A New Industrial Hybrid Ultrasonic Flow Meter for Oil Drilling Applications

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The measurement of the flow rate of drilling fluids is critically important for safe and effective drilling. Coriolis technology offers accuracy and reliability in measuring material flow and is often used in the oil and gas industry due to direct mass flow, fluid density, temperature, and precisely calculated volume flow rates. However, pressure loss could be a critical consideration in heavy oil applications, since frictional losses increase with increasing viscosity. There is therefore an incentive to minimize flow meter pressure drop and to reduce cost of installation and ownership. Ultrasonic flow meters are popular due to their clamp-on and non-invasive designs. They typically use the transit-time or continuous Doppler technique. However, both methods require a correction or profile factor (PF) to determine the correct flow rate. In an attempt to overcome the current limitations we combined the pulsed Doppler and transit-time techniques. The prototype hybrid flowmeter technology was installed and commissioned in a 2” stainless steel flow loop using water as commissioning fluid. It was then tested in a bentonite suspension (non-Newtonian) during laminar and turbulent flow and results were compared with a Coriolis mass flow meter as well as first principles (bucket and stop watch). Sensors were also deliberately misaligned to test the performance of the algorithms in low signal-to-noise environments. It was found that by including the complex flow profiles with the transit-time measurement the true flow rate could be determined with improved accuracy. Good agreement was found with the reference (BASW) flow rate across the entire range (0-300 l/min). New algorithms were developed to extract weak RF signals for accurate time-of-flight measurements. An important feature of the hybrid flow meter is that it can be used in open channel applications (free surface flows). The next step is to upscale the flow meter to 8” carbon steel pipe size and test in real drilling muds in partially filled pipes.

Keywords: Ultrasonic Doppler velocimetry, Transit-time ultrasonic flow meter, hybrid ultrasonic flow meter, in-line calibration

1. INTRODUCTION

The measurement of the flow rate of drilling fluids is critically important for safe and effective drilling. Accurately measuring the balance of the drilling fluids as a system (barrels-in versus barrels-out) provides important information to the driller and mud logger. It gives for example early warning kick detection and allows accurate monitoring of the mud transport velocity and lag times [1]. Drilling mud flow measurement can be a very challenging measurement for traditional flow meter technologies. Wide variations in the type of mud (water based, oil based, synthetic, emulsion), the solids content, the type of solids and other factors requires flow meters that can measure drilling fluids with wide ranges of fluid viscosity, density, conductivity and resistivity. Unfortunately, the performance of conventional flow meters when applied to complex viscous fluids remains relatively poorly known. Some technical challenges are immediately identifiable. These include the viscosity and non-Newtonian flow behavior of drilling fluids, varying velocity profiles due to changes in flow regime as well as secondary components in liquids such as settling solids or gas/air.

Different metering devices will be affected by these phenomena in different ways. Magnetic flowmeters are used to measure the flow of conductive liquids and slurries, including paper pulp slurries and black liquor. Their main limitation is that they cannot measure hydrocarbons very well, which are nonconductive. This makes them a bad fit for oil and gas drilling applications where drilling muds need to be monitored. Coriolis technology offers accuracy and reliability in measuring material flow and is often used in the oil and gas industry due to direct mass flow, fluid density, temperature, and precise calculated volume flow rates. However, pressure loss might be a critical consideration in heavy oil applications, since frictional losses increase with increasing viscosity. There is therefore an incentive to minimize flow meter pressure drop to avoid excess pumping power requirement and reduce cost of ownership. Coriolis flow meters are known to have a larger pressure drop than many other conventional flow meters due to the small diameter of the internal measurement tubes. Furthermore, due to the pipe diameter size the flow meter becomes excessively large and it becomes a challenge to install the flow meter and to calibrate due to installation issues. Ultrasonic flow meters have negligible pressure drop due to their non-invasive designs, have high turndown capability, and can handle a wide range of applications. Installation of ultrasonic meters is relatively straightforward, and maintenance requirements are low, which makes this an attractive solution for the oil and gas industry. They typically use the transit-time or continuous Doppler. However, both methods require a correction or profile factor (PF) to determine the correct flow rate. This factor strongly depends on the velocity profile in the pipe. Typically this value is determined by using theoretical

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simulations or experimental tests at a calibration facility. However, this is not sufficient as the velocity profile also depends on the pipe roughness, complex fluid properties that change with pressure and temperature. Therefore, in-line calibration of the PF is required to maintain the accuracy of the flow meter and to reduce maintenance / calibration costs. The development of multipath transit time flowmeters, which use more than one ultrasonic signal or "path" in calculating flowrate, has led to greater accuracy and is even used for custody transfer applications. However, these provide limited information on the flow profile as normally 4-6 paths are used. These flow meters also cannot be used in partially filled pipes and open channel applications found in drilling mud transportation.

To solve the current limitations in accurate flow metering we combined the pulsed Doppler and transit-time techniques. One of the performance areas of the industrial flow meter is robustness in a reduced signal-to-noise environment ratio due to large ultrasound attenuation and electromagnetic noise. This is because drilling muds contain water droplets, gas/air, wide particle size distribution and cause wax layer build-up (fouling) inside the pipe. The hybrid flowmeter technology was commissioned in tap water and then evaluated in a bentonite suspension that is typically used in drilling muds. Tests were conducted during laminar and turbulent flow and results were compared with Coriolis flow meter as well as first principles (bucket and stop watch) that served as the reference value.

2. METHODS AND APPARATUS

2.1 Hybrid ultrasonic flow meter

The Incipientus^{TM} system is a commercial and fully integrated platform for high resolution Doppler measurements as well as in-line rheometry. 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), are capable of producing bursts, typically at up to 80 Vpp with a frequency ranging between 0.7–7 MHz. The inputs are amplified with Time Gain Control (TGC) units featuring a gain up to 55 dB, converted to digital at 16-bit 100 MS/s, and processed in an FPGA. The FPGA include coherent demodulators, filters and a FFT processor for spectral analysis [3-4]. Non-invasive sensors that can measure velocity profiles in highly attenuating suspensions through stainless steel formed part of the hybrid flow meter setup [5].

2.2 Experimental flow loop

The DN51 MM, 2" flow loop consists of a storage tank, a frequency-controlled positive displacement pump and a closed stainless steel piping circulation system including PT100 temperature sensors (Pentronic, Gunnebo, Sweden), a coriolis mass flow meter (Krohne Optimass 6400 S50, ATEX) and two non-invasive ultrasound sensor units (Incipientus AB, Gothenburg, Sweden) for Doppler and transit-time measurements. Two differential in-line pressure sensors (Incipientus AB) were installed adjacent to the ultrasound sensors with a distance 0.65 m apart for in-line rheology measuremens. The rheology was measured to determine non-Newtonian Reynolds numbers [6] during the experiments with bentonite suspensions. The bentonite suspension was characterized with a yield stress of 5.4 Pa and consistency index of 50 mPa.s. The reason for choosing bentonite was to test in non-Newtonian yield stress fluids (plug-flow). Real drilling fluids have viscosities more than ten times higher, but with similar yield stress. Figure 1 shows a photo of the experimental flow loop at the Incipientus AB laboratory in Gothenburg, Sweden.

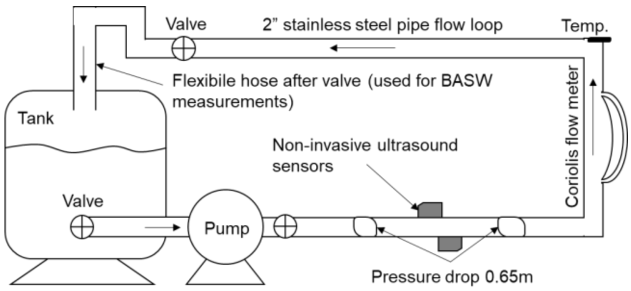

Figure 1: Schematic of experimental flow loop consisting of non-invasive ultrasound sensors (hybrid ultrasonic flow meter) and Coriolis mass flow meter.

2.3 Experimental procedures

Six flow rates (25, 50, 100, 150, 200, 250, 300 l/min) were tested. The flow rates were confirmed by using the gravitational "bucket and stop-watch" (BASW) method. These values were used as the reference and an error difference was calculated between the results obtained using the Coriolis and hybrid ultrasonic flow meter. For each flow rate an average of three BASW readings were used and any outliers were excluded from this (at high flow speeds up to five readings were done depending on outliers). Measurement time depended on the flow rate and ranged from 60 to 10 seconds. The density reading from the Coriolis mass flow meter was used to convert the BASW values to volume flow rate. An average of 64 Doppler profiles were taken in both directions of the pipe flow. For transit-time (flow metering) and speed of sound measurements 3000 pulses were used up- and downstream in total. The temperature during experiments varied between 19 and 21 ºC. The Coriolis flow meter output was logged using an DAQ (National Instruments) setup during the same time.

3. RESULTS AND DISCUSSION

3.1 Low SNR performance

Drilling fluids exhibit unique acoustic properties and one important parameter is the velocity of sound in the fluid medium. This parameter is also influence the accuracy of velocity profiles and transit-time measurements. Usable RF data and velocity of sound measurements can be used to determine density, homogeneity and to study aeration effects. Having access to this data in-line may provide the oil industry a powerful tool to investigate and monitor complex flow properties during processes/transportation.

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One objective was therefore to simulate an environment with where SNR is low. This was done by misaligning the ultrasound sensors opposite to one another and therefore only measuring a weak or low amplitude signal in the presence of electromagnetic noise. Figure 2 shows a graph of fifty RF signals received up- and downstream in the presence of noise. The measurements were done in the bentonite suspension at 100 l/min.

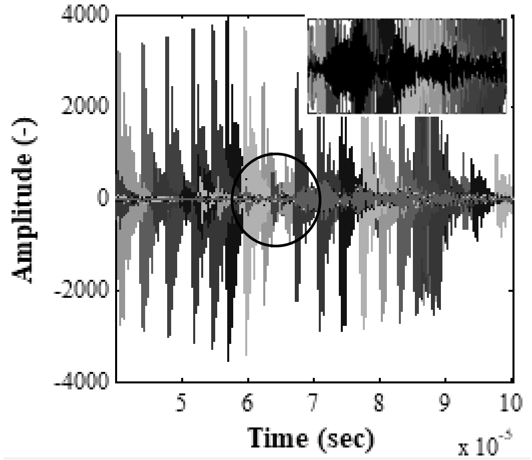

Figure 2: Fifty RF signals received (pitch-catch mode) in the presence of electromagnetic noise in bentonite. The waveform inside the circle (magnified) is extracted to for velocity of sound and transit-time measurements.

Note that in total 3000 pulses are sent in pitch-catch mode and thus with time the received waveform becomes completely embedded within noise. The noise amplitude level is more than 11 times higher than the signal amplitude level in this example. Figure 3 shows the up- and downstream time-of-flight values after signal processing. It can be observed that the upstream (Tup) time-of-flight (ToF) values fluctuate more than the downstream ToF values probably because the one sensor was not coupled correctly. Even so it was still possible to achieve accurate ToF measurements. Due to the flow velocity (volume flow rate 100 l/min) it can be clearly observed that there is a difference between the up- and downstream tof measurements. The average Tup = 71.335 us and Tdown = 71.3 us, which yields a time difference of 35 ns. Using cross-correlation the difference obtained was 27.4 ns. This means that the accuracy achieved is less than one sample (sampling time = 10 ns), bearing in mind that the sampling frequency of the electronics is 100 MHz. The fluctuations decrease with increasing flow rate as the time difference between up- and downstream increases (higher accuracy achieved). A new algorithm had to be developed that work together with the electronics digitizing output to extract the weak or attenuated RF signals. Based on the results it can be concluded that the hybrid flow meter can successfully extract the important data needed for speed of sound and transit-time calculations. The next step will be to evaluate the hybrid flow meter in real drilling fluids (oil- and water based) and on oil-drilling platforms.

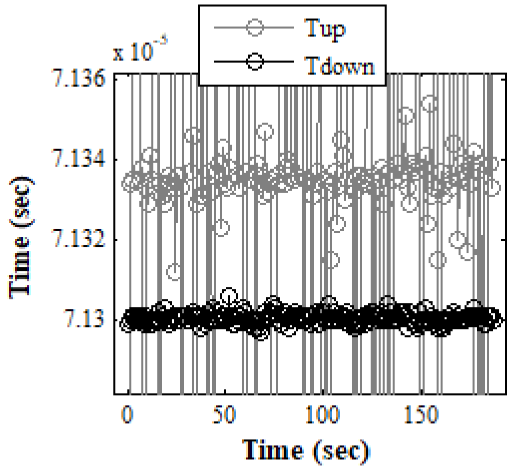

Figure 3: Time-of-flight measurements for up- and downstream measurements in bentonite suspension (flow rate 100 l/min).

3.2 Flow meter performance in water

Figure 4 shows the error percentage difference for both flow metering methods (compared to BASW reference). Note that the hybrid flow meter has a good agreement to the Coriolis flow meter over the entire range. At the lowest flow rate the hybrid flow meter retained its accuracy. The average percentage deviation for the hybrid flow meter was 2.4% over the entire flow rate range. The Coriolis average error was 4.3%.

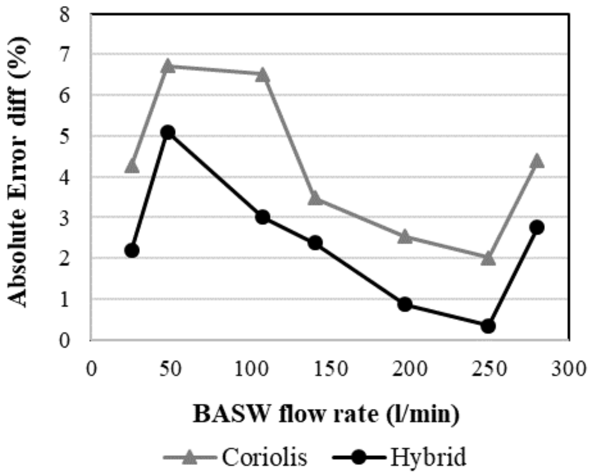

Figure 4: Comparison of Coriolis and hybrid ultrasonic flow metering methods with reference measurements (BASW) in water.

3.2 Flow meter performance in bentonite suspension

During the bentonite experiments the flow regime varied from laminar (25 – 150 l/min) to turbulent (200 – 300 l/min) flow. Figure 5 shows two Doppler profiles (spectra) measured in bentonite during laminar (25 l/min) and turbulent flow (300 l/min). Non-Newtonian Reynolds numbers varied from 322 to 6400. The hybrid flow meter adjusted the PF to compensate for the change in velocity profile. Good agreement to the Coriolis flow meter (and reference value) over the entire range was found, see

Figure 6. It is interesting that the error percentage deviation for the Coriolis flow meter decreased in the bentonite suspension, probably due to the increase in viscosity.

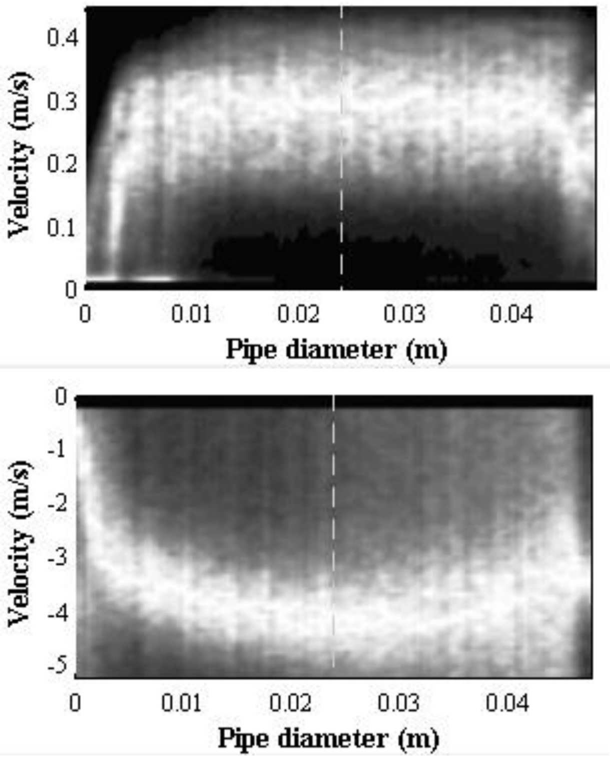

Figure 5: Laminar Doppler profile (top) and turbulent Doppler profile (bottom) measured in bentonite suspension.

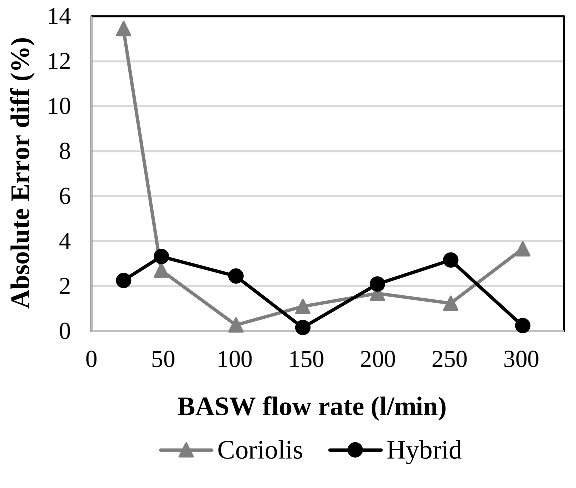

Figure 6: Comparison of Coriolis and hybrid ultrasonic flow metering methods with reference measurements (BASW) in bentonite suspension.

At the lowest flow rate (25 l/min) the hybrid flow meter retained its accuracy. The average percentage error for the hybrid flow meter was 1.9% over the entire flow rate range. The Coriolis flow meter had a higher total error difference of 3.4%, which was mainly due to the larger error at the lowest flow rate. When excluding that value the error difference reduced to 1.8%, similar to what was obtained with the hybrid ultrasonic flow meter.

4. SUMMARY AND CONCLUSION

The key benefits of ultrasonic technology, low pressure and low maintenance are highly attractive for the oil industry. Transit-flow meters are best operated at the higher flow ranges for optimum accuracy. However, with the combined Doppler technique accurate measurement at the lower flow ranges can also be achieved. No pressure loss results in reduced operating costs. No moving parts results in increased service life and may reduce the frequency of proving since usage wear is a key reason why meters must be recalibrated. One disadvantage is the need for upstream piping, however, less than 0.5% accuracy can be achieved by adding more sensors (up to three), even for asymmetrical flow [2].

There are still other challenges remaining before a commercial system for oil-drilling applications can be deployed. This mainly revolves around the automation of ultrasound parameter settings to maintain accuracy and robustness as critical measurement parameters are today still operator dependent. This includes automatic PRF control, de-aliasing profiles and automatic gain control. This is already under development [7-8]. One limitation that can be easily overcome is the electronics sampling rate. By increasing the sampling rate higher time resolution can be achieved as well as higher accuracy at lower flow rates. The next steps are to upscale to 8” carbon steel pipes and test real drilling fluids. An important feature of the hybrid flow meter is that it can be used in open channel applications (free surface flows). In the next phase flow rates will also be measured in partially filled pipes (8”) using real field oil-based drilling muds.

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