Characterization of Acoustic Beam Propagation Through High-Grade Stainless Steel Pipes for Improved Pulsed Ultrasound Velocimetry Measurements in Complex Industrial Fluids

Tafadzwa John Shamu, Reinhardt Kotzé, and Johan Wiklund

***Abstract*— The newly developed Flow-Viz rheometric system is capable of performing detailed non-invasive velocimetry measurements through industrial stainless steel pipes. However, in order to improve the current design for non-invasive measurements in industrial fluids, pulsed ultrasound sensors need to be acoustically characterized. In this paper, acoustic characterization tests were carried out, with the aim of measuring the ultrasound beam propagation through stainless steel (SS316L) pipes and into water. For these tests, a high-precision robotic XYZ-scanner and needle hydrophone setup was used. Several ultrasound sensor configurations were mounted onto stainless steel pipes, while using different coupling media between the transducer-to-wedge and sensor wedge-to-pipe boundaries. The ultrasound beam propagation after the wall interface was measured by using a planar measuring technique along the beam's focal axis. By using this technique, the output for each test was a 2-D acoustic color map detailing the acoustic intensity of the ultrasound beam. Measured beam properties depicted critical parameters, such as the start distance of the focal zone, focal zone length, Doppler angle, and peak energy within the focal zone. Variations in the measured beam properties were highly dependent on the acoustic couplants used at the different interfaces within the sensor unit. Complete non-invasive Doppler ultrasound sensor technology was for the first time acoustically characterized through industrial grade stainless steel. This information will now be used to further optimize the non-invasive technology for advanced industrial applications.**

***Index Terms*— Non-invasive ultrasound sensor, pulsed ultrasound, velocimetry, ultrasonic transducer, acoustic measurements.**

I. Introduction

PULSED ultrasound based velocity profile measurement in industrial pipe flow has now reached a high level of development, since its first application to general fluids [1]. When Pulsed Doppler Ultrasound Velocimetry (PUV) was combined with Pressure Difference (PUV+PD) measurement, the PUV+PD technique for measuring fluid flow properties was developed [2]. PUV+PD is mainly used as an in-line rheometric technique for quality control purposes [3]–[6]. Over the past decade, the PUV+PD technique has been continually optimised and evaluated for a wide range of complex industrial fluids, however, no commercial in-line rheometric system was developed for industrial implementation. Recently, Flow-Viz a novel, non-invasive 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 Centre (FPRC) at Cape Peninsula University of Technology (CPUT), Cape Town [7]. The commercially available Flow-Viz system consists of three integral parts which are the operator's panel, system software and the non-invasive sensor unit [7]. The main problem which still persists, and requires more attention is related to the development of more advanced non-invasive ultrasound sensor technology [8]. The ideal ultrasound beam required for accurate measurements should be able to penetrate across the entire measurement depth, especially in highly attenuating industrial fluids. Moreover the beam should be as narrow as possible throughout the measurement depth, inorder to achieve a higher spatial and lateral resolution [9]. With the new non-invasive 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. Hence, knowing the beam properties of current sensors within such setups is of prior importance in the development of improved sensor designs. This work was aimed at the acoustic characterisation 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 characterised. The tests investigated the propagation of the pulsed ultrasound beam from sensors using different couplant, 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.

A. Pulsed Ultrasound Velocimetry (PUV) – Theoretical Background

The primary sensing element in a pulsed ultrasound velocimetry system is the ultrasound transducer.

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T. J. Shamu and R. Kotzé are with the Cape Peninsula University of Technology, Cape Town 8000, South Africa (e-mail: sbshamu@gmail.com; reinhardtkotze@yahoo.com).

J. Wiklund is with the SP Technical Research Institute of Sweden, Gothenburg 402 29, Sweden (e-mail: johan.wiklund@sp.se).

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The performance of a PUV system is highly dependent on the type of ultrasound sensor used [10]. To carry out a one-dimensional velocity profile measurement, the ultrasound transducer is excited by the pulser/receiver electronics to transmit preprogramed repetitive ultrasound pulses at a fixed interval known as the pulse repetition interval (PRI). The transmitted ultrasound beam is divided into a number of segments known as gates or channels. Each of these gates returns an echo signal from a target particle at a certain depth along the ultrasound beam axis. Hence, each gate is in fact a measuring volume by which the axial velocity of a target particle is calculated [10]. Detailed descriptions of the PUV principle of operation can be found in [3] and [11]–[13]. The main equation which is used to calculate the velocity v at different axial depths, is given by (1):

$$v = \frac{c f_d}{2 f_0 \cos\theta} \tag{1}$$

where f_0 is the fundamental transmission frequency, c is the velocity of sound, f_d the Doppler shift frequency and θ is the Doppler angle (angle between the ultrasound beam axis and the pipe axis). To efficiently transmit the pulsed ultrasound beam into the fluid under test at a predetermined Doppler angle, there needs to 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 [14]. Several mounting fixtures have been described by authors and most of these are invasive flow adaptor designs [15]. The flow adaptors normally include a transducer which is pulled back some distance from the inner pipe wall; creating a cavity to cater for the elimination of the near-field distance, where variations in the ultrasound field are non-uniform [9], [16]. In other configurations, the sensor is installed in flush with the inner pipe wall as described in [3] and [17]. Another design in which the transducer is in flush with the inner pipe wall is that presented by [9]. This assembly was used prior to the development of the Flow-Viz non-invasive sensors. The main difference with other in flush installations was that a special delay line material was fitted in front of the transducers [9]. With the delay line sensor, improved velocity profiles were noted especially in the near wall region. To improve the accuracy of measurements as well as to advance the PUV+PD technology to applications within the food processing industry a non-invasive sensor solution was needed. Food processing applications require non-invasive and non-intrusive sensor installations which comply with the industry's hygienic standards. Moreover, the former delay line setup presents a safety hazard when high pressures or temperatures are present during measurements and therefore a completely non-invasive sensor unit had to be developed. With the new non-invasive sensor configuration, the drive is to obtain an ultrasound beam with a focal point right at the pipe wall in order to avoid erroneous measurements within the near wall region where the velocity gradient is the highest. Secondly, sensors need to emit high intensity beams which cover the pipe diameter, even in highly attenuating fluids. These advances will greatly increase the measurement capabilities of the PUV system.

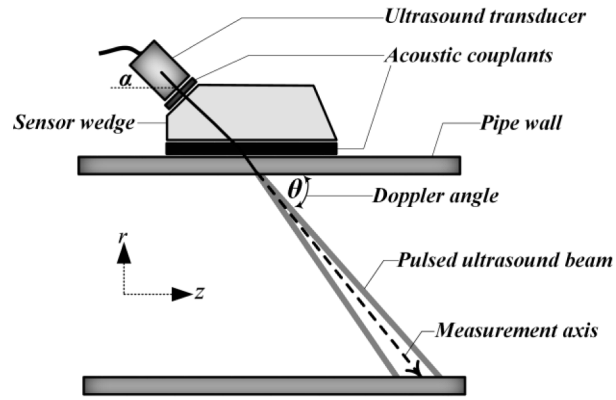

Fig. 1. Non-invasive ultrasound sensor setup showing beam incidence angle at boundary layers.

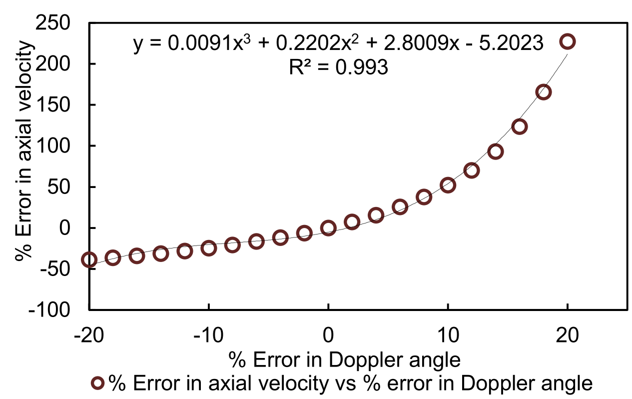

Fig. 2. Percentage errors in axial velocity due to error in Doppler angle.

B. Non-Invasive Sensor Technology

A completely non-invasive ultrasound sensor solution which is capable of measuring through stainless steel (SS316L), was developed by Flow-Viz [8]. The new non-invasive sensors require a coupling material between the sensor surface and the outer pipe wall in order to improve the acoustic coupling between the sensor surface and the outer pipe wall. The improved coupling corresponds to an increase in ultrasound transmission [14]. Acoustic couplants can either be liquid or solid materials and must be placed accordingly at the different sensor boundaries. Fig. 1 shows a typical non-invasive setup illustrating critical parameters such as the Doppler angle θ.

The acoustic couplants used at the different interfaces should be chosen correctly, so as to obtain a specific Doppler angle and desirable focal zone properties, which are consistent for the different sensor configurations. For example, [18] and [19] describe the necessary guidelines for non-invasive sensor installations. Factors such as proper preparation and cleaning of the mounting surface greatly improve the measurements if procedures are adhered to. The authors of [20] further pointed out that the effective function of acoustic couplants in facilitating optimum transmission of the ultrasound beam through boundary layers is highly influenced by the test conditions. Acoustic properties of couplants are greatly dependant on temperature, and thus proper care has to be taken in considering a specific couplant for temperature

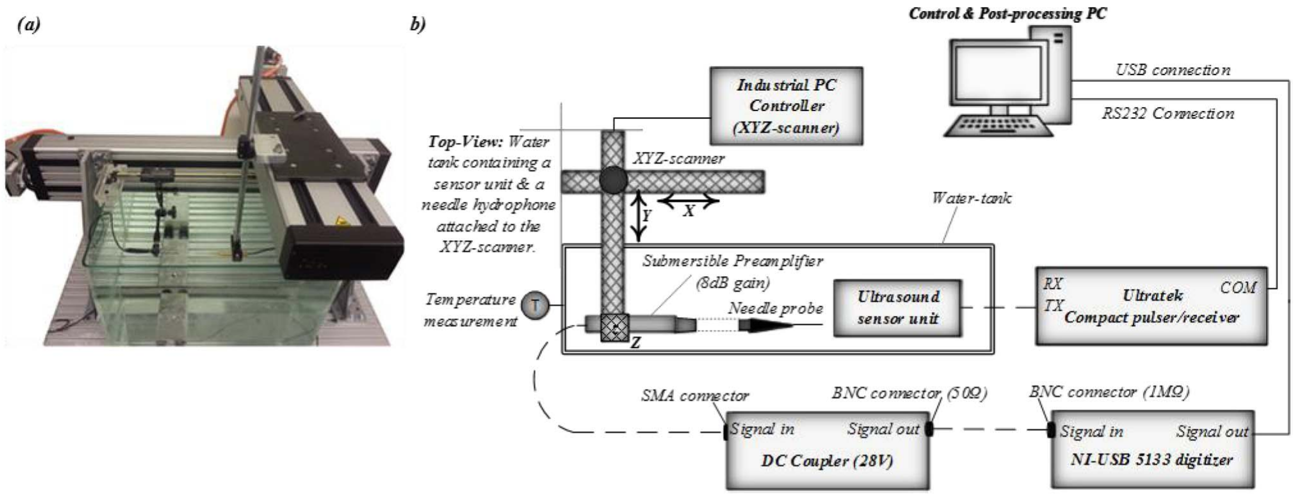

Fig. 3. (a) XYZ-scanner setup. (b) Schematic of XYZ-scanner experimental setup showing data acquisition system components.

extensive industrial applications, especially if a longer couplant replacement time is required. The effect of couplants on critical beam properties (e.g. Doppler angle, intensity distribution) for industrial stainless steel pipe coupling is further discussed as a major part of this paper. As shown in (1), correct values of the velocity of sound c and the Doppler angle θ need to be determined with good accuracy in order to obtain correct values of the measured axial velocity distribution. For non-invasive sensor configurations, several sources of error in the Doppler angle usually result from misalignment or misinterpretation of the ultrasound beams axis to that which is normally measured on the physical sensor unit. Fig. 1 shows that with the non-invasive setup, the initial ultrasound beam angle α is not the same as the final propagation angle θ, since the ultrasound beam passes through several materials of different sound speeds.

In an effort to show the importance of using the correct Doppler angle for velocimetry measurements, [21] described the relationship between the errors in Doppler angle and the resulting errors in the determined axial velocities. Based on the reference Doppler angle used in [21] i.e. 20°, a Doppler angle error of ~30% was seen to introduce corresponding velocity errors of ~5%. A similar analysis was done for this work to determine the velocity variation due to an error in the Doppler angle. In this case, a Doppler angle of 70° was taken as the reference value. This value of the Doppler angle was selected as it is optimal for non-invasive sensor installations on stainless steel pipes and is also used with the current Flow-Viz sensors. Fig. 2 shows how the Doppler angle affects the axial velocity.

It should be noted that errors of the same magnitude (e.g., 2% angle error and −2% angle error) result in different error magnitudes in the velocity error. These nonlinearities are due to the division with the cosine function in (1). Similar relationships in velocity errors due to Doppler angle errors were also noted by [22]. As shown in Fig. 2, the impact of the Doppler angle error in the calculated velocity has to be considered carefully.

A ~10% error in the Doppler angle would mean a ~50% error in the calculated velocities. From the above discussion it can be seen that the correct determination of the Doppler angle and the acoustic beam properties for non-invasive velocimetry are necessary to achieve more accurate measurements. It should also be noted here that, an incorrect Doppler angle (together with velocity of sound) will also result in an incorrect conversion from the ultrasound beam axis to the lateral axis. This contributes to errors in rheology calculations when using the PUV+PD methodology. Furthermore, knowledge of how these critical parameters affect measurement data, enables informed design improvements to be implemented: for the development of more accurate sensors with narrower and high intensity beams. Acoustic characterisation tests similar to those carried out by [6] were carried out in this work inorder to determine critical beam properties of different non-invasive sensors. Similar methods to those used by [6] were also presented in [23]. The work by [23] describes acoustic characterisation tests to measure the variation of acoustic pressure in the focal region of the beam produced by High Intensity Focused Ultrasound (HIFU) type transducers. The focal zone geometry was illustrated by using colour and contour plots. The measurement techniques used for this research work, which incorporate a needle hydrophone setup are described accordingly.

II. Methodology

A. Experimental Apparatus

To determine the sensors' beam properties, acoustic characterisation tests were carried out using a high-precision needle hydrophone and an advanced XYZ-scanner setup. The XYZ-scanner setup with a spatial resolution of 1 micrometer is illustrated in Fig. 3 together with the schematic of test setup. The setup consisted of a robotic XYZ-scanner mounted on top of a transparent water tank. The submersible needle hydrophone and the different acoustic sensors where 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 area where the beam was located. The 1 mm needle hydrophone probe was connected to a submersible preamplifier with a gain of 8 dB. Temperature readings within the water tank fluctuated between

TABLE I
TRANSDUCER AND SENSOR COUPLING CONFIGURATIONS USED FOR TESTS

Transducer type	**Description**
TYPE-A transducer (numbered 78, 79, 80, 81)	(1.8-2.2) MHz emission frequency, optimised for 22.4 mm and 47.8 mm pipes
SENSOR DESCRIPTION	
Sensor type	**Description**
Prototype sensor unit for 22.4 mm and 47.8 mm pipes	Flow-Viz prototype sensors unit using TYPE-A transducer numbered (78, 79, 80 and 81)
Industrial commercial sensor unit for 47.8 mm pipe	Flow-Viz commercial sensor unit with integrated TYPE-A transducer (latest clamp-on design).

(21-23) °C for the duration of the tests. In this work only two dimensions were used to map out a complete acoustic map i.e., XY for the transducer tests or YZ for the tests through stainless steel.

An *Ultratek* compact pulser/receiver was used to excite the ultrasound transducers. The pulser/receiver was controlled from the host computer via RS232 serial (9600 baud-rate, 8 bit data) communications. The main reason for using this unit was that it allowed continuous pulsing throughout the characterisation tests. Furthermore, the *Ultratek* unit was chosen as it offered a simple interface for lower cost and it is often used in industry for Non-destructive Testing (NDT). The needle hydrophone system (www.precision-acoustics.com/) used was made up of a combined needle probe and preamplifier with a voltage gain of 8 dB. The pre-amplifier was linked to the 28 V supplied DC-Coupler using a coaxial connection with a Sub-Miniature type A (SMA) connector. Fig. 3 shows that the output impedance of the system was 50 Ω and the unit was connected to a National-Instruments (NI-5133) digitiser with an input impedance of 1 MΩ. A correction factor of 1.953 was applied for impedance mismatch. The value of the correction factor was determined by comparing several voltages measured throughout the measuring grid using an impedance matched Agilent oscilloscope (DSO-X-3024A) with those from the NI-digitiser. The digitiser acquired the hydrophone measurement signal for each point within the scanning grid at set times, which were determined by the Matlab® based application. All the measured voltages from the different grid points were then combined during post processing in Matlab® to form the acoustic colour map of voltages, which shows the beam intensity. A sampling frequency of 100 MHz was used with the digitiser.

B. Experimental Procedures

The test matrix included several transducers which were mounted in different configurations with solid and liquid couplants. Two transducer housing cases for clamp-on mounting were used to attach the transducers under test onto the stainless steel (SS316L) pipes i.e., a solid prototype wedge and the other being the latest Flow-Viz black casing. The

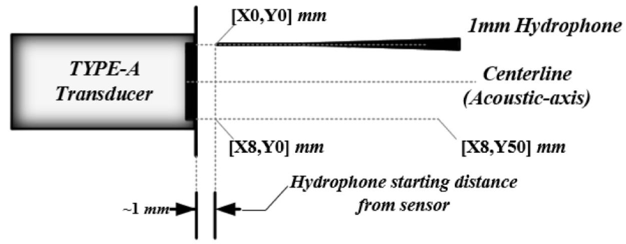

Fig. 4. Top view schematic of the horizontal scanning grid for prototype transducers showing the reference point.

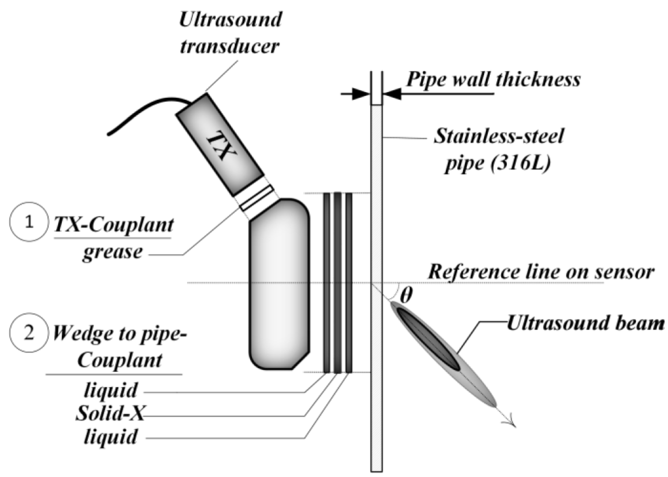

Fig. 5. Transducer (TX) and wedge to pipe couplants in pipe tests.

pipes used had internal diameters of 22.4 mm and 47.8 mm, with thicknesses of 1.15 mm and 1.38 mm respectively. The black casing is an improved design that allows easy installation of the sensor onto the pipe. It also features an integrated design between the transducer and sensor wedge technology. For each test setup two main couplants i.e., a liquid couplant and a solid (solid-X, solid-Y and solid-Z) couplant were used. The purpose of the couplants was to facilitate the transmission of the acoustic energy from the transducer through the pipe wall. Before each test the needle hydrophone was soaked in water for at least 30 minutes so that the output stabilised before any measurement was taken. All test materials and specific transducer designs used for this research work are guarded by confidentiality agreement, thus schematics instead of original images will be used for some sensor setups. Actual manufacturer specifications and product names are therefore omitted from the research paper. The sensor units that were tested are described in Table I. Different configurations were exploited in order to ensure that the hydrophone measurements were accurate and that readily identifiable reference points could be established. For example, the tests to measure the beam propagation through stainless steel were conducted as illustrated in Fig. 5 and Fig. 6; whereas those to characterise the individual transducers were carried out as depicted in Fig. 4. For all test setups in this paper, a *sensor unit* consists of a mounting wedge and ultrasound transducer whereas the *transducer* is not coupled to any additional material such as a couplant or wedge.

The beam properties of transducers were determined from measuring a full acoustic map without using any mounting

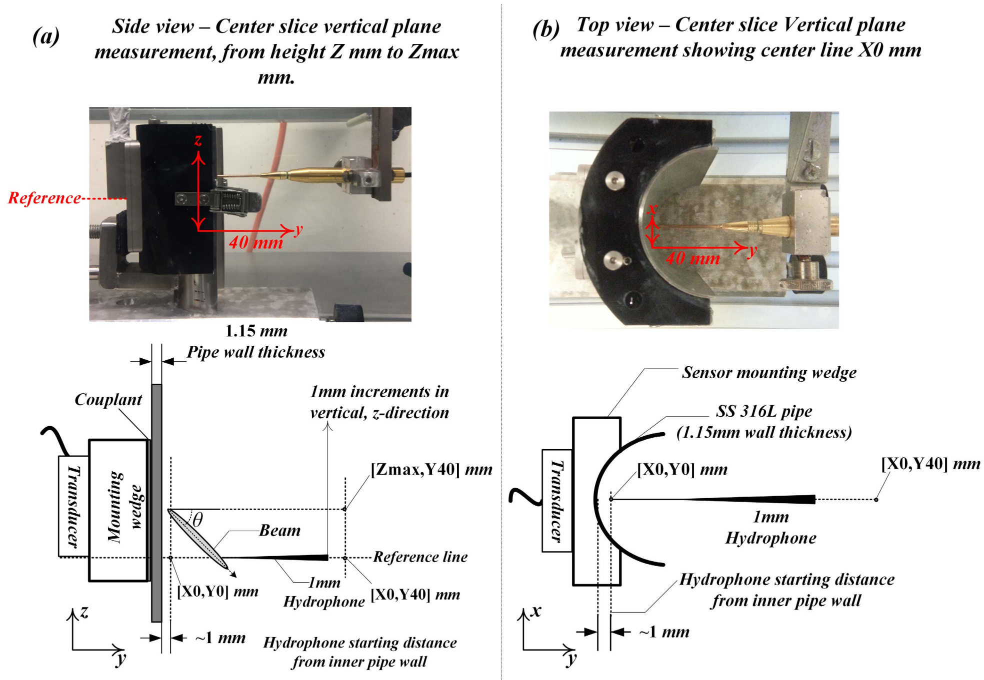

Fig. 6. (a) Side-view schematic of the vertical distance covered in the vertical direction (Z0 to Zmax). (b) Top-view schematic of the lateral distance covered (Y0-Y40) along beam center line (X0).

wedge or couplant material. For the subsequent test measurements, the transducers were mounted onto a stainless steel pipe spool piece cut in half. This was done so that the transmitted ultrasound beam from the near wall could be captured by the needle hydrophone. The needle hydrophone was moved within a predefined 2-dimensional (2D) grid in 1 mm increments, to cover the transmitted beam accordingly. The methods followed for scanning and measurement were similar to those presented in [9] and [23].

1) Measurement Reference Point Description: For each test (single transducer or through stainless steel) a spatial reference (origin) point was first established in order to determine the position of the beam on the physical sensor unit.

For the ***single transducer characterisation***—with no wedge attached to a pipe, the reference was first set by scanning for the point of maximum acoustic energy. This was done by viewing the hydrophone output on an Agilent oscilloscope which was set to a high sensitivity (5 mV per division). This point was then set as the centre of the X-axis (or centre of the acoustic beam). By knowing the centre value (maximum energy), the origin at X0 mm was set using the XYZ-scanner controller, such that a symmetrical acoustic map could be obtained after a complete test run. The complete 2D acoustic grid is illustrated by the schematic in Fig. 4 which depicts the X0 origin point.

For the ***vertical grid measurements***—once a physical reference point on the physical sensor unit was first established, a point of maximum acoustic energy was located along the physical reference line. This was also carried out by viewing the hydrophone output on the Agilent oscilloscope (sensitivity of 5 mV per division). The hydrophone was navigated vertically along the z-axis from the point of maximum energy on the reference line (see Fig. 6), in order to find where the beam's boundaries (lower energy regions) were located. This allowed simpler determination of the entire beam orientation in the completed acoustic map, by using the physical reference line on the sensor unit as a spatial reference (origin).

The single transducer (*Horizontal plane measurement*) and acoustic tests through stainless steel (*Vertical plane pipe measurement*) are described briefly as follows:

(i) **Horizontal plane measurement (Prototype sensors, no wedge):** The scanning area started at the reference point [X0, Y0] mm illustrated on Fig. 4. From this reference point a rectangular grid was mapped to cut the face of the transducer at the plane of maximum intensity (voltage). The setup is illustrated in Fig. 4.

(ii) **Vertical plane pipe measurements:** The reference points for the vertical plane measurements were taken as the points at which the needle hydrophone is parallel to:

- **a.** For the 22.4 mm and 47.8 mm prototype sensors, the reference was the corner point of the diagonal line marking on the prototype wedge. The schematic for the vertical pipe tests is shown in Fig. 5.
- **b.** For the industrial commercial sensor optimised for 47.8 mm pipes, the bottom of the silver/grey edge of the sensor clamp-on housing. The tests setup is shown in Fig. 6.

The spatial reference point was used as the origin of height measurement or as the zero height level in millimeters [Z0], in order to cover a rectangular grid which cuts across points of maximum measurable voltage, i.e., a rectangular (2D) centre slice with points of maximum measurable peak voltage; the length of the rectangle being millimeter increments from [X0 to X40] with a height defined by vertical millimeter increments from [Zmin to Zmax] (see Fig. 6). Zmax and Zmin were the

TABLE II
PULSER SETTINGS USED FOR DIFFERENT TYPES OF TRANSDUCERS

Sensor type	Center Frequency [MHz]	Transducer number	Pulse length [ns]	Voltage [V]
TYPE-A for 47.8 mm pipe	1.8 - 2.2	78, 80	250	100
TYPE-A for 22.4 mm pipe	1.8 - 2.2	79, 81	250	100

TABLE III
AN OVERVIEW OF THE MAIN PROPERTIES OF THE ACOUSTIC COUPLANTS

TYPES OF ACOUSTIC COUPLANTS AND PROPERTIES			
Couplant type	**~Thickness of couplant**	**High temperature tolerance**	**Ease of installation**
Solid-X	(< 1 mm)	low	low
Solid-Y	(2 mm max.)	low	low
Solid-Z	(2.5 mm)	low	low
Liquid	film (< 1 mm)	High (slow drying)	high

maximum and minimum heights at which V_{pk-pk} voltages could not be detected by the digital oscilloscope or NI-5133 digitizer, whereas Z0 was the height at the reference line (0 mm). Measurements in the negative Z-direction i.e., below the Z0 reference line were also taken, in order to sufficiently cover a horizontal focal zone distance equal to at least the pipe radius (velocimetry measurements require a minimum focal zone coverage which extends to at least the pipe radius). Necessary alignment of the needle hydrophone with the transducer was done to ensure that the needle hydrophone was kept in parallel with the horizontal reference line. This was first done by visual alignment followed by finer adjustments with appropriate alignment instruments (level and ruler). Once the physical alignment of the transducer and needle hydrophone was completed, the test run was started from the control computer. Fig. 5 further illustrates the arrangement of the acoustic couplants used on the ultrasound transducer-to-wedge interface as well as the wedge-to-pipe mounting for all vertical pipe measurements.

The pulser/receiver was set to pulse continuously for the duration of the test, whilst a specially developed Matlab® graphical user interface (GUI) program was used to control the digitizer for acquiring and logging purposes. The Matlab® program made use of the NI-USB 5133 device driver. The GUI application enabled manual and automatic saving of the voltages measured for each grid point to a mat-file. Matlab® post-processing code was also written to allow visualisation of the complete acoustic maps of V_{pk-pk} voltages using appropriate plots and colour mapping to highlight the voltages present in the focal zone and the angle the beam makes with the horizontal reference line at the near-pipe wall. The pulser/receiver settings shown in Table II were used, with a voltage gain of 20 dB for all the tests.

For the vertical pipe tests, different types of materials were used as acoustic couplants at the transducer-to-wedge interface and at the wedge-to-pipe interface. The couplants consisted of three solid couplants (Solid-X, Solid-Y and Solid-Z) and a liquid couplant. The solid couplants were also combined with the liquid couplant inorder to improve the overall installation. Table III describes properties of the sensors used in the vertical pipe acoustic characterisation tests.

For solid couplants, regular checks on fastening are required to eliminate air gaps and maintain accurate measurements. Installation surfaces need to be cleaned thoroughly before application as outlined in [19]. These guidelines were followed for all pipe tests. Table IV is a matrix of all the single transducer and vertical pipe characterisation tests.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The acoustic maps presented for both the vertical configuration and the single sensor characterisation tests show the peak to peak voltage (V_{pk-pk}) measured at each spatial point within the two-dimensional scanning area covered by the high-precision XYZ-scanner.

A. Ultrasound Transducer Characterisation Tests (No Pipes)

Fig. 7 shows the acoustic colour maps for the Flow-Viz TYPE-A prototype transducers numbered 78, 79, 80 and 81. The acoustic maps for transducers with the same design i.e., (78 and 80) and (79 and 81) are similar especially in the shape of the focal zone. The single transducer characterisation tests for all TYPE-A transducers show that the beam profiles are mostly centred and symmetrical across the scanning area. From Fig. 7 (a) and (b) the focal zone is seen to start at ~16 mm and is narrower from position ~35 mm onwards as compared to sensors 79 and 81 which show a much wider focal zone and higher energy throughout the whole acoustic map. The characteristic extended focal zone length which was seen for transducers 79 and 81 is more desirable as it allows greater penetration to provide velocity information even in highly attenuating fluids.

B. Vertical Pipe Tests – Sensor Characterisation Through Stainless Steel Pipes

1) TYPE-A (78) – Prototype Wedge Sensor Configuration for 47.8 mm Pipe: The arrangement shown earlier in Fig. 5 also serves as a description of how the beams presented in the acoustic colour maps are oriented with respect to the sensor; i.e., for all pipe tests the sensor unit position is to 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. Fig. 8 shows that for the 47.8 mm prototype sensor, the solid-Z couplant (2.5 mm thickness) resulted in the most undesirable beam of the three configurations 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 Fig. 8 (a), despite having less energy than the latter.

2) TYPE-A (79) – Prototype Wedge Sensor Configuration for 22.4 mm Pipe: A prototype sensor for the 22.4 mm pipe was also tested using the same planar method used for the 47.8 mm sensors. A different transducer-to-wedge

TABLE IV
TEST MATRIX: SINGLE TRANSDUCER AND VERTICAL PIPE TESTS

SINGLE TRANSDUCER TESTS

Transducer type	Transducer numbers	Center Frequency	XYZ-spatial resolution
TYPE-A	(78,79, 80,81)	(1.8-2.2) MHz	1 mm

VERTICAL PIPE TESTS

Non-invasive Sensor dimensions	Transducer type	Transducer number	Couplant Transducer-to-wedge	Wedge type	Couplant Wedge-to-pipe	Pipe-wall thickness	XYZ-spatial resolution
47.8 mm pipe	TYPE-A	(78)	liquid	prototype	liquid	1.15 mm	1 mm
47.8 mm pipe	TYPE-A	(78)	liquid	prototype	liquid + solid-Y + liquid	1.15 mm	1 mm
47.8 mm pipe	TYPE-A	(78)	liquid	prototype	liquid + solid-Z + liquid	1.15 mm	1 mm
47.8 mm pipe (sensor 1) *(integrated transducer, Fig. 6)*	TYPE-A	-	integrated	industrial	solid-Y	1.15 mm	1 mm
47.8 mm pipe (sensor1) *(integrated transducer, Fig. 6)*	TYPE-A	-	integrated	industrial	liquid	1.15 mm	1 mm
47.8 mm pipe (sensor 2) *(integrated transducer, Fig. 6)*	TYPE-A	-	integrated	industrial	liquid	1.15 mm	1 mm
22.4 mm pipe	TYPE-A	(79)	solid-X	prototype	liquid	1.38 mm	1 mm
22.4 mm pipe	TYPE-A	(79)	solid-X	prototype	liquid + solid-Y + liquid	1.38 mm	1 mm
22.4 mm pipe	TYPE-A	(80)	liquid	prototype	liquid	1.38 mm	1 mm
22.4 mm pipe	TYPE-A	(80)	liquid	prototype	liquid + solid-Y + liquid	1.38 mm	1 mm

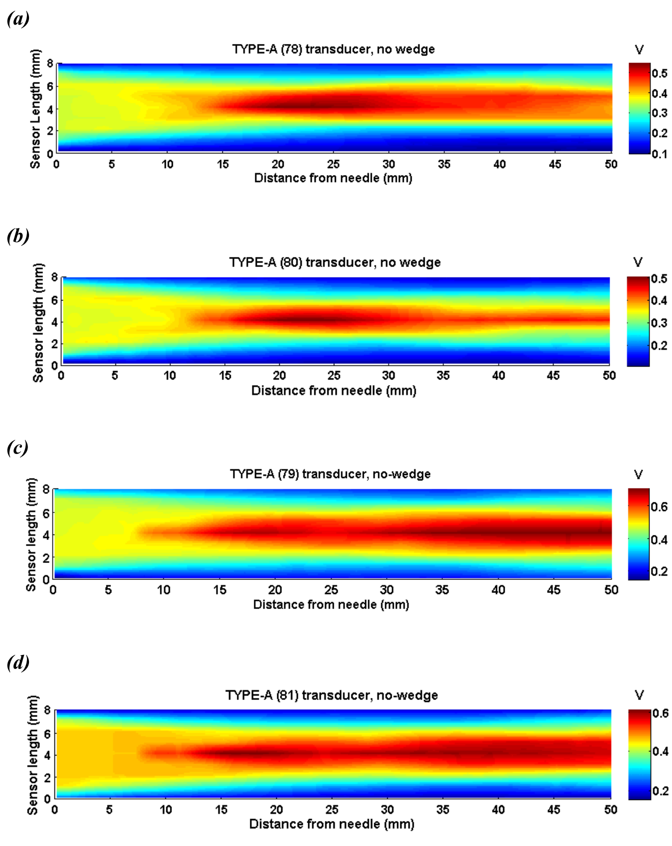

Fig. 7. Single transducer acoustic maps for the TYPE-A transducers (a) and (b) with the same wafer design; (c) and (d) have the same design.

couplant in the form of solid-X material (thickness (<1 mm), see Table III) was used. Solid-X couplant has a thickness which is approximately half that of solid-Y (thickness ~2 mm). The combined liquid and solid-Y couplants were then used for the wedge-to-pipe mounting. Fig. 9 shows the beam properties of the two different non-invasive sensor configurations. The significant increase in energy with transducer 79 in Fig. 9 is mainly attributed to the thin solid-X couplant between the transducer and wedge interface. By comparing the maximum voltages (V_{pk-pk}) obtained with the solid-X couplant with those from the setups in Fig. 8 and Fig. 10, in which the liquid couplant was used for the transducer-to-wedge coupling, it can be observed that the voltages are almost doubled. The maximum voltages within the focal zone for Fig. 9 (a) and (b) were 127 mV and 93 mV, respectively, whereas those from the test with liquid transducer-to-wedge couplant were in the range of ~(53-55) mV. Since the high energy output with solid-X was an exception when compared to the other solid couplants, it must be pointed out that the transducer (79) with the thin solid-X couplant had a different design compared to transducer 80 (as shown in Fig. 7), which could also be another contributing factor for the increased energy output.

Altogether, the thin solid-X couplant proved to be an effective transducer-to-wedge couplant since the resulting beams offer significantly higher energies in the focal zone across the whole pipe radius. This result also shows that alternating couplants between the wedge-to-pipe and transducer-to-wedge interfaces can significantly improve the resulting beam properties due to more effective acoustic coupling.

3) TYPE-A (80) – Prototype Wedge Sensor Configuration for 22.4 mm Pipe: Another 22.4 mm pipe sensor, with a TYPE-A (80) transducer was tested to determine whether a more optimal beam could be obtained using a liquid couplant at the transducer-to-wedge interface. The measured acoustic map for the TYPE-A (80) sensor for 22.4 mm pipes showed similar beam properties with sensor 79 in Fig. 9.

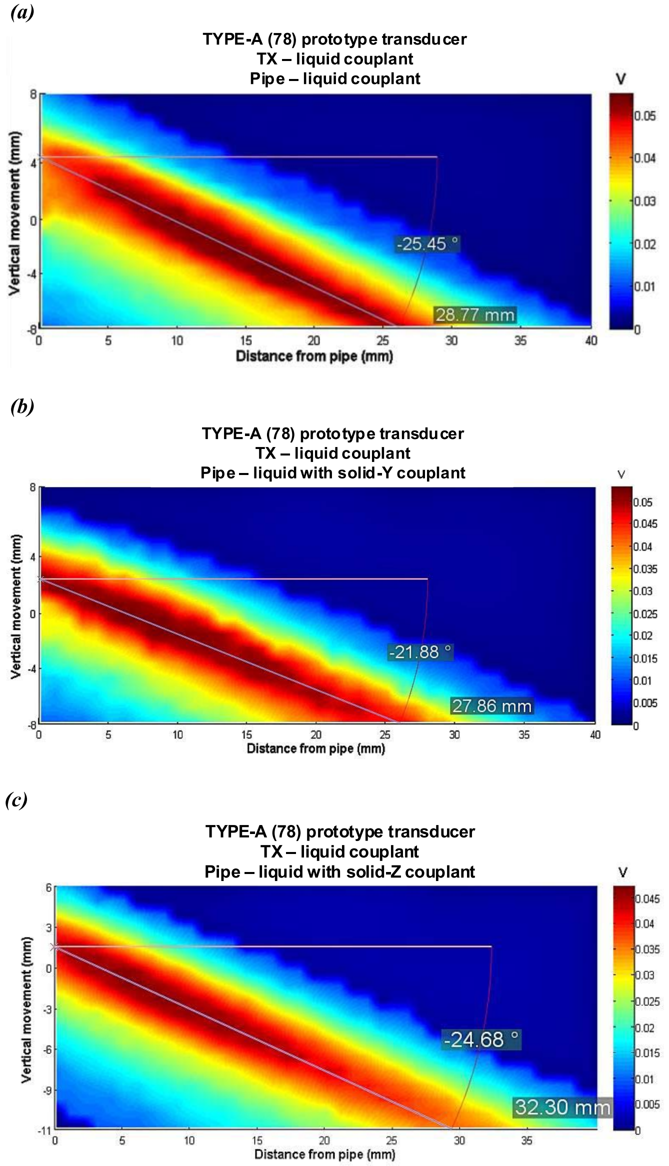

Fig. 8. Acoustic maps for 47.8 mm (78) sensor with liquid transducer-to-wedge (TX) couplant: (a) liquid couplant; (b) liquid and solid-Y couplant; and (c) liquid and solid-Z couplant at the wedge-to-pipe interface.

The similarity was that the wedge-to-pipe couplant with solid-Y moves the focal zone closer to the pipe wall and results in a smaller angle (24.75°) compared to the liquid couplant alone (27.16°). The acoustic maps are displayed in Fig. 10.

A notable difference in the peak energy measured in the focal zone for the two tests was that, with the liquid only couplant at the wedge-to-pipe interface the maximum voltage was 57.7 mV, whereas with the combined liquid and solid-Y couplant less energy (47.2 mV) was recorded. Another observation was that the beams from both setups are not entirely symmetrical (also Fig. 8). The lower half of both beams (bottom left corner of acoustic maps) looks wider than the top half in the top left corner. Although the hydrophone is considered omnidirectional, the observed asymmetry could be influenced by misalignment between the hydrophone and the beam's focal area. This can only be verified by conducting

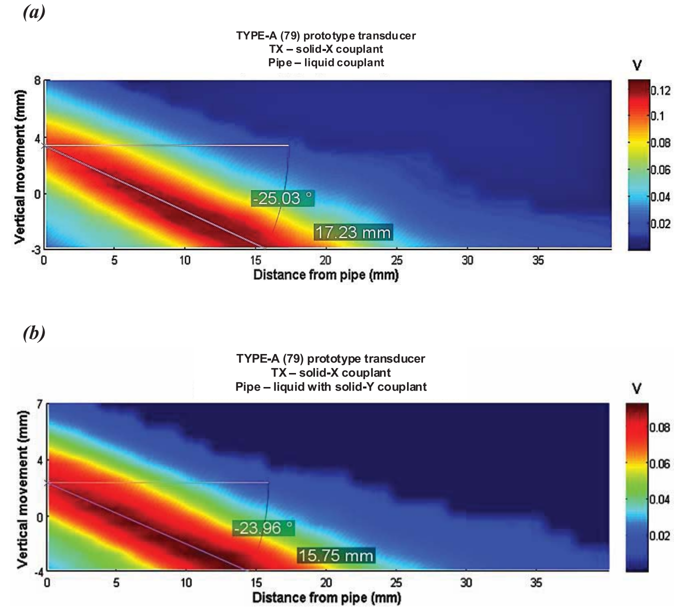

Fig. 9. Acoustic maps for 22.4 mm pipe (79) sensor with solid-X transducer-to-wedge (TX) couplant: (a) liquid couplant and (b) combined liquid and solid-Y couplant at the wedge-to-pipe interface.

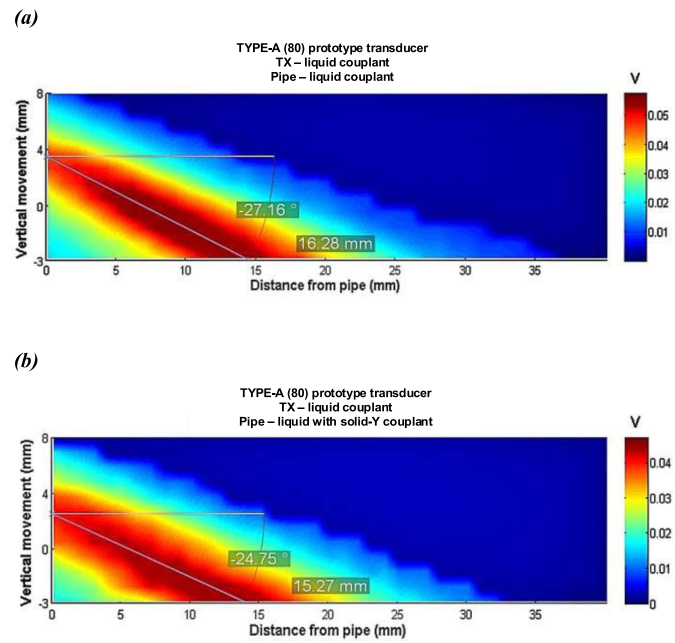

Fig. 10. Acoustic maps for 22.4 mm pipe (80) sensor with liquid transducer-to-wedge (TX) couplant: (a) liquid couplant and (b) combined liquid and solid-Y couplant at the wedge-to-pipe interface.

three-dimensional hydrophone measurements in order to determine the three-dimensional direction of the ultrasound beam propagation. The beams in both setups have a focal zone which spans the entire pipe radius which is of great importance in order to determine the flow properties from the velocity profile more accurately in highly attenuating fluids.

4) TYPE-A Sensors – Comparison of Flow-Viz Commercial and Prototype Configuration: Two non-invasive Flow-Viz commercial clamp-on sensors made for 47.8 mm pipes that feature an integrated transducer-to-wedge coupling were

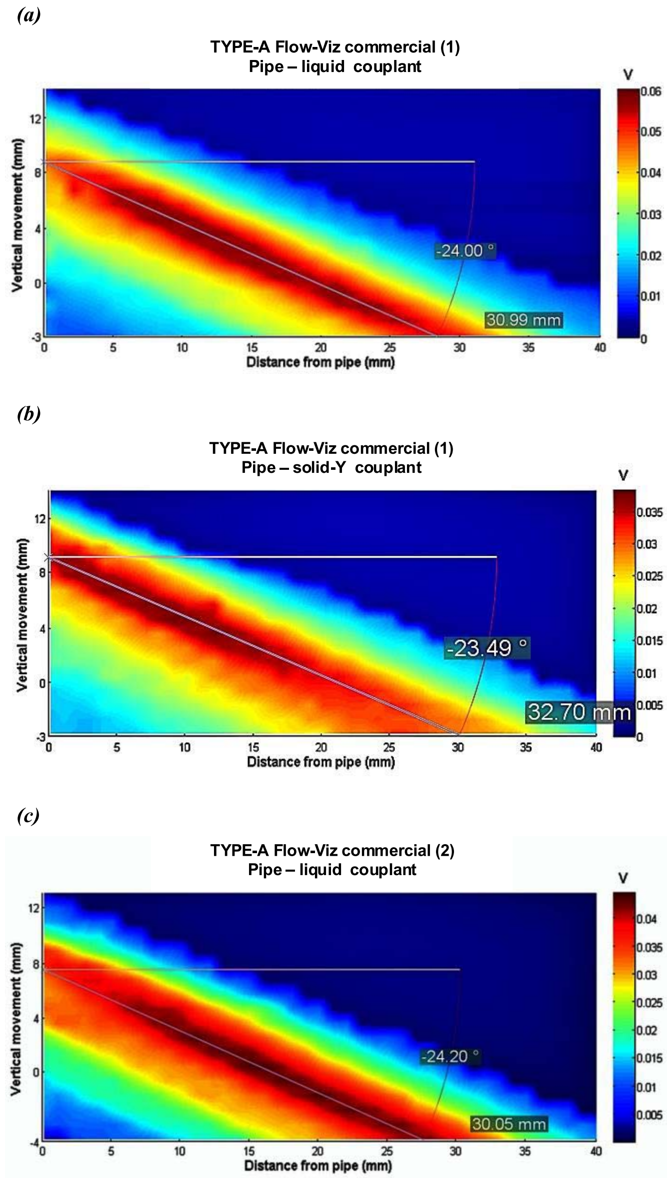

Fig. 11. 47.8 mm Flow-Viz commercial sensor 1 with: (a) liquid couplant; (b) solid-Y couplant at wedge-to-pipe interface; and (c) Flow-Viz commercial sensor 2 with liquid couplant at wedge-to-pipe interface.

tested. This design requires only coupling material between the sensor unit's wedge and stainless steel pipe. Two couplants were used i.e., the liquid couplant and solid-Y couplant. Fig. 11 depicts the measured acoustic maps obtained using the two different wedge-to-pipe coupling materials. In order to test the quality and consistency of the Flow-Viz manufacturing process, two identical non-invasive sensors were tested and compared as shown Fig. 11 (a) and (c).

The beams from the two setups are similar, with focal zone lengths which extend to cover a horizontal length of ∼27 mm which is more than the 47.8 mm pipe with inner centre at (23.9 mm). The difference in the measured peak energies between (a) and (c) can be attributed to slight differences in the test conditions, however by noting the similarities in the beam angles 24.00° and 24.20° as well as the focal zone lengths the overall measurement shows consistent designs.

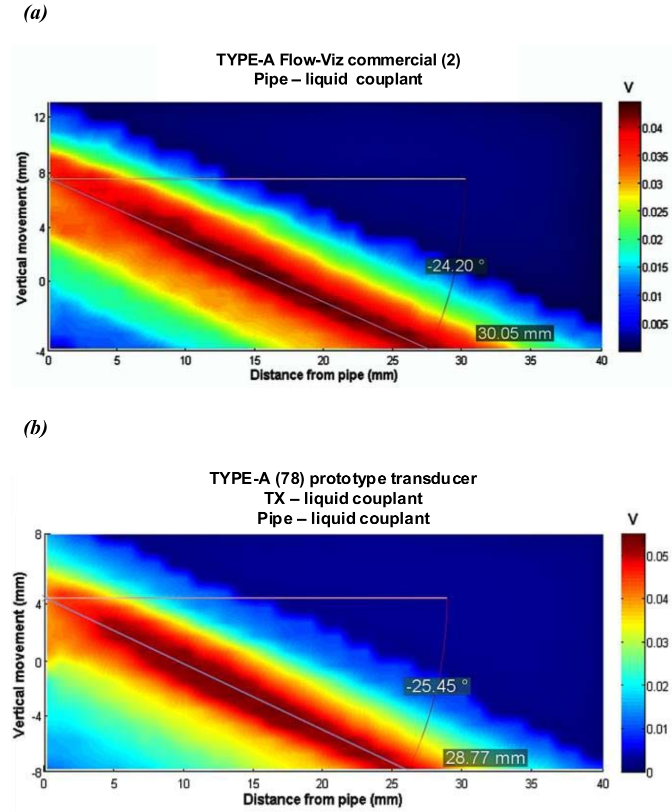

Fig. 12. A comparison of the 47.8 mm (a) Flow-Viz commercial and (b) prototype sensor configuration with liquid wedge-to-pipe couplants.

By considering the beam energy across the length of the focal zone it can be observed that the liquid couplant is a more effective couplant than the solid couplant with the new Flow-Viz sensor unit. The solid couplant seemed to have more attenuating effects on the beam propagation.

5) Comparison of Flow-Viz Commercial and Prototype TYPE-A Sensors: After conducting the tests for 22.4 mm and 47.8 mm sensor configurations, a comparison of the 47.8 mm prototype and the Flow-Viz was then carried out. The 47.8 mm sensor units were chosen for the comparison since 47.8 mm pipe-lines are more common in industrial setups compared to 22.4 mm ones. The other reason for this comparison was that, the 47.8 mm version of the commercial Flow-Viz is a recent design and by comparing it with a 47.8 mm prototype more knowledge on the properties of the resultant beam through stainless steel is gained and future sensor designs can be improved. Fig. 12 shows the results obtained for the two sensor technologies.

It can be seen that the beam properties from the two different sensor units have slight differences in the shape of the focal zone as well as the beam angle. The focal zone shape for the commercial sensor is narrower, but has the same width throughout the acoustic field; compared to that of the prototype wedge configuration which starts off wide and narrows (from ∼20 mm onwards) with distance. The narrower focal zone seen in the commercial sensor is more preferable as it increases lateral and spatial resolution.

The final comparison presented is important as it summarizes the outcome of the acoustic characterisation of

TABLE V
TEST MATRIX: SINGLE TRANSDUCER AND VERTICAL PIPE TESTS

NON-INVASIVE SENSOR BEAM PROPERTIES (STAINLESS STEEL PIPE)							
Sensor type	Installation position (interface)		~Start of focal Zone from pipe wall [mm]	~Peak energy [mV]	Length of focal zone extends to pipe centre	~Doppler angle [°]	†Rating
	TX-to-wedge	Wedge-to-pipe					
TYPE-A (79) 22.4 mm pipe	solid-X [2]	liquid [1]	3 [3]	127 [1]	YES [1]	65.0	8
	solid-X [2]	solid-Y + liquid [2]	0 [1]	93 [1]	YES [1]	66.0	7
TYPE-A (80) 22.4 mm pipe	liquid [1]	liquid [1]	3 [3]	57.7 [2]	YES [1]	65.0	8
	liquid [1]	solid-Y + liquid [2]	1 [2]	47.2 [3]	YES [1]	63.0	9
TYPE-A (78) 47.8 mm pipe	liquid [1]	liquid [1]	4 [4]	55.1 [2]	YES [1]	65.6	9
	liquid [1]	solid-Y + liquid [2]	0 [1]	53.3 [2]	YES [1]	68.1	7
	liquid [1]	solid-Z + liquid [4]	0 [1]	47.2 [4]	NO [4]	65.3	14
TYPE-A commercial 47.8 mm pipe (1)	liquid [1]	liquid [1]	5 [4]	60.3 [2]	YES [1]	66.0	9
TYPE-A commercial 47.8 mm pipe (1)	liquid [1]	solid-Y [3]	0 [1]	38.5 [4]	NO [4]	66.5	13
TYPE-A commercial 47.8 mm pipe (2)	liquid [1]	liquid [1]	5 [4]	44.6 [3]	YES [1]	65.8	10

† Rating — the superscript rating values show how well the sensor setup performed for each of the properties which were evaluated. The assigned rating value of each property (column) is as follows: [1] Excellent, [2] Good, [3] Average and [4] Poor. The sensor setup with the **LOWEST** overall score (**Rating**) shows the most suitable coupling configuration.

non-invasive sensor technology through stainless steel. The acoustic test results give a better understanding of the how important couplants are in non-invasive sensor technology. By changing between configurations with different solid couplants i.e., solid-X, solid-Y and solid-Z and combinations with liquid couplant it was seen that the shape, starting point and length of the focal zone can be significantly altered. From most of the tests it was seen that although a solid couplant attenuates the beam significantly more than the liquid couplant, it conveniently draws the focal zone starting point to the pipe wall to increase the near wall accuracy of measured profiles. However, an exception was observed where higher energy was measured with the setup in which a thin filmed solid-X couplant was used as the transducer-to-wedge couplant. On the other hand the liquid couplant at the pipe interface is less attenuating and results in a focal zone which extends over the entire pipe radius. Table V summarizes the measured beam properties from the acoustic characterisation tests. The results are a summary of the effect of the different couplants on the resultant beam properties. Each sensor coupling configuration is rated based on different properties which are: the measured beam focal zone properties (start of focal zone, length of focal zone and peak energy [mV]), the couplant's temperature tolerance and ease of installation (described in Table III). The rating of each sensor configuration was carried out by assigning the ratings of: [1] Excellent, [2] Good, [3] Average and [4] Poor, for each property (column) which was evaluated. For example, a rating of one ([1]) was assigned to the setups with solid-X couplant in the *peak energy* column, since it resulted in the most focal zone energy compared to other sensor setups. The ratings for the couplants (*installation position*) at the different interfaces were based on the couplant's temperature tolerance and ease of installation (Table III). The final rating score of each sensor setup was obtained by summing the singular scores obtained from the evaluation of each column attribute. Thus, the lowest overall score per row determined the most suitable sensor configuration.

IV. CONCLUSION

In this work, detailed acoustic characterisation maps of the Flow-Viz non-invasive ultrasound sensors were obtained. Ultrasound transducers and sensor assemblies optimised for 22.4 mm and 47.8 mm pipes were characterised. The tests revealed that correct selection of solid and liquid couplants is important in order to improve the overall transmitted beam properties. The overall analysis of the acoustic characterisation data as illustrated by the acoustic maps and described by Table V revealed that the solid couplants (solid-X, solid-Y and solid-Z) result in a larger Doppler angle and a focal zone which is directly at the pipe wall although the overall beam energy is reduced when compared to the liquid couplant. This observation implies that future sensor designs can be improved by incorporating some of solid-X and solid-Y material into the clamp on mounting surfaces in a way which produces a beam with a focal zone at the pipe wall. Table V shows that amongst the solid couplants, solid-Z results in a beam which fails to meet the required focal zone coverage i.e. extending to the pipe radius. This is not suitable especially for measurements carried out in highly attenuating media. The liquid couplant offers less attenuation when used as a wedge-to-pipe couplant, resulting in a beam which covers the pipe radius, although the focal zone does not start at the pipe wall (~5 mm away from the wall interface). The most energy was generated by having a thin solid-X couplant at the transducer-to-wedge interface with liquid couplant at the wedge-to-pipe boundary. The beam from this setup had a focal zone starting at the pipe wall, with almost twice the acoustic intensity compared to the other configurations. A different result with solid-Y was observed when it was used as a wedge-to-pipe couplant with TYPE-A commercial 47.8 mm pipe sensor-1 (Fig. 11 (b)). The beam's focal zone from this setup did not extend to cover the pipe radius as with other setups which made use of solid-Y. The most probable reason being improper bonding of the pipe and sensor surfaces in the absence of the additional liquid couplant which is normally combined with the solid couplants. Despite these differences, the liquid couplant was noted to be more versatile as an industrial couplant as it is very easy to install for industrial usage. Furthermore, the liquid couplant can be used in high temperature conditions compared to the solid couplants which have poor thermal properties. These tests showed how various couplants for non-invasive sensor coupling can significantly alter the propagated beam properties.

This acoustic characterisation data is critical for developing the next generation non-invasive sensor. The advantages of an integrated transducer-to-wedge setup and liquid couplant between the pipe and wedge will be considered in the next design criteria. The reason for this is that the integrated design offers a much easier installation procedure using less coupling materials. Furthermore, optimised thermal properties for the integrated sensor design to cater for the industrial requirements in higher temperature environments can also be introduced. The next generation of sensors will also have an optimised beam with a high energy focal zone which starts at the pipe wall and extends further over the pipe radius to improve measurements in attenuating fluids. With such an integrated sensor more accurate in-line rheological characterisation in a wide range of industrial fluids and applications, such as food products, oil drilling, paper-pulp and cosmetics can be achieved.

Future tests will include the effect of other important parameters such as pipe curvature (diameter) and wall thickness. It is also recommended to conduct more detailed 3-dimensional (3-D) tests, which result in complete 3-D acoustic maps. With detailed 3-D measurements more insight into the intensity distribution and shape of the actual ultrasound beam will be gained.

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REFERENCES

[1] Y. Takeda, "Velocity profile measurement by ultrasound Doppler shift method," *Int. J. Heat Fluid Flow*, vol. 7, no. 4, pp. 313–318, 1986.

[2] P. O. Brunn, J. Vorwerk, and R. Steger, "Optical and acoustic rheometers: Three examples," *Appl. Rheol.*, vol. 3, no. 1, p. 20, 1993.

[3] E. J. Windhab and B. Ouriev, "Rheological study of concentrated suspensions in pressure-driven shear flow using a novel in-line ultrasound Doppler method," *Exp. Fluids*, vol. 32, no. 2, pp. 204–211, Feb. 2002.

[4] B. Birkhofer, S. A. K. Jeelani, B. Ouriev, and E. J. Windhab, "In-line characterization and rheometry of concentrated suspensions using ultrasound," in *Proc. 4th ISUD*, Sapporo, Japan, 2004, pp. 65–68.

[5] J. Wiklund and M. Stading, "Application of in-line ultrasound Doppler-based UVP–PD rheometry method to concentrated model and industrial suspensions," *Flow Meas. Instrum.*, vol. 19, nos. 3–4, pp. 171–179, Jun. 2008.

[6] R. Kotze, J. Wiklund, and R. Haldenwang, "Optimization of the UVP PD rheometric method for flow behavior monitoring of industrial fluid suspensions," *Appl. Rheol.*, vol. 22, no. 4, pp. 42760-1–42760-11, 2012.

[7] J. Wiklund *et al.*, "Flow-Viz—A fully integrated and commercial in-line fluid characterization system for industrial applications," in *Proc. 9th ISUD Conf. (Ubertone)*, Strasbourg, France, 2014.

[8] R. Kotzé, S. Ricci, B. Birkhofer, and J. Wiklund, "Performance tests of a new non-invasive sensor unit and ultrasound electronics," *Flow Meas. Instrum.*, vol. 48, p. 104–111, Apr. 2016.

[9] R. Kotzé, J. Wiklund, and R. Haldenwang, "Optimisation of pulsed ultrasonic velocimetry system and transducer technology for industrial applications," *Ultrasonics*, vol. 53, no. 2, pp. 459–469, Feb. 2013.

[10] Y. Takeda, *Ultrasonic Doppler Velocity Profiler for Fluid Flow*, vol. 101. Tokyo, Japan: Springer, 2012.

[11] S. Ricci, M. Liard, B. Birkhofer, D. Lootens, A. BruÌˆhwiler, and P. Tortoli, "Embedded Doppler system for industrial in-line rheometry," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 59, no. 7, pp. 1395–1401, Jul. 2012.

[12] J. Wiklund and M. Stading, "Application of in-line ultrasound Doppler based UVP-PD method to concentrated model and industrial suspensions," in *Proc. 5th ISUD Conf.*, Zürich, Switzerland, 2006, pp. 145–149.

[13] R. Kotzé, R. Haldenwang, and P. Slatter, "Rheological characterisation of highly concentrated mineral suspensions using an ultrasonic velocity profiler," in *Proc. 6th Int. Symp. Ultrason. Doppler Methods Fluid Mech. Fluid Eng.*, Prague, Czech Republic, 2008, pp. 99–104.

[14] P. Theobald, B. Zeqiri, and J. Avison, "Couplants and their influence on AE sensor sensitivity," *J. Acoust. Emission*, vol. 26, pp. 91–97, Sep. 2008.

[15] B. Birkhofer, "Doppler ultrasound-based rheology," in *Practical Food Rheology: An Interpretive Approach*, I. T. Norton, F. Spyropoulos, and P. Cox, Eds. Chichester, U.K.: Wiley, 2011.

[16] J. Wiklund, I. Shahram, and M. Stading, "Methodology for in-line rheology by ultrasound Doppler velocity profiling and pressure difference techniques," *Chem. Eng. Sci.*, vol. 62, no. 16, pp. 4277–4293, Aug. 2007.

[17] Y. J. Choi, K. L. Mccarthy, and M. J. Mccarthy, "Tomographic techniques for measuring fluid flow properties," *J. Food Sci.*, vol. 67, no. 7, pp. 2717–2724, 2002.

[18] J. M. Szebeszczyk, "Application of clamp-on ultrasonic flowmeter for industrial flow measurements," *Flow Meas. Instrum.*, vol. 5, no. 2, pp. 127–131, 1994.

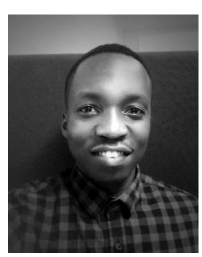
[19] M. L. Sanderson and H. Yeung, "Guidelines for the use of ultrasonic non-invasive metering techniques," *Flow Meas. Instrum.*, vol. 13, no. 4, pp. 125–142, 2002.

[20] J. Krautkrämer and H. Krautkrämer, *Ultrasonic Testing of Materials*, 4th ed. Heidelberg, Germany: Springer-Verlag, 1990.

[21] R. Kotzé, J. Wiklund, R. Haldenwang, and V. Fester, "Measurement and analysis of flow behaviour in complex geometries using the ultrasonic velocity profiling (UVP) technique," *Flow Meas. Instrum.*, vol. 22, no. 2, pp. 110–119, Apr. 2011.

[22] M. Yamamoto, J. Carrillo, A. Insunza, G. Mari, and Y. Ville, "Error introduced into velocity measurements by inappropriate Doppler angle assignment," *Ultrasound Obstetrics Gynecol.*, vol. 28, no. 6, pp. 853–854, 2006.

[23] S. Umchid, "Measurement of the field characteristics from high intensity focused ultrasound transducer," in *Proc. 7th Biomed. Eng. Int. Conf. (BMEiCON)*, 2014, pp. 1–5.



Tafadzwa John Shamu was born in Harare, Zimbabwe, in 1990. He received the bachelor's and master's degrees in electrical engineering from the Cape Peninsula University of Technology, South Africa, in 2013 and 2015, respectively. Since 2014, he has been with the Flow Process and Rheology Centre as a Research Assistant.

He is currently conducting his doctoral studies. His research interests include in-line rheology and flow visualisation, signal processing, and fluid dynamics. He is part of the Flow-Viz development team, aimed at advancing the newly developed Flow-Viz system for real-time monitoring of complex industrial fluid flow.

Reinhardt Kotzé was born in Cape Town, South Africa, in 1982. He received the B.Tech. and M.Tech. degrees in electrical engineering, and the D.Tech. degree in electrical engineering from the Cape Peninsula University of Technology (CPUT), South Africa, in 2005, 2008, and 2012, respectively. In 2011, he was appointed Senior Researcher with CPUT. He has authored over 15 peer-reviewed journal articles and five peer-reviewed conference papers. His research interests include developing novel algorithms and techniques for complex fluid behavior monitoring using ultrasound technology and electrical resistive tomography as well as technology transfer/commercialization. He is a member of the Scientific Committee of the International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering. He is a co-inventor of international patents and was shortlisted for the Africa Prize for Engineering Innovation 2014, organized by the Royal Academy of Engineering, London, U.K.—Top 14 innovations of Sub-Saharan Africa.

Johan Wiklund was born in Gothenburg, Sweden, in 1975. He received the B.S. and M.S. degrees in engineering from the Chalmers University of Technology, Gothenburg, in 1998 and 2002, respectively, and the Ph.D. degree from Lund University of Technology, Lund, in 2007. From 2007 to 2009, he held a post-doctoral position with the SP-Technical Research Institute of Sweden. Since 2009, he has been an Assistant Professor and a Manager for the Flow-Viz In-Line Fluids Characterization System Development Project with the SP Technical Research Institute of Sweden. He has authored two book chapters, and over 50 articles, and holds international patents.

His research interests include advanced R&D projects in ultrasound sensor development, Doppler ultrasound electronics, signal processing, fluid dynamics and rheology with the aim to overcome technology road-blocks, and value-adding to existing academic and industrial client projects and applications.

He is a member of the Scientific Committee of the International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering and an Editor of the European Society of Rheology.

Dr. Wiklund was a recipient of the Nordic Society of Rheology Young Scientist Rheology Award for Excellence in 2006 and the Fourth International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering Outstanding Paper Award in 2004.