Pulsed-Array Sonar-based Flow Measurement Technology for Clamp-on Wet Gas Metering

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1 ABSTRACT

Accurate, reliable clamp-on measurement of wet gas flow has been a long-standing challenge for the upstream oil and gas industry. Since its commercial introduction in 2000, strain-based sonar flow meter technology has been developed and demonstrated to provide clamp-on measurement of volumetric flow rate for Type I and Type II wet gas mixtures in laboratory and field testing. A primary benefit of the clamp-on, strain-based meter has been its ability to measure primary gas flow rates with little sensitivity to liquid loading over a wide range of wet gas mixtures. However, the application of strain-based sonar meters to wet gas production has been limited to relatively high rate gas wells in which the flow rates met the minimum flow requirements of the current generation sonar meters.

This paper describes a new clamp-on sonar-based flow measurement technology, termed pulsedarray sonar, primarily targeted for wet gas applications. This new approach to sonar flow measurement leverages pulsed-array technology to actively track naturally-occurring disturbances within wet gas flows and is designed to extend the low flow operating range of clamp-on sonar flow meters significantly beyond that currently addressed by clamp-on, strain-based sonar measurement technology.

Multiphase flow loop data is presented demonstrating that the pulsed-array sonar technology can provide accurate clamp-on measurement of dry and wet gas flow rates over a broad range of Type I and Type II wet gas flow conditions.

2 SCOPE

The scope of this paper is limited to an introduction to the capabilities of clamp-on, pulsed-array sonar flow measurement technology for use on Type I and Type II wet gas flows. The paper does not attempt to provide a detailed description of the methodology, but rather to provide a general overview of pulsed-array sonar technology and present flow loop data suggesting that the technology has the potential to provide clamp-on surveillance for a wide range of wet gas wells.

3 HISTORY OF SONAR-BASED FLOW MEASUREMENT

Sonar-based flow measurement technology was first introduced to the oil and gas industry with the deployment of the first down-hole, fiber-optic-strain, multiphase flow meter from the Shell Mars Platform in October, 2000 [1]. The fiber-optic-strain sonar meter used sonar-based passivelistening techniques to provide flow rate and compositional information for downhole oil, water, and gas mixtures and served as a technology demonstrator for a product line of downhole, fiber optic flow meters commercially available today.

In 2004, a clamp-on version of a strain-based sonar meter was introduced in which the fiber-opticstrain sensors were replaced with piezo-strain sensors [3]. The use of clamp-on, piezo-strain sensors provided similar functionality as the original spool-piece, fiber-optic-strain sonar technology with the benefit of significantly reduced cost and complexity. The clamp-on, piezostrain sonar flow meters have been applied to a wide range of single and multiphase mixtures, ranging from gaseous hydrogen, gas / liquid mixtures and high solids content slurries. The addition of the piezo-strain sonar meter to the fiber-optic-strain sonar meter helped establish sonar flow measurement as a new class of industrial flow measurement technology, with sonar-based flow meters currently being used in a wide range of industries [3].

4 SONAR-BASED FLOW MEASUREMENT METHODOLOGY

Sonar-based flow measurements utilize an array of sensors, aligned axially along the pipe, to characterize the speed at which naturally occurring, coherent flow structures convect past the sensor array using sonar processing techniques. Since both single and multiphase flows typically exhibit these coherent structures, the methodology is suitable for a wide range of applications.

Figure 1 illustrates the naturally occurring, self-generated, coherent structures present within turbulent process flow of Newtonian fluids. As shown, the time-averaged axial velocity for a turbulent pipe flow velocity profile is a function of radial position, from zero at the wall to a maximum at the center line of the pipe. The flow near the wall is characterized by steep velocity gradients and transitions to relatively uniform core flow near the center of the pipe. Naturally occurring, self-generating, turbulent eddies are superimposed over the time-averaged velocity profiles. These coherent structures contain fluctuations with magnitudes on the order of 10 percent of the mean flow velocity and are carried along with the mean flow. These eddies generated within turbulent boundary layers remain coherent for several pipe diameters and convect at, or near, the volumetrically-averaged flow rate in the pipe [4]. Although this description of naturally-occurring coherent structures is based on empirical and theoretical understanding of turbulent Newtonian fluids, additional mechanisms serve to generate similar naturally occurring, coherent structures in more general, non-Newtonian multiphase flows that also convect at or near the volumetrically averaged flow velocity [5].



Figure 1: Sonar-based Flow Meters with Coherent Structures within Pipe Flows

Sonar-based flow meters use the convection velocity of coherent structures (eddies) within pipe flows to determine volumetric flow rate. The sonar-based algorithms determine the speed of these structures by characterizing both the temporal and spatial frequency characteristics of the flow field. For a series of coherent eddies convecting past a fixed array of sensors, the temporal and spatial frequency content of pressure fluctuations are related through a dispersion relationship, expressed as follows:

$$V_{convect} = \omega / k \tag{1}$$

Where, k is the wave number, defined as $k=2\pi/\lambda$ in units of 1/length, ω is the temporal frequency in rad/sec, and V_{convect} is the convection velocity or phase speed of the disturbance, and λ is the spatial wavelength.

In sonar array processing, the spatial / temporal frequency content of sound fields are often displayed using "k- ω "plots. k- ω plots are three-dimensional power spectra in which the power of a sound field is decomposed into bins corresponding to specific spatial wave numbers and temporal frequencies. The power level is represented by a color map shown to the right of the k- ω plot. On a k- ω plot, the power associated with coherent structures convecting along with the flow is distributed along "the convective ridge" [6]. The slope of this ridge indicates the speed of the turbulent eddies. Thus, identifying the slope of the convective ridge provides a means to determine the convection speed of the coherent disturbances within the flow; and with calibration, a means to determine volumetric flow rate.



Figure 2: K- ω plot from a Clamp-on, piezo-strain sonar meter operating on a 4 inch, schedule 80 pipe with 7 mmscfd Methane at nominally 300 psia

Figure 2 shows an example of a k- ω plot generated from the diagnostic output of a piezo-strain sonar flow meter clamped on to a 4 inch, schedule 80 pipe operating with ~7 mmscfd of methane gas flowing at 300 psia. As shown, the k- ω plot exhibits a well-defined convective ridge. The slope of the convective ridge was determined to be 54.4 ft/sec using a parametric optimization procedure, the results of which are shown in the insert of Figure 2.

5 LIMITATIONS OF STRAIN-BASED SONAR METERS ON WET AND DRY GAS

The ability of sonar-based meters to provide accurate, clamp-on flow rate measurement of multiphase mixtures prompted the evaluation of sonar meter for clamp-on wet gas mixtures. During the last several years, the clamp-on, strain-based sonar has been shown to be capable of providing accurate, reliable gas flow rate measurement for wet and dry gas applications [7].

Application of strain-based sonar meter on wet gas applications has been, however, limited to high rate applications due in large part to the relatively high flow rates required for accurate and reliable rate determination. Strain-based clamp-on meters rely on flow-driven disturbance to strain the wall of the pipe. The amplitude of the flow driven pressure disturbances and, therefore, the signal to noise ratio of the strain-based sonar meters, typically scale with the dynamic head of flow. The dynamic head of a flow, q, is defined as:

$$q \equiv \frac{1}{2}\rho v^2 \tag{2}$$

Where ρ is the density and v is the volumetrically averaged flow velocity. Typically, clamp-on, piezo-strain sonar meters require flows to have a dynamic head > 500 pascals (Pa). For a 300 psia methane application, this criterion results in a minimum flow rate of ~30 ft/sec, or ~4 mmscfd in a 4 inch line. The dynamic head of the gas flow for the k-w plot shown in Figure 2 was ~2000 Pa, well above the minimum recommended dynamic head of 500 Pa.

6 PULSED-ARRAY SONAR FLOW MEASURMENT TECHONOLOGY

As described above, sonar-based flow metering technology relies on an array of sensors to observe naturally occurring flow disturbances at multiple axial locations to provide input into array processing algorithms to determine flow rate. Thus, provided that the naturally occurring coherent structures exist within a given pipe flow, the ability of a sonar flow meter to determine the flow rate is inherently linked to the ability of the sensors within the array to observe these coherent structures above background noise levels. For strain based sonar flow meters, empirical data has shown that, for a broad range of applications, the dynamic head of the flow should be > ~ 500 Pa for the strain sensors to measure the flow-generated coherent pressures with sufficient signal-to-noise and to provide an accurate and reliable flow measurement. As discussed above, this imposes a fairly restrictive minimum flow rate requirement for gas well applications.

Pulsed-array sonar technology, introduced herein, observes the naturally-occurring coherent structures within the flow by monitoring interactions of externally-generated acoustic pulses with those coherent structures. As with other sonar-based meters, the coherent structures are observed at multiple locations and used as input to sonar processing algorithms to determine the flow rate. Using externally generated acoustic pulses to essentially illuminate the coherent structures enables the pulsed-array sonar technology to measure to significantly lower rates than current generation strain-based sonar methods. In this manner, the relationship of pulsed-array sonar flow technology to strain-based sonar flow technology is analogous to the relationship between active sonar and passive sonar in underwater acoustic technology [8].

Figure 3 shows a k- ω plot generated from a pulsed-array sonar meter operating at the same nominal conditions as those for a piezo-strain sonar meter in Figure 2, i.e. a 4 inch, schedule 80 pipe with 7 mmscfd Methane at nominally 300 psia.

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Figure 3: K- ω plot from a Clamp-on, Pulsed-Array Sonar meter operating on a 4 inch, schedule 80 pipe with 7 mmscfd Methane at nominally 300 psia, 1800 Pa dynamic head

Comparison of the k- ω plot for the piezo-strain sonar and the pulse-array sonar meter indicate that for these relatively high rate conditions (dynamic head = 1800 Pa), the two types of sonar meters exhibit similar characteristics.



Figure 4: K- ω plot from a Clamp-on, Pulsed-Array Sonar meter operating on a 4 inch, schedule 80 pipe with 1.5 mmscfd Methane at nominally 300 psia, 85 Pa dynamic head

The advantage of the enhanced signal to noise properties of the pulse-array technology is indicated in Figure 4. Figure 4 shows a k- ω plot from a pulse-array sonar meter operating at dynamic head of 85 Pa, significantly below the minimum dynamic head of 500 Pa required for a piezo-strain sonar meter. As shown, the k- ω plot for the lower flow is similar in quality to that for the higher flow rate shown in Figure 4, with no indication of deterioration due to the reduced dynamic head at the lower flow rate.

7 FLOW LOOP TESTING

Experiments were conducted on the 4 inch multiphase flow loop at the Colorado Engineering Experimental Station, Inc.(CEESI) facility in Nunn, Colorado to evaluate the performance of pulsed-array sonar technology on wet gas flows. Figure 5 shows a production prototype pulsed-array sonar meter clamped on to a 4 inch schedule 80 pipe at the facility.

The flow facility generated fully-developed wet gas flows of known input liquid rate and input gas rate using Stoddard Oil (decane) and Natural Gas as the working fluids. The performance of the pulsed-array sonar technology was characterized over a range of pressures (300 psia and 800 psia), flow velocities (<3 ft/sec to >60 ft/sec) and liquid loadings representative of type I and type II wet gas flows.



Figure 5: Photograph of Clamp-on, Pulsed-Array Sonar meter installed at Wet Gas Flow Facility

7.1 DRY GAS RESULTS

Figure 6 shows dry gas calibration data for a clamp-on, pulsed-array sonar meter installed on a 4 inch schedule 80 pipe versus facility reference (a single phase, wetted ultrasonic flow meter). The dynamic head of the flow ranged from a low of <10 Pa at 3 ft/sec at 300 psia to a high of >6000 Pa at 60 ft/sec at 800 psia. For test points with the calibrated range of the facility (>10 ft/sec), the pulsed-array sonar meter was within ~1% of reading. Diagnostic plots for the pulsed-

array sonar meter are shown at the high and low flow rates evaluated, indicating that meter performance is similar throughout the range of flow rates evaluated.



Figure 6: Pulsed-Array SONAR Dry Gas Calibration over a range of 2 ft/sec to 60 ft/sec for Methane at 300 and 800 Psia corresponding to dynamic heads of 5 Pa to 6000 Pa.

7.2 WET GAS RESULTS

The oil and gas industry defines liquid loading of wet gas flows in a variety of ways. The Lockhardt-Martinelli (X_{LM}) number, defined below, is a well-accepted measure of the liquid loading of a wet gas mixture within the technical community [9]. The liquid-to-gas-mass-flow-ratio (LGMR) of a wet gas mixture is also widely used within the technical community and is related to the Lockhardt-Martinelli through the gas to liquid density ratio also as defined below:

$$X_{LM} \equiv \sqrt{\frac{\rho_l V_{s_l}^2}{\rho_g V_{s_g}^2}} = \sqrt{\frac{\rho_g}{\rho_l}} \frac{\dot{m}_{liq}}{\dot{m}_{gas}} = \sqrt{\frac{\rho_g}{\rho_l}} LGMR$$
(3)

Type I wet gas flow is typically defined as wet gas flow with Lockhardt-Martinelli numbers X_{LM} <0.01, and type II wet gas flows have X_{LM} >0.01, but X_{LM} <0.3.

The operating community with oil and gas tend to use gas-to-liquid volume ratios at standard conditions to describe wet gas flows, such as standard cubic feet of gas per barrel of liquid (scf/bbl) or barrels of liquid per million standard cubic feet of gas (bbl/mmscf). Using the approximate relationship that mass 6000 standard cubic feet of gas is equivalent to 1 barrel of liquid hydrocarbon, one can readily translate between LGMR and SCFB:

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$$Wetness[SCF / B] \approx \frac{6000}{Wetness[LGMR]}$$
(4)

The Froude number, defined below, is another important parameter used to characterize wet gas flows and serves as an indication of the propensity of the wet gas mixture to stratify in horizontal flows. Flows with low Froude numbers, Fr<~1, tend to stratify and flows with high Froude numbers, Fr>~2, tend toward well-mixed flows. The Froude numbers investigated ranged from 0.5 to 5.

$$Fr = \sqrt{\frac{\rho_{gas} V_{mix}^2}{(\rho_{liq} - \rho_{gas})gD}}$$
(5)

The pulsed-array sonar meter also exhibited good performance over Type I and Type II wet gas flows. Figure 7 shows the over-reading of the pulse-array sonar meter as a function of liquid-to-gas-mass-ratio for a representative Froude number of Fr=~1.0. The over-reading is defined in this paper as the velocity (or equivalently, volumetric flow rate) reported by the meter operating on a wet gas mixture normalized by the superficial velocity of the gas phase of the wet gas mixture. The over reading of the pulsed-array sonar meter is shown to scale directly with the wetness of the wet gas mixture. K- ω plots of the diagnostic data from the pulse-array sonar meter are shown for several wetness levels, indicating that pulsed-array sonar meter maintained functionality over the relatively large range of liquid loading. Using the approximation given above, the data point shown in Figure 7 with the highest liquid loading, LGMR = 1.8 corresponds to a gas to liquid volume ratio of ~3,300 scf/b, or ~300 bbl/mmscfd.



Overreading Due to Wetness of Pulsed-Array Sonar

Figure 7: Over-Reading due to Wetness of Pulsed-Array Sonar Meter operating on Wet Gas at 24 ft/sec at 300 psia in Methane Gas Clamped-on a 4 inch, schedule 80 pipe corresponding to a dynamic head of ~300 Pa and Froude Number of Fr=1.0

Although characterizing the over reading due to wetness of the pulsed-array meter for a complete range of wet gas flow parameters is beyond the scope of this paper, broadly similar results were obtained for type II wet gases for Froude numbers ranging from 0.5 to 5.0.

8 CONCLUSIONS

Pulsed-array sonar-based flow meters represent a new type of sonar-based flow meter. Pulsedarray sonar flow metering technology uses the interaction of externally generated acoustic pulses with naturally occurring coherent structures to provide significantly enhanced signal-to-noise capabilities compared to strain-based sonar meters over a broad class of single and multiphase flows.

Flow loop data is presented which suggests that pulsed-array sonar meters can provide accurate clamp-on volumetric flow rate measurement of Type I and Type II wet gas flows over a large range of gas flow velocities. The laboratory data was recorded using natural gas and decane at realistic pressures and is viewed to be representative of field conditions, however, field trials of pulsed-array sonar meters are ongoing in efforts to validate that the laboratory results presented herein translate to actual field conditions.

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10 NOTATION

V	Velocity	q	dynamic head
k	Wave number	ρ	density
λ	Wave Length	X _{LM}	Lockhardt-Martinelli No.
ω	frequency (rad/sec)	Fr	Densimetric Froude No.
g	acceleration due to Gravity	ṁ	mass flow rate

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