SONAR-BASED, CLAMP-ON FLOW METER FOR GAS AND LIQUID APPLICATIONS

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Abstract

A sonar-based flow measurement technology, capable of clamp-on flow measurement of single and multiphase flow applications within the chemical and petrochemical industries, is described. Developed and field proven in oil and gas production industry over the last five years, sonar-based flow measurement technology provides robust accurate volumetric flow rate measurement for a broad range of process fluids, slurries, pipes sizes and flow conditions.

The sonar-based flow metering technology utilizes an array of sensors to listen to, and interpret, unsteady pressure fields within standard process flow lines. The methodology is implemented using strain-based sensors which clamp-on to existing process piping. This paper presents data for sonar-based flow meters utilizing two independent, yet complimentary, techniques to determine volumetric flow rate. The first technique measures the speed at which turbulent eddies, inherent to turbulent pipe flow, convect past the sensor array and is well-suited for liquid-continuous single and multiphase flows. The second technique, well-suited for gas-continuous single and multiphase applications, measures the flow rate by comparing the speed at which ambient acoustic waves propagate with the flow to that speed which acoustic waves propagate against the flow. Both the convective and acoustic techniques are based on listening to, and interpreting, naturally occurring pressure fields within process flows lines using sonar-based algorithms and each can be implemented with common sensor arrays.

Introduction

Volumetric flow rate of process fluids is a critical parameter in process control and optimization within the chemical and petrochemical industries. Reflecting this, the chemical and petrochemical industry is the single largest user of industrial flow meters, spending upwards of $1 billion dollars annually on process flow meters. This paper describes a new class of flow meters that offers advantages over conventional flow measurement technologies for applications important to the chemical and petrochemical industry.

Industrial flow meters are often classified into two technology-based categories: old technology and new technology flow meters. The old technology category refers to flow measurement technologies that have been in use for greater than 70 years, and includes turbine meters, orifice plates and variable area flow meters. The new technology category includes technologies which have emerged over the last 30~50 years. The major types of new technology flow meters include coriolis, electromagnetic, ultrasonic and vortex flow meters. Typically, new technology flow meters offer advantages over the old technology flow meters in performance, functionality, and reliability. Each type has evolved to serve various aspects of the diverse range of applications within the industrial flow meter landscape. Despite the diverse array of measurement technologies currently available, the chemical and petrochemical processing industries continue to have unmet needs for accurate, reliable, and economical monitoring of many single and multiphase flow applications, including, for example, large diameter pipes and liquid-conveyed solid particle slurries.

Sonar-based flow measurement technology was first introduced into the oil and gas industry in 1998 for use in downhole multiphase flow metering applications (Kragas, 2002), and is currently being adapted for use in other industries including the chemical and petrochemical industries. Sonar-based flow measurement utilizes an array of sensors, aligned axially along the pipe, to characterize and interpret naturally-occurring, unsteady pressure fields within process piping. Although applicable to single phase flows as well, sonar-based flow measurement techniques were specifically developed for multiphase flows. This paper describes two approaches to determine volumetric flow rate utilizing sonar-based techniques.

The first approach, termed convective, involves characterizing the speed at which coherent vortical structures flow past an array of sensors, pressure or strain-based sensors, mounted axially along the pipe. Since the coherent structures within the process fluid are inherent features of turbulent boundary layer, no internal geometry is required to generate these structures. The convective approach is well suited for liquid and liquid-continuous single and multiphase applications.

The second technique, termed acoustic, utilizes an acoustic technique whereby it measures the flow rate by comparing the speed at which ambient sound waves propagate with the flow to those propagating against the flow. Unlike the convective techniques, the acoustic technique relies on the difference in propagation velocity with and against the flow and well-suited flow applications in which the average volumetric flow velocity is an appreciable fraction of the acoustic velocity for the fluid at rest. Thus, the approach is well suited for gas and steam applications with flow velocities on the order of 10% of the speed of sound of the fluid.

Each measurement technique is distinct from other existing flow measurement technologies, and has attributes that differentiate it from existing flow measurement technologies. From an array signal processing perspective, both of the sonar-based flow measurement techniques described herein utilized techniques analogous to beam-forming applications developed over several decades for underwater sonar-based navigation (Nielsen, 1991). With its ability to clamp-on to existing process lines eliminating any process-wetted hardware, clamp-on sonar-based flow measurement is particularly well-suited for many corrosive and abrasive process flows commonly encountered in the chemical and petrochemical industries.

Sonar-based Convective Flow Measurement

A schematic of the relevant structures within a turbulent process flow is shown in Figure 1. As shown, the time-averaged axial velocity is a function of radial position, from zero at the wall to a maximum at the centerline 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. The turbulent eddies are superimposed over a time averaged velocity profiles. These coherent structures contain fluctuations with magnitudes typically less than 10% percent of the mean flow velocity and are carried along with the mean flow. Experimental investigations have established that eddies generated within turbulent boundary layers remain coherent for several pipe diameters and convect at roughly 80% of maximum flow velocity (Schlichting, 1979).

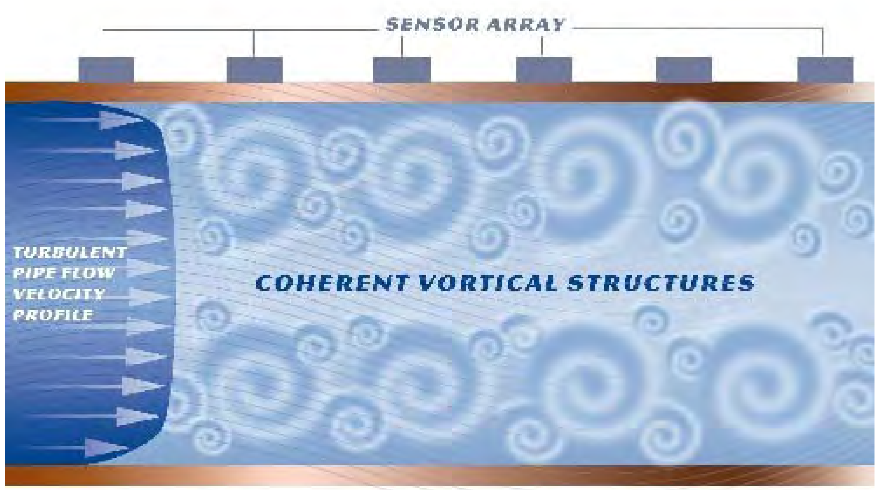


Figure 1: Coherent Structures within Turbulent Pipe Flows

The Reynolds number (Re), based on pipe diameter (D), characterizes many of the engineering properties of the flow. The Reynolds number is a non-dimensional ratio representing the relative importance of inertial forces to viscous forces within a flow:

$$\mathrm{Re} = \frac{inertial}{viscous}\ forces = \frac{\rho u \frac{\partial u}{\partial x}}{\mu \frac{\partial^2 u}{\partial y^2}} = \frac{UD}{\nu}$$

Where ρ is the fluid density, μ is the dynamic viscosity, U is the volumetrically averaged flow velocity and ν (= μ /ρ) is the kinematic viscosity.

The critical Reynolds number for pipe flows, above which flows are considered turbulent, is ~2300. Most flows in the chemical and petrochemical industry have Reynolds number ranging from one hundred thousand to several million, well within the turbulent regime. In addition to demarcating a boundary between laminar and turbulent flow regimes, the Reynolds number is a similarity parameter for pipe flows, i.e. flows in geometrically similar pipes with the same Reynolds number are dynamically similar (Schlichting p.12).

The Convective Ridge

Operating in the convective mode, sonar-based flow meter use the convection velocity of coherent structures (eddies) inherent within turbulent pipe flows to determine the volumetric flow rate. The sonar-based algorithms determine the speed of the turbulent eddies by characterizing both the temporal and spatially 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:

$$\omega = kU_{convect}$$

Here 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 $U_{convect}$ is the convection velocity or phase speed of the disturbance. The dispersion relationship basically states that temporal variations observed at a fixed location are proportional to the convection speed and inversely proportional to the spatial wavelength of the disturbance.

In sonar array processing, the spatial / temporal frequency content of time stationary 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 wavenumbers and temporal frequencies. On a k-ω plot, the power associated with a pressure field convecting with the flow is distributed in regions that satisfy the dispersion relationship developed above. For turbulent boundary flows, this region is termed "the convective ridge" (Beranek, 1992) and the slope of this ridge on a k-ω plot 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 turbulent eddies; and with calibration, the precise volumetric flow rate within a pipe.

K-ω plot showing Convective Ridge

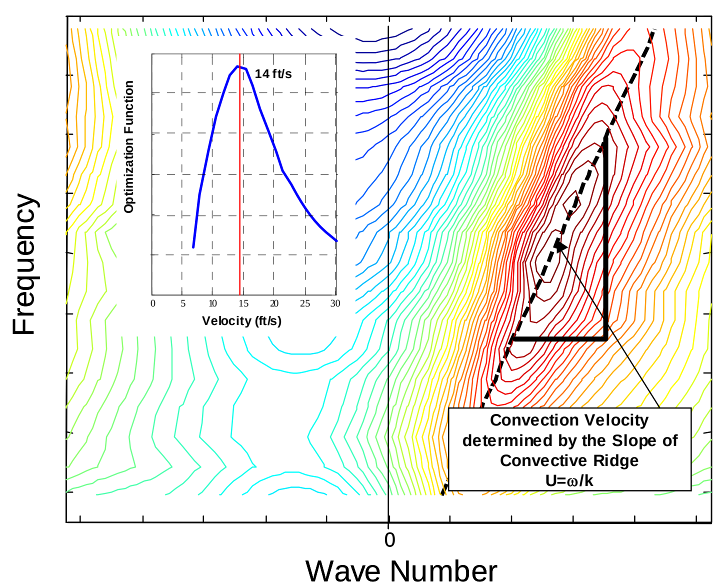


Figure 2: K-ω plot generated from an array of sensors listening to water flowing in a 6 inch pipe at ~1000gpm.

Figure 2 shows a k-ω plot generated from the using the 6-inch diameter sonar-based flow meter, operating at a water-only calibration facility. As shown, the power contours show a well-defined convective ridge. A parametric optimization method was used to determine the "best" line representing the slope of the ridge. For this case, a slope of 14.2 ft/sec was determined. The optimization function is displayed in the insert as a function of convection velocity, showing that optimized value is a well-defined optimum.

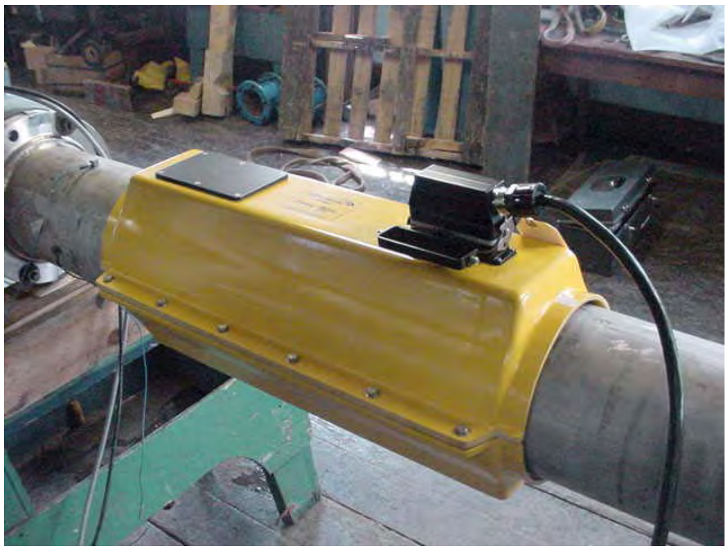


Figure 3: Photograph of a Clamp-on, Sonar-based flow meter installed in an 8inch, Schedule 10 pipe at a Water Calibration Facility

Calibration

The k-ω plot shown in Figure 2 illustrates the fundamental principle behind sonar-based convective flow measurements, namely that axial arrays sensors can be used in conjunction with sonar processing techniques to determine the speed at which naturally occurring turbulent eddies convect within a pipe. The slope of the convective ridge can be calibrated to the volumetrically averaged flow rate as a low-order function of Reynolds to provide accurate flow measurement. Figure 4 shows the volumetric flow rate measured by the calibrated sonar-based flow meters plotted versus reference flow. Figure 5 shows the error in volumetric flow rate compared to the reference flow rate. As shown the sonar-based convective flow meter reported the flow rate to within +/- 0.5% accuracy from flow rates between 2.5 ft/sec (~400 gpm) and 32 ft/sec (5400 gpm) in the 8 inch meter.

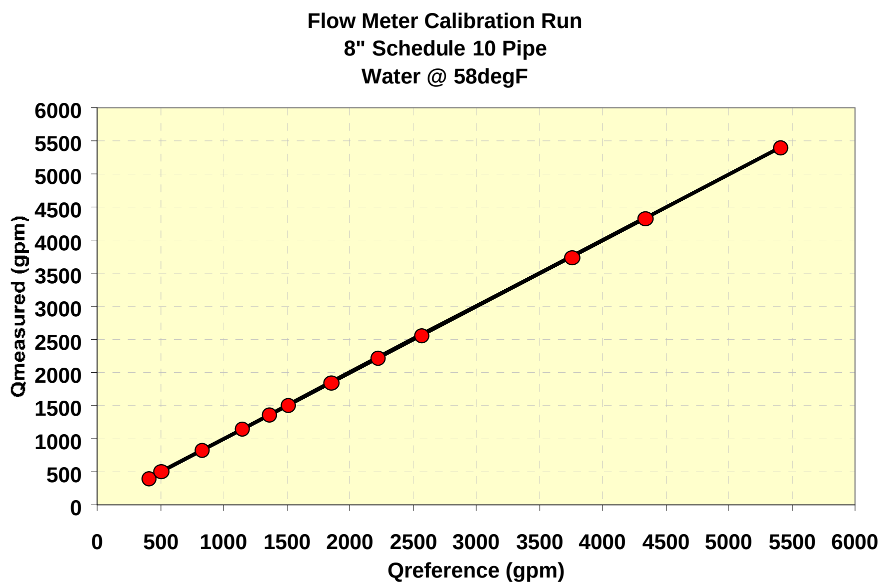


Figure 4: Volumetric Flow Rate measured using Sonar-based Convective flow meter versus Reference Flow Rate

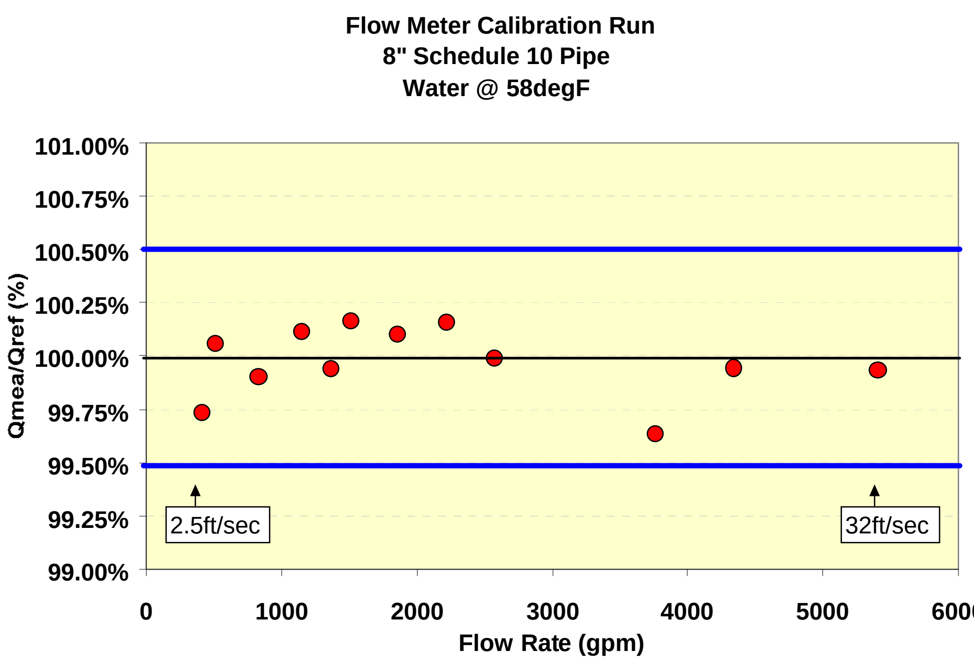


Figure 5: Accuracy of Calibrated Volumetric Flow Rate measured using Sonar based Convective flow measurement

Field Test Results: Polymer Slurry Application

The calibration data presented above demonstrates that sonar-based flow meters can provide an accurate, first principles-based, flow measurement over a range of pipes using either ported pressure or clamp-on based strain sensors in clean, single phase (water) applications. However, unlike many conventional flow metering technologies, sonar-based flow measurement is equally well-suited for both single and multiphase flows.

To evaluate the applicability of sonar-based flow measurement technology to multiphase flows important to the chemical processing industry, a field trial was conducted on 3 inch flow line carrying a near-boiling, water-conveyed slurry of 1/8" to 1" sized polymer crumbs ranging from 0 to 8% mass fraction. Liquid-conveyed, solid-particle slurries are widely used in chemical manufacturing. Due to the erosive nature of the flow, varying chemical composition, potential for clogging, and other reasons, an accurate and reliable flow measurement of these slurries has proved difficult for conventional flow meter technologies.

For the field trial a ported-pressure spool-piece was designed and fabricated to meet the specifications of the plant operator. The spool-piece housed five, flush-mounted pressure transducers, and was fabricated using standard, 3 inch, 150 lb flanges. Prior to installation, the spool-piece was hydrostatically tested to 250 psi. As a benchmark, the sonar-based flow meter was compared with the output of a 3-inch electromagnetic (mag) flow meter installed in-line on the same process piping. A comparison of the sonar-based convective flow meter and the existing mag meter is shown in Figure 6 during, and just prior to, process start-up. During this part of the process, the operator had high confidence in the electromagnetic flow meters ability to measure the flow rate, as shown, the mag meter and sonar-based flow meter show good correlation, demonstrating the applicability of sonar-based flow measurement technology to this important class of multiphase slurries.

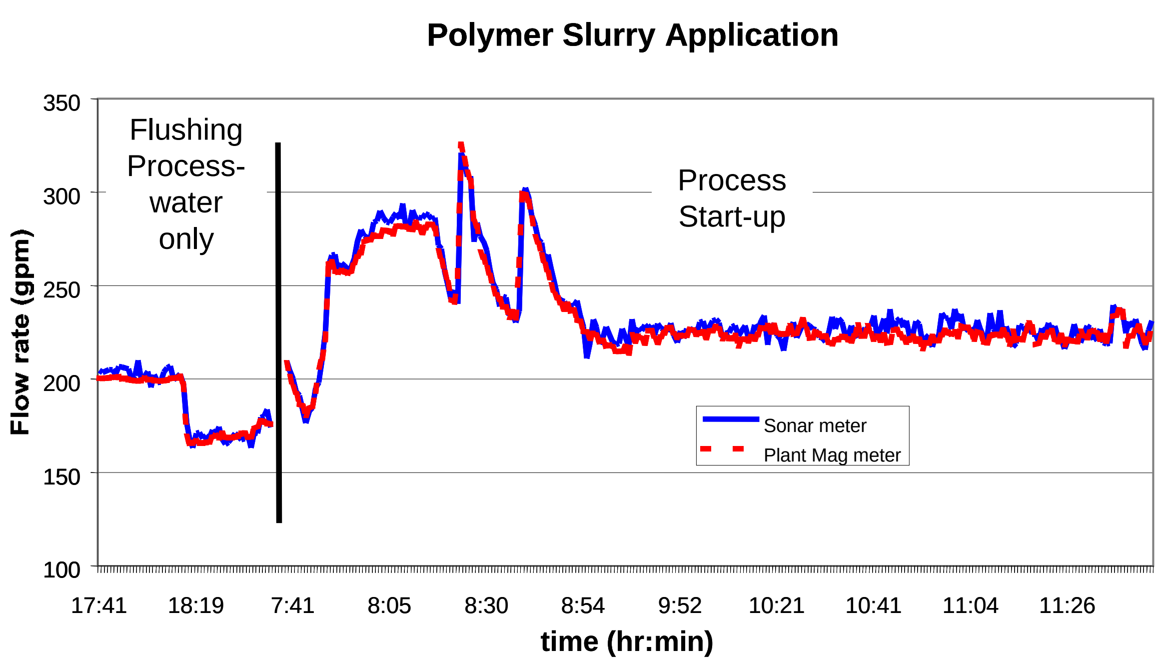


Figure 6: Comparison of Sonar-Based Flow meter with Electromagnetic flow meter on a liquid-conveyed, solid-particle slurry

Sonar-based Acoustic Flow Measurement

In additional to being able to extract information from the convective pressure field associated with the convection of coherent vortical structures, sonar processing techniques can also be used in some applications to determine volumetric flow rates by characterizing the acoustic pressure field.

Industrial processes involving pumps, valves and other machines inevitably generate acoustic noise across a wide range of frequencies. Process lines are typically efficient wave guides for acoustic waves for the wavelength of the sound is long compared to the diameter of the pipe. For frequencies below a cut-on frequency, only one-dimensional waves can propagate. For circular pipes, this cut-off frequency is given as a function of sound speed (SOS) and pipe diameter (D) :

$$f_{cut-on} = \frac{1.84}{\pi D} SOS$$

For a 6-inch schedule 40 pipe filled with air at near ambient conditions, this cut-on frequency is approximated 1400 Hz. For a similar pipe containing water, the cut-on frequency is approximately 6000 Hz. Thus, for frequencies below this cut-on frequency, the propagating acoustic sound field is comprise of only one-dimensional dimensional waves.

The one-dimensional acoustic waves represent coherent pressure fields propagating along the axis of the pipe. The flow rate within a process line can be determined by comparing the speed of propagation of the one dimensional acoustic waves propagating with the flow (V^{+}_{prop}) with those propagating against the flow (V^{-}_{prop}). A schematic of a sonar-based acoustic, volumetric flow meter is shown in Figure 7. As shown, one-dimensional sound propagating with the flow travels at the speed of sound of the fluid at rest plus the mixture velocity ($SOS+V_{mix}$), and propagation speed of sound traveling against the flow travels at the speed of sound of the fluid at rest minus the mixture flow velocity ($SOS-V_{mix}$). Thus, the mixture flow velocity and the sound speed of the fluid at rest are given by half of the difference, and half of the sum, of the two propagation velocities.

$$V_{mix} = \frac{V^{+}_{prop} - V^{-}_{prop}}{2} \quad \text{and} \quad SOS = \frac{V^{+}_{prop} + V^{-}_{prop}}{2}$$

Although conceptually this sonar-based acoustic method for determining flow rate is applicable to any flow with sufficient acoustic energy propagating both with and against the flow, this methodology is only well-suited for flows with non-negligible axial Mach number. The axial Mach number defined is the ratio of the mixture flow rate to the speed of sound of the fluid at rest.

$$M_x \equiv V_{mix} / SOS$$

The relative uncertainty in mixture flow velocity is proportional to the relative uncertainty in sound speed divided by the axial Mach number.

$$\Delta\%_{V_{mix}} \propto \frac{\Delta\%_{SOS}}{M_x}$$

Thus, as the approach becomes unfeasible as the axial Mach number approaches zero. For most liquid based flow applications, the axial Mach numbers are quite small. The speed of sound in most liquids is upwards of 4000 ft/sec and mixture flow velocities tend to be limited to ~10 ft/sec, resulting in axial mach numbers on the order of ~0.001. This is not the case, however, for many gas and steam applications where flow velocity are higher and sound speeds lower, resulting flows that often have axial Mach numbers of 0.1 or greater.

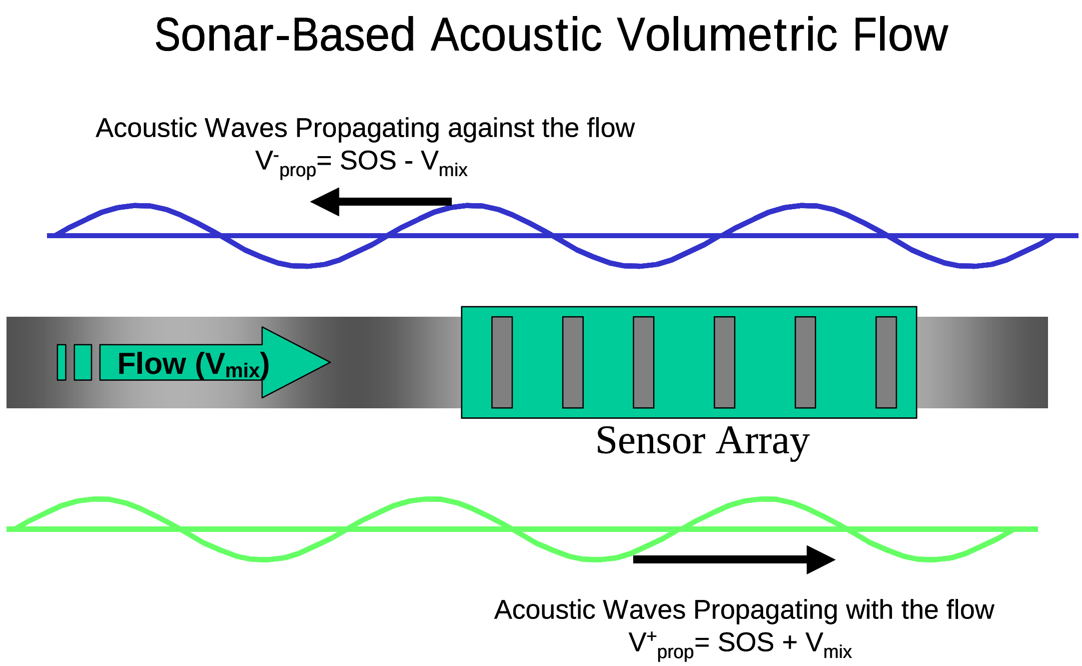


Figure 7: Schematic of a Sonar-based Acoustic Volumetric Flow Meter

Figure 8 shows an example of a volumetric flow measurement made using the sonar-based, acoustic volumetric flow techniques described above on a 6 inch, schedule 40, steel pipe flowing air at near ambient conditions. The k-w plot shows two acoustic ridges, one traveling with the flow, and one traveling against the flow. For this example, the slopes of the two acoustic ridges were determined to be 1305 ft/sec with the flow and 941 ft/sec against the flow. From these values the mixture velocity and speed of sound at rest are measured to be 182 ft/sec and 1123 ft/sec, respectively.

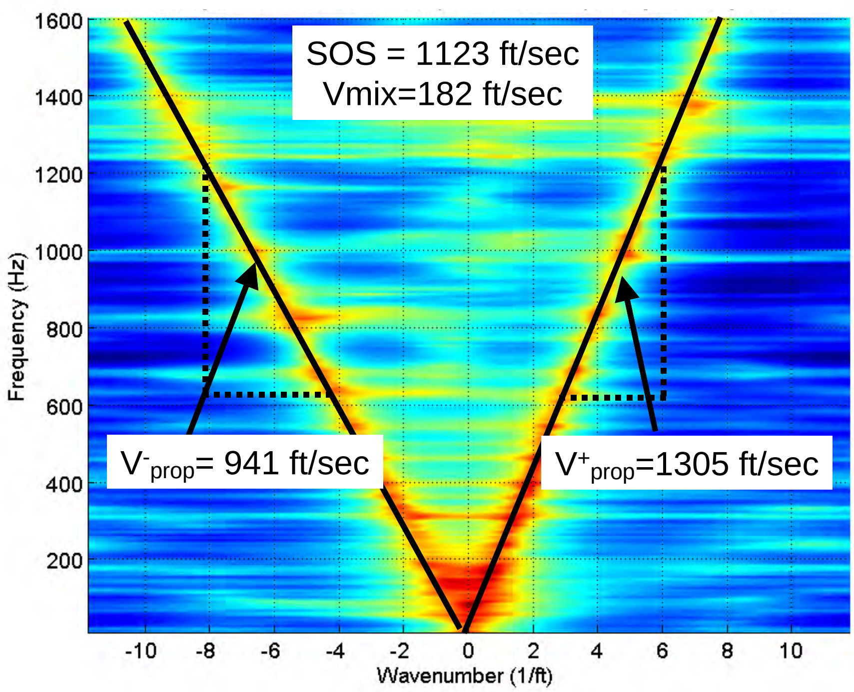
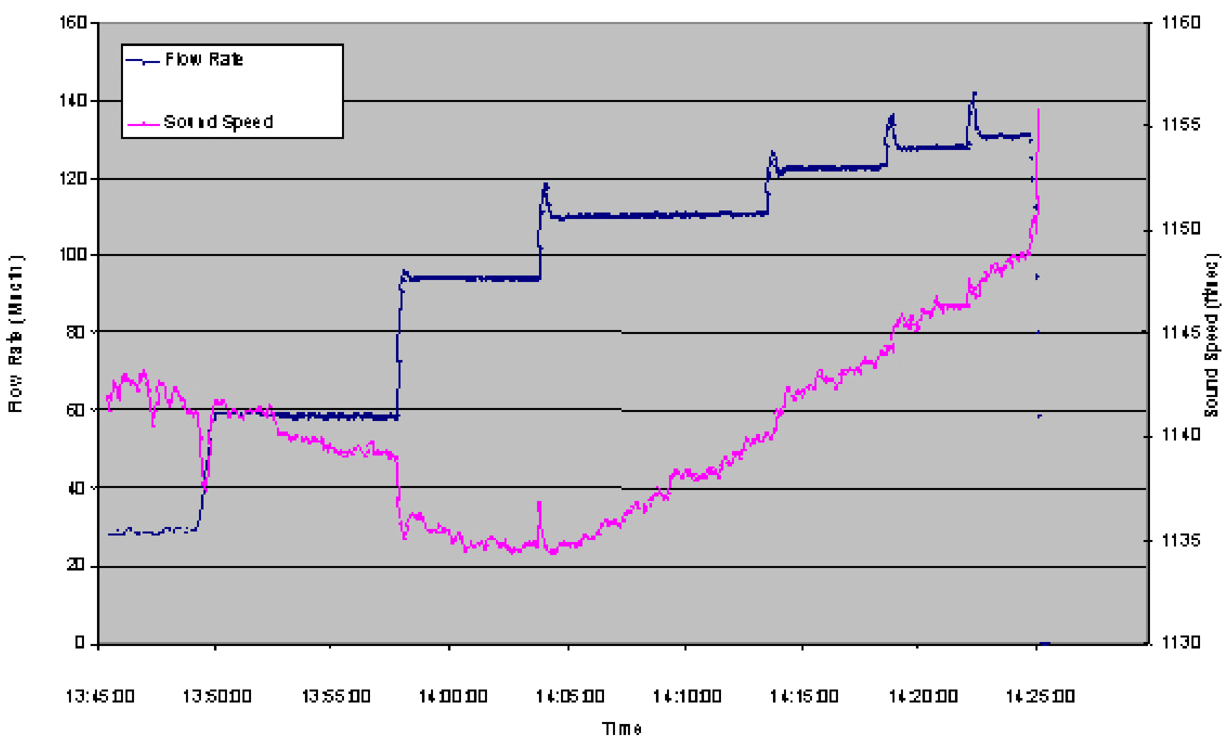


Figure 8: Example plot from a clamp-on Sonar-based acoustic volumetric flow meter showing the acoustic ridges for sound traveling with and against the flow for air at near ambient conditions flowing in a 6 inch, Schedule 40, Steel pipe

The performance of the flow meter over a range of flow rates for this configuration is shown in Figure 9. Flow rate is presented in thousand standard cubic feet per hour. Unfortunately, no reference data is available for a quantitative assessment of the accuracy of this sonar-based, acoustic volumetric flow measurement. However, the data did agree with estimates of the flow rates and trended with valve position.

Sonar-Based Acoustic Volumetric Flow



Summary

Sonar-based flow measurement is an emerging class of industrial flow metering technology. Sonar flow meters use sonar array processing technology to characterize the speed at which naturally occurring, coherent pressure fields propagate through process flow lines. The sonar-based techniques can be implemented with strain-based sensors, clamped-on to existing industrial process lines.

Examples of two sonar-based volumetric flow measurement techniques were presented. The first approach, termed sonar-based convective flow measurement, uses sonar-processing techniques to track the speed at which coherent vortical structures convect with the flow field. This approach is well-suited for liquid and liquid-continuous slurries. Data was presented on this approach from a calibration facility where the meter demonstrated the ability to measure flow rate within 0.5% accuracy of a wide operating range. Data was also presented from a field trial on a co-polymer slurry application in which the sonar-based flow meter demonstrated comparable performance to a mag meter in this two-phase application.

A second, sonar-based acoustic flow measurement technique was also presented. This approach uses sonar technology to measure the speed at which acoustic waves propagate with and against the flow direction of the mixture in a process line to determine mixture flow rate. Data from a clamp-on, sonar-based acoustic flow meter was presented for an air application at near ambient conditions in which the sonar-based acoustic flow meter measured flow rate over a wide range of flow rates.

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