance non-invasive sensor designs.

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