SELF-CALIBRATING SENSOR FOR MEASURING DENSITY THROUGH STAINLESS STEEL PIPELINE WALL

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ABSTRACT

An ultrasonic instrument to measure the density of a liquid or slurry [1,2] through the 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 time-of-flight (TOF) are well known, 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. A U.S. Patent application has been filed.

EXPERIMENTAL MEASUREMENTS

A schematic diagram of the experimental apparatus is shown in Figure 1. A longitudinal transducer is mounted upon a thin plate of stainless steel (or other solid material) plate and the base of the plate is 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 shows an oscilloscope trace using a stainless steel plate 6.4 mm thick. Matlab is used to analyze the data files.

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:

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

Inverting Eq. 1 gives the acoustic impedance of the liquid:

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

where Z_{liq} is the acoustic impedance of the liquid and Z_s, that of SS 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 example, Eq. 1 shows that 93.7% of the ultrasound is reflected back at the SS-water interface, each time the ultrasound strikes the interface. That is, the reflection coefficient is equal to 0.937. For water the velocity of sound is 1480 m/s. For stainless steel the density is 7900 kg/m^3 and the velocity of sound is 5790 m/s. For sugar water having a density of 1.06 g/cm^3, 93.1% of the ultrasound is reflected back. These two values differ very little, and determining the acoustic impedance of a liquid using only one echo is very difficult. It also shows little sensitivity to small changes in the

density. However, using multiple echoes amplifies 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.

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). Fig. 3 shows that a straight line results when the logarithm of the FFT amplitude is plotted versus the echo number. A least-squares fit is used to obtain 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.

In order to obtain the relationship between the slope and the reflection coefficient, we use the fact that the voltage of the Nth echo is given by:

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

Water is used for calibration of the slopes. Using Eq. 3 for water and another liquid, we obtain the following for the echo N_1:

$$\frac{V_{liqN1}}{V_{wtrN1}} = \frac{R_{liq}^{N1}}{R_{wtr}^{N1}} \tag{4}$$

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:

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

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

Eq. 5 is used to determine the reflection coefficient for the liquid and then Eq. 2 yields the acoustic impedance of the liquid.

Self-calibrating Feature

Suppose that the pulser voltage changes and is reduced by, say, 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 voltage. This was confirmed experimentally by using a 6.3-mm SS plate in contact with water and sending signals of different voltage and shape to the send transducer. This resulted in amplitudes of the echoes that changed by as much as 20%. For five sets of data, the value of the maximum slope and the minimum slope differed 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 nm was applied to the transducer. The base of the plate was immersed in water and various concentrations of sugar water. Fig. 3 shows a plot of the logarithm of the FFT amplitude at 5 MHz versus the echo number for 10% sugar water. The slope is -0.206988. Table 1 shows the data, in which there are two entries for water. One measurement was obtained at the beginning of the experiments and the other, at the end. Looking at the oscilloscope traces for these two sets of data, it was apparent that the amplitudes differed and, in fact, they differed by about 5%. The *very* important point, however, is that the slopes were essentially the same—differing only by 0.1%. This shows how important the self-calibrating feature really is.

Table 1 shows that data were also 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. The data show that it is very close to this value.

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 2 shows 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 shown 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 used in these experiments 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).
- The self-calibrating feature makes it possible to design 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 used 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.

We are currently developing a computer-controlled system using a 12-bit 100-MHz digitizer for measuring the acoustic impedance and the TOF as well, in order to determine the density.

REFERENCES

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2. Greenwood, M. S., and J. A. Bamberger, 2002, "Ultrasonic sensor to measure the density of a liquid or slurry during pipeline transport," *Ultrasonics* **40**, 413-417.

ACKNOWLEDGMENTS

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Fig. 1. Schematic diagram of experimental apparatus.

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.

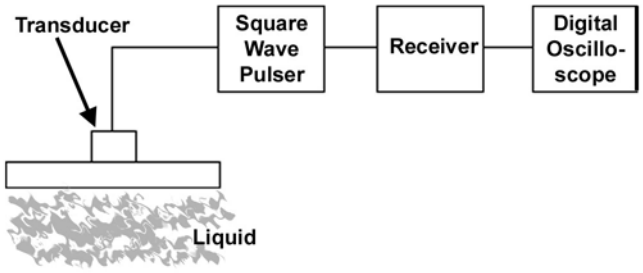
Transducer
Square Wave Pulser
Receiver
Digital Oscillo-scope
Liquid

Fig. 1.

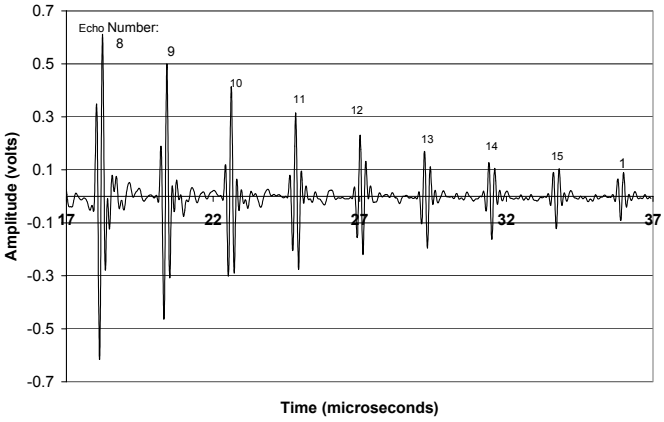
Echo Number:
8
9
10
11
12
13
14
15
1
0.7
0.5
0.3
0.1
-0.1
-0.3
-0.5
-0.7
17
22
27
32
37
Amplitude (volts)
Time (microseconds)

Fig. 2.

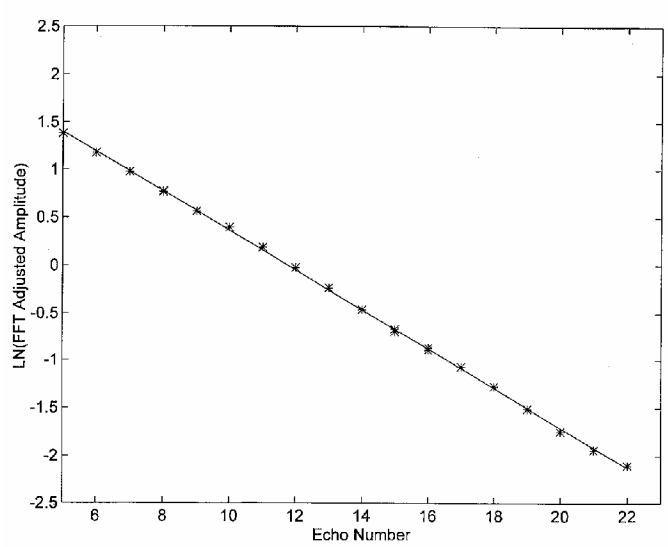
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
LN(FFT Adjusted Amplitude)
6
8
10
12
14
16
18
20
22
Echo Number

Fig. 3.

Table 1. 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 x 10^6**	**Independent Measurement of Acoustic Impedance, kg/m^2 sec x 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 2. 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 x 10^6	Independent Measurement of Acoustic Impedance, kg/m^2 sec x 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			