CLAMP-ON, SONAR-BASED ENTRAINED AIR MEASURMENT FOR PULP AND PAPER APPLICATIONS

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Abstract

SONARtrac flow meters represent a new class of clamp-on flow monitoring technology well-suited for paper and pulp applications. Separate and distinct from ultrasonic technology, SONARtrac devices utilize clamp-on, strain-based sensors combined with sonar processing techniques to simultaneously measure the percent of entrained air present in a paper or pulp slurry as well as measure the volumetric flow rate of that slurry on a real time basis. To measure entrained air, the meter utilizes the sensor array to determine the speed at which naturally occurring, process-generated sound propagates through the process fluid. The speed of sound measurement is then used to determine entrained air levels accurate to within 0.01% for typical paper and pulp applications. In addition to entrained air measurement, sonar-based meters can also provide volumetric flow measurement by tracking the speed at which naturally occurring turbulent structures convect with the flow past the same sensor array. By utilizing these two, first-principles based measurements to track the naturally occurring pressure field within process piping, sonar-based flow monitoring systems provide new insight to multi-phase flow for the pulp and paper industry.

Introduction

Multiphase process flow rate and composition are critical process control parameters for the paper and pulp industry. Knowing the amount of liquid, solids and entrained gas flowing in process lines is key to optimizing the overall papermaking process (Matula, 2000). Sonar-based flow monitoring technology offers the capability to address the long, unserved need for accurate, reliable monitoring of multiphase flow rates of paper and pulp slurries. This paper focuses on using sonar-based meters for measuring entrained air. Previous work addresses sonar-based volumetric flow measurement (Gysling, 2003).

It is well known that excessive levels of entrained air lead to significant degradation in paper quality and process efficiency. From a quality perspective, excessive entrained air levels can result in pinholes in the sheet, paper breaks, increased drainage time, cleanliness issues due to increase growth of aerobic bacteria and pressure pulsation in the head box. From a process efficiency perspective, entrained air impairs the accuracy and reliability of many process instruments such as mag flow meters, microwave consistency measurements, and coriolis mass flow meters, decreasing the observability and controllability of the process.

In an effort to manage entrained air, the pulp and paper industry spends significant resources each year to limit entrained air levels in stock mixtures, particularly lines in the paper machine approach system. Most paper machines employ chemical defoaming techniques for which defoamer usage typically runs into the hundreds of thousands of dollars per year per paper machine. Other approaches to minimize entrained involve using deculators to mechanically de-aerate pulp slurries.

Despite the numerous consequences of excessive entrained air levels, the exact amount and variability of entrained air levels, as well as the source of the entrained air, are typically not well-understood, nor well-monitored. Currently, many operators rely on periodic sampling to determine entrained air levels. Over the years, several technologies have been introduced in an attempt to provide real time entrained air measurement (Woodworth, 1990). Although assessing the effectiveness of these devices is beyond the scope of this paper, on-line entrained air meters employ a variety of technologies ranging from density measurement, to ultrasonic velocity and absorption, to fluid compressibility. All of these devices are intrusive and rely on a small sample of the flow through the pipe to determine the entrained air level. Sonar-based, entrained air systems offer a robust, first principles based method using hardware clamped on to the outside of existing pipes. Entrained air levels are determined by directly measuring the speed at which naturally occurring, one-dimensional sound field is propagating within the pipe. Sonar-based array processing technology is employed to assure a robust, accurate, repeatable sound speed determination over a wide range of operating conditions.

Entrained Air Measurement System

Figure 1 shows a schematic of a sonar-based entrained air measurement. The output from an array of strain based, sensors clamped on to the outside of standard process piping are interpreted using sonar-based algorithms to determine the speed at which naturally occurring, one-dimensional acoustic waves propagate through the process fluid. The measured sound speed is then used, in conjunction with knowledge of the liquid density and line pressure, to determine entrained air content of the process fluid.

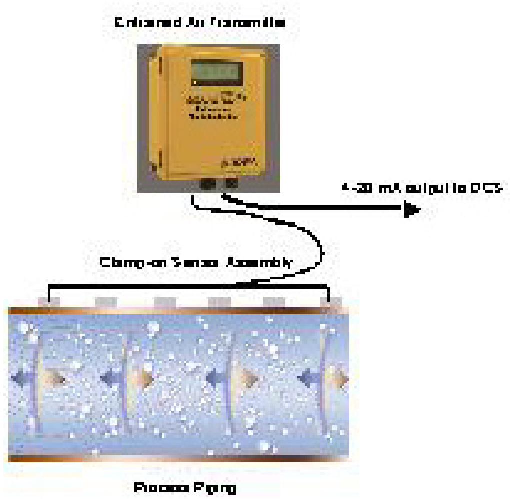

Figure 1: Schematic of Sonar-Based Entrained Air Measurement System showing sensor array on pipe with one-dimensional sound waves propagating within an aerated fluid mixture

Speed of Sound Measurement

As described above, the relationship between mixture sound speed and entrained air in bubbly liquids is well-established. These relationships, however, are typically only applicable for the propagation of relatively low frequency, long wavelength sound. While this restriction does not present any significant obstacles for the sonar meter, it does present significant challenges to ultrasonic sound speed measurement devices.

Sonar-based flow meters use an approach developed and commercialized specifically for multiphase flow measurement in the oil and gas industry (Kragas, 2003) in which multiphase challenges associated with bubbly flows described above are routinely encountered. Sonar-based meters measure the propagation velocity of operationally generated sound in the ~100 to 1000 Hz frequency range. In this frequency range, sound propagates as a one-dimensional wave, using the process pipe as a wave-guide. The wavelength of sound in this frequency range (>1 m) is typically several orders of magnitude larger than the length scale of any bubbles or flow non-uniformities. The long wavelength acoustics propagate through multiphase mixtures unimpeded, providing a robust and representative measure of the volumetrically averaged properties of the flow.

For the sound speed measurement, the sonar-based entrained air meters utilizes similar processing algorithms as those employed for sonar-based volumetric flow measurements (Gysling, 2003). As with convective disturbances, the temporal and spatial frequency content of sound propagating within the process piping is related through a dispersion relationship.

$$k = \frac{\omega}{a_{mix}}$$

Where k is the wave number, defined as $k=2\pi/\lambda$, ω is the temporal frequency in rad/sec, and a_{mix} is the speed at which sound propagates within the process piping.

Utilizing sonar processing techniques, data from an array of sensors can be processed to decompose the sound field into specific temporal and spatial frequency components. The result of this two-dimensional, Fourier-based composition can be represented with a k-ω plot, in which the power of the sound field is plotted as a function of both temporal and spatial frequencies. Under this transformation, all the acoustic energy is distributed in regions of the k-ω plot where the wave number and temporal frequency are related through the propagation velocity as described above. The result is that the acoustic energy forms what is often termed, the acoustic ridge. Since sound typically propagates both with and against the flow, k-ω plots of the acoustic field often appear as “v” like structures in the k-w plane. Determining the slope of the acoustic ridges provides a measure of the speed of sound.

Entrained Air Determination

The connection between speed of sound of a two-phase mixture and phase fraction is well established for mixtures in which the wave length of the sound is significantly larger than flow inhomogenieities, i.e. bubbles, in the flow. Thus, for long wavelength sound propagation, the sound speed of a mixture can be related to volumetric phase fraction (ϕ_i) of the components and the sound speed (a_i) and densities (ρ_i) of the components through these well established mixing rules. A simplistic mixing rule, suitable for discussion purposes and known as the isentropic mixing rule, is given as follows:

$$\frac{1}{\rho_{mix} a^2_{mix_\infty}} = \sum_{i=1}^{N} \frac{\phi_i}{\rho_i a_i^2} \qquad \text{where}$$

$$\rho_{mix} = \sum_{i=1}^{N} \rho_i \phi_i$$

The mixing rule essentially states that the compressibility of a mixture ($1/(\rho a^2)$) is the volumetrically-weighted average of the compressibilities of the components. For gas / liquid mixtures at pressure and temperatures typical of paper and pulp industry, the compressibility of gas phase is orders of magnitudes greater than that of the liquid. Thus, the compressibility of the gas phase and the density of the liquid phase primarily determine mixture sound speed., and as such, it is necessary to have a good estimate of process pressure to interpret mixture sound speed in terms of volumetric fraction of entrained air. Although process pressure does have a significant influence on the relationship between mixture sound speed and entrained air, pulp suspension consistency does not. Thus, knowledge of slurry consistency is not required for accurate entrained air measurement.

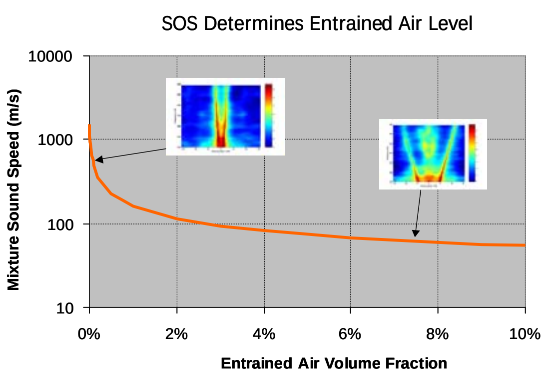

Figure 2: Mixture Sound Speed as a function of entrained air volume fraction. Inserts show K-w plots measured in field applications for significantly different entrained air levels.

Figure 2 shows a typical relationship between entrained air and mixture sound speed for pulp suspensions. Inserts show the characteristic acoustic signatures from field data covering a large range of entrained air levels.

Sonar-based volumetric and entrained measurements have been performed for numerous applications within the pulp and paper industry. Some results from a meter installed on 24 inch diameter feed line to a headbox application are shown in Figure 3. The data demonstrates the ability to track small variations in entrained air levels on a real time basis. Real time entrained air measurement such as that presented in Figure 4 can be employed in a variety of applications including real time defoamer dosing., real time microwave consistency correction, and real time system diagnostics.

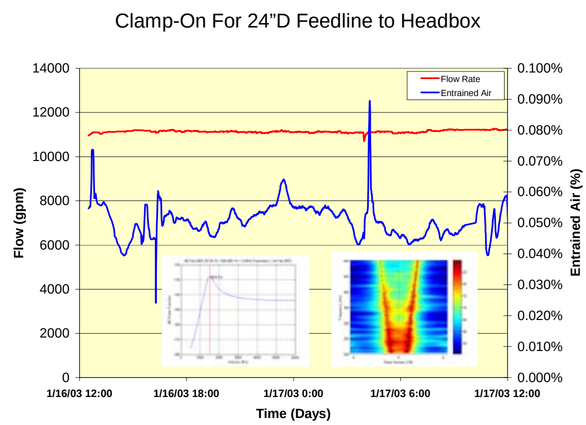

Figure 3: Sonar-based volumetric flow and entrained air measurement from a 24 inch, feed line to Headbox application with ~1% consistency stock. Inserts show k-w plot of sound field and optimization result determining speed of sound from acoustic sound field.

Summary

A novel method to determine entrained air content in pulp suspensions was developed. The method utilizes clamp-on, sonar-based technology to determine entrained air levels through the use of a first-principles based measurement of the propagation velocity of naturally occurring sound within the process fluid. The entrained air measurement can be performed with the same clamp-on, strain-based sensor utilized for sonar-based volumetric flow measurements.

An analytical relationship between mixture sound speed and entrained air levels was presented, showing the link between mixture sound speed and entrained air content in pulp suspensions. The relationship provides an accurate means to measure gas volume fraction (within ~0.01% by volume) without requiring detailed knowledge of slurry consistency.

Data was presented showing the ability of the sonar meter to characterize the acoustic pressure field and extract sound speed from field applications, including data from a 24 inch, feed line to headbox from an operating paper machine.

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