Self-Calibrating Sensor for Measuring Density Through Stainless Steel Pipeline Wall

Margaret S. Greenwood

Judith A. Bamberger

Pacific Northwest National Laboratory
P.O. Box 999
Richland, Washington 99352

An ultrasonic instrument to measure the density of a liquid or slurry through a stainless steel pipeline wall is described. By using multiple reflections of the ultrasound within the stainless steel wall, the acoustic impedance (defined as the product of the density of the liquid and the velocity of sound in the liquid) is determined. Thus, the wall is part of the measurement system. The density is obtained by coupling the acoustic impedance measurement with a velocity of sound measurement. By basing the measurement on multiple reflections, instrument sensitivity is increased by the power of the reflection coefficient. The measurement method is self-calibrating because the measurement of the acoustic impedance is independent of changes in the pulser voltage. Data are presented over a range of pulser voltages for two wall thicknesses. These results can be applied to develop an ultrasonic sensor that (1) can be attached permanently to a pipeline wall, possibly as a spool piece inserted into the line or (2) can clamp onto an existing pipeline wall and be movable to another location. The self-calibrating feature is very important because the signal strength is sensitive to the pressure on the clamp-on sensor. A sensor for immersion into a tank could also be developed. [DOI: 10.1115/1.1677462]

Introduction

Recent advances in computers and in particular high-speed A/D signal conversion make on-line real-time ultrasonic measurements an attractive addition to a suite of process measurement capabilities and a tool for chemometrics [1]. An ultrasonic instrument to measure the density of a liquid or slurry [2,3] through a stainless steel (SS) pipeline wall is described. By using multiple reflections of the ultrasound within the SS wall, the acoustic impedance (defined as the product of the density of the liquid and the velocity of sound in the liquid) is determined. Thus, the wall is part of the measurement system. The density is obtained by coupling the acoustic impedance measurement with a velocity of sound measurement. Since methods for measuring the velocity of sound in the fluid [time-of-flight (TOF)] are well known [4], the research presented here will focus on the measurement of the acoustic impedance. The self-calibrating feature is very important because the measurement of the acoustic impedance is *independent* of changes in the pulser voltage. The objective is to develop an ultrasonic sensor that (1) can be attached permanently to a pipeline wall, possibly as a spool piece inserted into the line and (2) can clamp onto an existing pipeline wall and be movable to another location. The self-calibrating feature is very important because the signal strength is sensitive to the pressure on the clamp-on sensor. A sensor for immersion into a tank could also be developed.

Experimental Measurements

A schematic diagram of the experimental apparatus is depicted in Fig. 1. A 5 MHz, longitudinal transducer is mounted upon a thin plate of stainless steel (or other solid material) plate with the base in contact with the liquid. A pulser sends a high-voltage signal to the transducer. The resulting ultrasound makes multiple reflections within the steel plate by reflecting each time the signal strikes the solid-liquid interface or the solid-transducer interface. The multiple echoes are recorded by the same transducer and then amplified by the receiver. They are viewed on a digital oscilloscope, as well as recorded on a file. Figure 2 displays an oscilloscope trace obtained using a stainless steel plate 6.4 mm thick. The plot shows 15 discrete echoes in the plate. Bold numbers along the axis indicate the elapsed time in micro seconds. The data files were analyzed by Matlab, a commercial code.

When the ultrasound strikes the solid-liquid interface, some of the ultrasound is reflected and some is transmitted into the liquid. The amount reflected, defined by the reflection coefficient, is given by:

$$R=\left(\frac{Z_s-Z_{\text{liq}}}{Z_s+Z_{\text{liq}}}\right) \tag{1}$$

where acoustic impedance is the product of the material density and the speed of sound in the material $(Z=\rho\ c)$. Inverting Eq. (1) gives the acoustic impedance of the liquid:

$$Z_{\text{liq}}=Z_s\left(\frac{1-R}{1+R}\right) \tag{2}$$

where Z_{liq} is the acoustic impedance of the liquid and Z_s, that of stainless steel or any other solid.

Using the reflection at a liquid-solid interface is a well-known method for measuring the acoustic impedance of a liquid. However, stainless steel is usually not used for this measurement because of its large acoustic impedance. For water ($Z=1.48\text{E}6\ \text{kg/m}^2\text{s}$) and steel ($Z=4.54\text{E}7\ \text{kg/m}^2\text{s}$), Eq. (1) shows that 93.7% of the ultrasound is reflected back at the stainless steel-water interface, each time the ultrasound strikes the interface. That is, the reflection coefficient is equal to 0.937. As an example, for water the density and speed of sound are 1000 kg/m^3 and 1480 m/s at ambient conditions, while the values for stainless steel are 7900 kg/m^3 and 5790 m/s. From Eq. (1), the reflection coefficient is 0.937. In comparison for 15% sugar water with a density of 1060 kg/m^3, the reflection coefficient is 0.931. These two values differ very little, and determination of the acoustic impedance of a liquid from one echo is very difficult. Little sensitivity occurs to small changes in the density. However, multiple echoes amplify the effect. After 10 echoes, the reflection corresponds to $(0.937)^{10}=0.522$ and similarly, $(0.931)^{10}=0.489$. These values are quite different and can be easily distinguished. Thus, the sensitivity is greatly increased.

Contributed by the Fluids Engineering Division for publication in the JOURNAL OF FLUIDS ENGINEERING. Manuscript received by the Fluids Engineering Division November 1, 2002; revised manuscript received June 4, 2003. Associate Editor: D. Siginer.

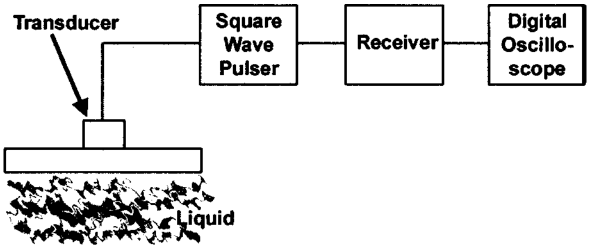

Fig. 1 Schematic diagram of experimental apparatus

Each echo, such as those shown in Fig. 2, is analyzed by taking the fast Fourier transform (FFT) of the signal to determine the amplitude at a frequency of 5 MHz (usually). Figure 3 shows that a straight line results when the logarithm of the FFT amplitude is plotted versus the echo number. A least-squares fit provides the slope of the line. The important point is that, for different liquids, the slopes are different because the reflection coefficients at the solid-liquid interface are different. The goal is to relate the slope of this line to the reflection coefficient for the liquid. Then, using Eq. (2) the acoustic impedance of the liquid is obtained. A separate measurement of the time-of-flight through the liquid yields the density of the liquid.

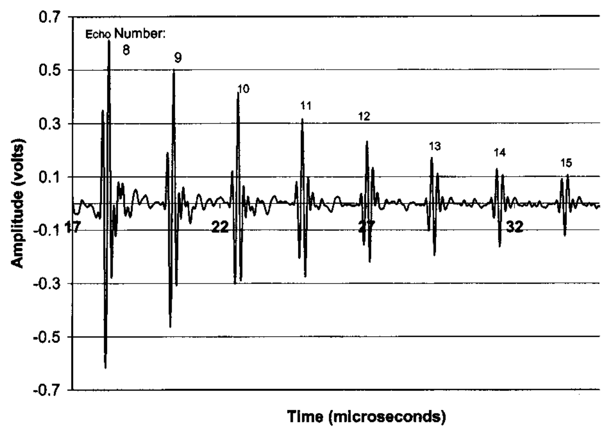

Fig. 2 Oscilloscope trace showing multiple echoes with 6.4-mm-thick steel plate

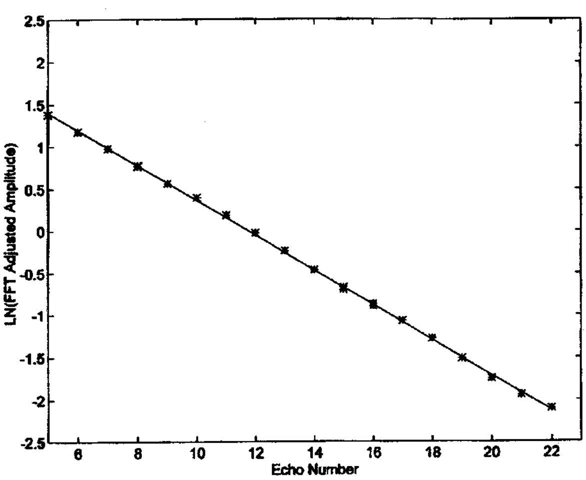

Fig. 3 A graph of the logarithm of the FFT amplitude versus the echo number for 10% sugar water in contact with 6.3-mm-thick SS plate

To obtain the relationship between the slope and the reflection coefficient the relationship for the voltage of the Nth echo is employed.

$$\text{Voltage } \alpha \text{ (reflection coefficient for liquid)}^N \tag{3}$$

Water is the fluid for calibration of the slopes. From Eq. (3) for water and another liquid, the following relationship is obtained for the echo N_1:

$$\frac{V_{\mathrm{liq}N1}}{V_{\mathrm{wtr}N1}} = \frac{R_{\mathrm{liq}}^{N1}}{R_{\mathrm{wtr}}^{N1}} \tag{4}$$

A similar equation can be written for echo N_2. Taking the logarithm of both equations and subtracting yields the desired relationship between slope and reflection coefficient:

$$\frac{R_{\mathrm{liq}}}{R_{\mathrm{wtr}}} = e^{(\text{slope for liquid}) - (\text{slope for water})} \tag{5}$$

The term ''slope'' refers to the slope on a logarithmic plot shown in Fig. 3.

The reflection coefficient for the liquid is determined from Eq. (5), and then Eq. (2) yields the acoustic impedance of the liquid.

Self-Calibrating Feature. Suppose that the pulser voltage changes and is reduced by 5%. The ultrasound produced is likewise reduced, but each echo is reduced by *the same amount*. This means that, while the straight line is located at a slightly different position on the LN(FFT amplitude)-versus-echo graph, its *slope is the same*. Thus, the measurement of slope is independent of the pulser output. This was confirmed experimentally by using a 6.3-mm SS plate in contact with water. A square wave pulse was sent to the 5 MHz transducer, having a voltage of -300 V and a pulse width, which was varied to change the pulser output. Table 1 shows the data obtained for the natural logarithm of the FFT amplitude at 5 MHz for echoes 6, 9, 12, 15, 18, and 21; at the top of the column, the width of the square wave in nanoseconds is given. The data is plotted in Fig. 4. The slopes on a logarithmic plot of the FFT amplitude versus echo number are given in Table 1. For five sets of data, the value of the maximum slope and the minimum slope differ by only 0.2%.

Data for Stainless Steel Plates

Data were obtained for a 5 MHz transducer (diameter $=2.5$ cm) mounted upon a 6.3-mm-thick stainless steel plate. A square wave pulse with a voltage of -50 V and width of 100 nanoseconds was applied to the transducer. The base of the plate was immersed in water and various concentrations of sugar water. Figure 3 presents a plot of the logarithm of the FFT amplitude at 5 MHz versus the echo number for 10% sugar water. The slope is -0.2070. Table 2 lists the data for two entries of water. One measurement was obtained at the beginning of the experiments and the other, at the end. From the oscilloscope traces for these two sets of data, the amplitudes differed by ~5%. The *very* important point, however, is that the slopes were essentially the same—differing only by 0.1%. These results demonstrate how important the self-calibrating feature really is.

Table 2 presents data obtained for air. At the steel-air interface, all of the ultrasound is reflected and so the reflection coefficient is expected to be equal to 1.0; this is confirmed by the data.

Although the data in Table 1 and Table 2 were obtained using the same stainless steel plate and transducer, different pulser-receivers with different settings were used in each case. Also, the FFT analysis was obtained using the FFT function on the digital oscilloscope for the data in Table 1 and using Matlab for the data in Table 2. These differences are the reason that the slope for water in Table 1 and Table 2 are not the same.

Table 1 Multiple echo data

Echo Number	LN (FFT Amplitude)				
	Pulser Width (ns)				
	102	92	84	78	68
6	3.436	3.408	3.367	3.333	3.247
9	2.821	2.793	2.752	2.717	2.629
12	2.145	2.119	2.082	2.049	1.961
15	1.500	1.476	1.437	1.403	1.320
18	0.813	0.790	0.754	0.722	0.641
21	0.126	0.098	0.057	0.020	−0.067
Slope	−0.2212	−0.2210	−0.2209	−0.2209	−0.2207
R^2	0.9997	0.9997	0.9996	0.9996	0.9996

The independent measurement of the acoustic impedance was carried out by measuring the density of the liquid and determining the velocity of sound in the liquid. The velocity of sound was measured for water, 10% sugar water, and 30% sugar water. For other weight percentages, the velocity was found by interpolation. Therefore, there is some undetermined percentage error in this independent measurement. The independent measurement of density was obtained by weighing a known volume of the sample.

Table 3 lists the data obtained for a 5-MHz transducer mounted upon a stainless steel plate 3.8-mm thick. The dimensions of the transducer are 25 mm by 13 mm. The amplitude data were obtained by using a frequency of 5.5 MHz for the FFT analysis.

While signal averaging took place to obtain the echoes plotted in Fig. 2, only one value of the slope was obtained for each sample shown in Tables 1 and 2. In an automated system, many averages of the slope would be taken—10 at a minimum. The oscilloscope has an 8-bit digitizer, which means that the vertical axis of the oscilloscope (voltage) is divided into 2^8 or 256 bins. More accuracy would be obtained by using a 12-bit digitizer, or 4096 bins along the axis. Thus, the errors in the acoustic impedance can be reduced—possibly to 1% or less.

Summary and Conclusions

Some conclusions are as follows:

- The analysis method provides a way to measure very small changes in reflection coefficient, and hence, very small changes in the density when using stainless steel (or other solids).

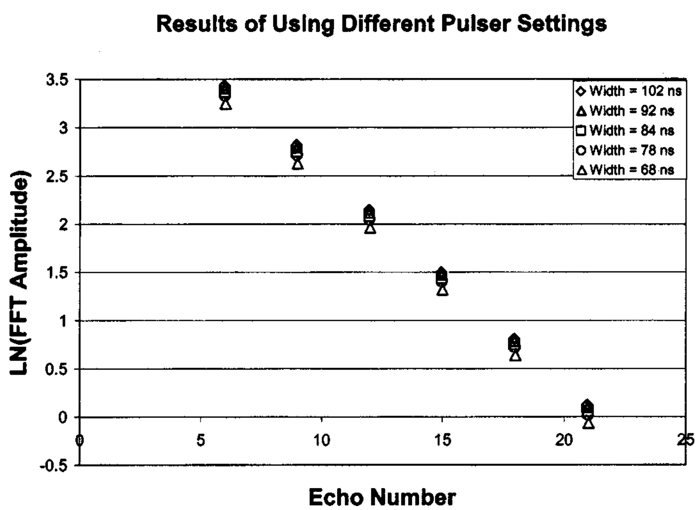

Fig. 4 A graph of the LN (FFT Amplitude) versus echo number for a range of pulse widths

Table 2 Data for 6.3-mm-thick stainless steel plate

Liquid	Independent Measurement of Density, kg/m^3	Slope Log Plot	Sensor Reflection Coefficient	Sensor Measurement of Acoustic Impedance, kg/m^2 sec×10^6	Independent Measurement of Acoustic Impedance, kg/m^2 sec×10^6	Percent Error, %
water-beg	998	−0.2042	0.9382	1.479	1.479	0.0
water-end	998	−0.2040	0.9385	1.472	1.479	−0.5
2.5% SW	1006	−0.2035	0.9389	1.462	1.499	−2.5
5.0% SW	1016	−0.2073	0.9354	1.549	1.521	1.8
7.5% SW	1026	−0.2058	0.9368	1.515	1.545	−1.9
10% SW	1038	−0.2070	0.9357	1.543	1.570	−1.7
15% SW	1065	−0.2094	0.9334	1.598	1.624	−1.6
20% SW	1097	−0.2126	0.9304	1.673	1.684	−0.7
air		−0.1344	1.0061			

Table 3 Data for 3.8-mm-thick stainless steel plate

Liquid	Independent Measurement of Density, kg/m^3	Slope Log Plot	Sensor Reflection Coefficient	Sensor Measurement of Acoustic Impedance, $kg/m^2\ sec \times 10^6$	Independent Measurement of Acoustic Impedance, $kg/m^2\ sec \times 10^6$	Percent Error, %
water		−0.2943			1.481	
5.0% SW	1010	−0.2968	0.9359	1.538	1.525	0.8
10% SW	1027	−0.2981	0.9347	1.567	1.578	−0.7
15% SW	1057	−0.3020	0.9310	1.658	1.627	1.9
20% SW	1074	−0.3026	0.9305	1.671	1.686	−0.9
30% SW	1115	−0.3153	0.9188	1.965	1.809	8.7
40% SW	1170	−0.3206	0.9139	2.089	1.964	6.4
air		−0.2197	1.0109			

- The self-calibrating feature enables the design of a clamp-on sensor.
- Changes in the pulser voltage do not affect the measurement due to the self-calibrating feature.
- The calibrating time is reduced due to the self-calibrating feature.
- Wireless technology could be utilized to design a sensor to measure density and velocity of sound and thus eliminate the long cables from the sensor to the computer acquisition system.

A computer-controlled system is currently being developed with a 12-bit 100-MHz digitizer for measuring the acoustic impedance and the TOF to determine the density.

A U.S. Patent application has been filed for this measurement technique.

Acknowledgments

Pacific Northwest National Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract No. DE-AC06-76RLO1830.

References

[1] Workman, Jr., J., Veltkamp, D. J., Doherty, S., Anderson, B. B., Creasy, K. E., Koch, M., Tatera, J. F., Robinson, A. L., Bond, L., Burgess, L. W., Bokerman, G. N., Ulhman, A. H., Darsey, G. P., Mozayeni, F., Bamberger, J. A., and Greenwood, M. S., 1999, ''Process Analytical Chemistry,'' Anal. Chem., **71**(12), pp. 121R–180R.

[2] Greenwood, M. S., Skorpik, J. R., Bamberger, J. A., and Harris, R. V., 1999, ''On-line density sensor for process control of liquids and slurries,'' Ultrasonics, **37**, 159–171.

[3] Greenwood, M. S., and Bamberger, J. A., 2002, ''Ultrasonic sensor to measure the density of a liquid or slurry during pipeline transport,'' Ultrasonics .

[4] Povey, M. J. W., 1997, Ultrasonic techniques for fluids characterization, Academic Press (New York).