Ultrasonic Meters for Liquid Measurement
Class #2400

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Background

Ultrasonic liquid flow meters have been in use in the industry for some time now. The first use of ultrasonic meters for liquid measurement dates back to the use of insertion type transducers in the trans-Atlantic pipeline for leak detection purposes. Since then, various types of ultrasonic meters have been available to help customers efficiently measure flow through pipelines. With progress in time, ultrasonic flow meters became more accurate and, in the early 1990s, ultrasonic flow meters were first used for custody transfer applications providing measurement accuracies of 0.15%. Now in the 21^{st} century with the advancement of microprocessors, flow meters have become more refined and offer extended diagnostic capability, thus reducing significant downtime and helping customers resolve issues much faster. This paper discusses the ultrasonic technology for measuring liquid and describes the types of meters that are available now for use in various applications.

Technology

Ultrasound is sound with a frequency of 20 KHz or more. Ultrasound is not audible to the human ear and the frequency of an ultrasound is much higher than naturally occurring sounds in nature. Ultrasound is produced by piezoelectric crystals. The conversion of electrical pulses to mechanical vibrations and the conversion of returned mechanical vibrations back into electrical energy is the basis for ultrasonic testing. The active element is the heart of the transducer as it converts the electrical energy to acoustic energy, and vice versa. The active element is basically a piece of polarized material (i.e. some parts of the molecule are positively charged, while other parts of the molecule are negatively charged) with electrodes attached to two of its opposite faces. When an electric field is applied across the material, the polarized molecules will align themselves with the electric field, resulting in induced dipoles within the molecular or crystal structure of the material. This alignment of molecules will cause the material to change dimensions. This phenomenon is known as electrostriction. In addition, a permanently-polarized material such as quartz (SiO_2) or barium titanate ($BaTiO_3$) will produce an electric field when the material changes dimensions as a result of an imposed mechanical force. This phenomenon is known as the piezoelectric effect. The piezoelectric crystal produces the ultrasonic wave that travels through the liquid.

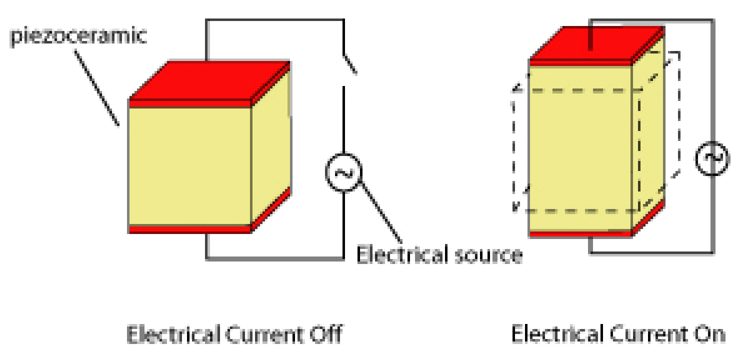
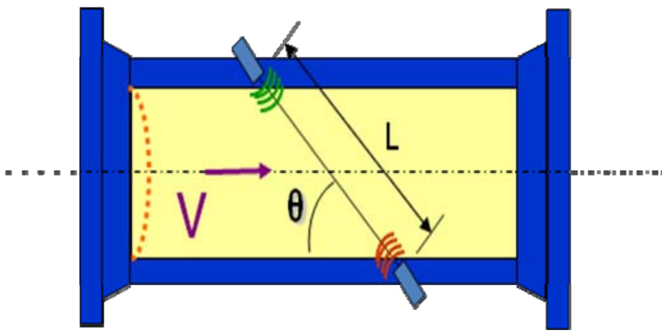


Figure 1. Working Principle of a Piezoelectric Crystal.

The ultrasound waves are then used to measure the velocity of flow through the pipeline, using the following two widely used concepts:

a) Transit Time:

As the name suggests, transit time refers to the use of measuring the transit time or the difference in time of flight between two transducers across the flow path. Depending on the direction of the flow, the time it takes for the sound wave to travel from one transducer to the other varies. A typical transit time flow measurement system utilizes two ultrasonic transducers that function as both ultrasonic transmitter and receiver. The flow meter operates by alternately transmitting and receiving a burst of sound energy between the two transducers and measuring the transit time that it takes for sound to travel between the two transducers. The difference in the transit time measured is directly and exactly related to the velocity of the liquid in the pipe.



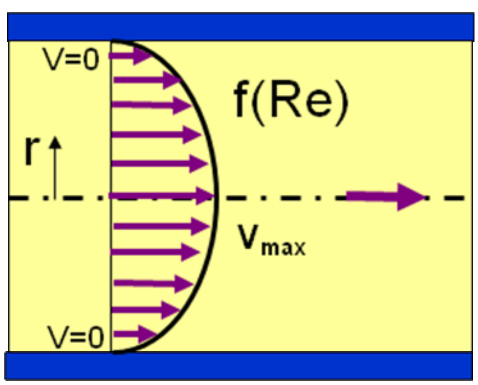
$$V = \frac{L\ (T_{up} - T_{down})}{2\ (T_{up} \times T_{down})\, Cos\ \theta}$$

$$T_{up} = \frac{L}{C - (V\ Cos\theta)}$$

$$T_{down} = \frac{L}{C + (V\ Cos\theta)}$$

Where, C = velocity of Sound through the liquid

Figure 2. The Basics of Transit Time Flow Measurement in Determining Flow Velocity.



$$Q = A * \int_0^R V dr$$

Where, Q = Volumetric flow rate
A = Cross sectional Area
R = Internal Radius
V = Velocity of the liquid
Re = Reynolds Number

Figure 3. The Basics of Volumetric Flow Rate Calculation from Flow Velocity.

As shown in Figure 3, the velocity of the liquid flowing through a pipe is not the same at any radius. The flow velocity varies from the center of the pipe to the wall of the pipe. The velocity of the liquid is highest at the center of the pipe and is zero at the wall (no slip boundary condition, only valid for Newtonian fluids). The change of velocity from the center of the pipe to the wall is a function of the Reynolds number. The Reynolds number is the ratio of the inertial forces to the viscous forces that the flow is subjected to, and for pipe flow, the Reynolds number is given by the expression below:

$$Re = \rho VD/\mu$$

Where, ρ = density of fluid
V = Velocity of the fluid
D = Internal Diameter or Hydraulic diameter of the pipe
μ = Dynamic Viscosity of the fluid

The velocity profile changes as the Reynolds number changes. Hence, to accurately measure the volumetric flow rate through the pipe, it is essential to measure the velocity of the liquid at as many points as possible. Hence, the higher the number of paths, the more accurate the flow meter. However, physical size of the transducers and the size of the pipe, limit the number of transducers that can be placed. Typically, custody transfer ultrasonic meters have four to five paths to provide customers accuracy of ±0.15%.

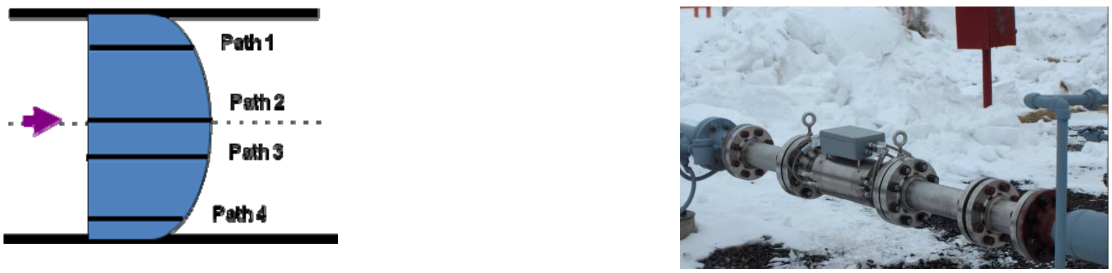


Figure 4. Use of Multiple Paths to Improve the Accuracy of Volumetric Measurement.

b) **Doppler**
Doppler ultrasonic flow meters use reflected ultrasonic sound to measure the fluid velocity. By measuring the frequency shift between the ultrasonic frequency source, the receiver, and the fluid carrier, the relative motion is measured.

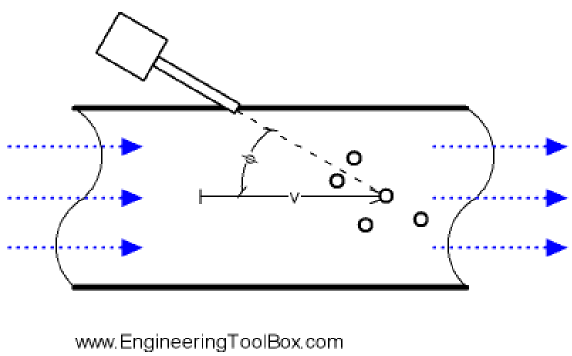


Figure 5. The Principle of Doppler Ultrasonic Flow Meters.

The fluid velocity can be expressed as:

$$v = c\,(f_r - f_t) / 2\, f_t \cos\Phi$$

where
f_r = *received frequency*
f_t = *transmission frequency*
v = *fluid flow velocity*
Φ = *the relative angle between the transmitted ultrasonic beam and the fluid flow*
c = *the velocity of sound in the fluid*

This method requires the presence of reflecting particles in the fluid. Doppler meters cannot work with clear fluids. Hence, the Doppler meters are ideal for measuring slurries and solutions with air bubbles. In order to eliminate noise, dual frequency Doppler instruments have become very popular whereby with the use of two independent frequencies, noise from sources like variable frequency drives can be eliminated. Doppler meters come in dedicated as well as portable options.

Figure 6. Portable (left) and Dedicated (right) Doppler Ultrasonic Flow Meters.

Types of Transit Time Flow Meters and Their Applications

Transit time ultrasonic flow meters can be broadly divided into two categories:

a) Clamped on or extrusive transducer type
b) Wetted transducer type

a) <u>Clamped On or Extrusive Transducer Type:</u>

In this type, the transducers do not touch the liquid. The transducers are mounted externally to the pipe by a clamping mechanism. In this case, the energy has to travel through the pipe material before it reaches the liquid. Clamped on meters are widely used when accuracy is not important but customers need to know the flow rate without cutting any pipe. Depending on the pipe diameter, various methods are used to obtain good signal strength and proper measurement values.

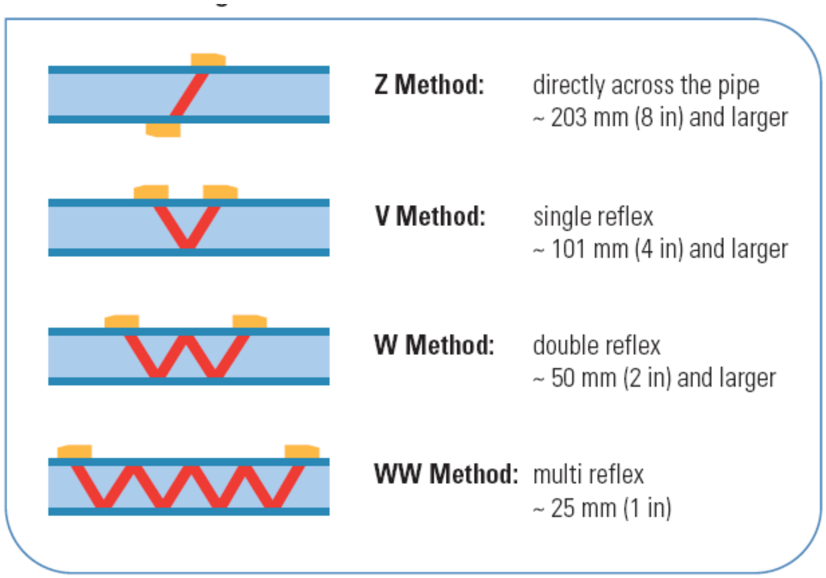


Figure 7. Different Transducer Placement Methods for Optimized Signal Strength.

Clamped on ultrasonic flow meters are also available as dedicated or portable types. Typically, single path clamped on flow meters are used for most field installations but, for extremely large pipes, the use of multipath clamped on flow meters is also being considered. A multipath clamped on system measures the velocity of the center of the pipe multiple times (based on the number of paths) and averages the values to give a more accurate reading. The accuracy of the reading improves by the square root of the number of paths.

Figure 7. Single Path Clamp-On System on a Large Pipe.

Figure 8. A Portable Clamp-On Flow Meter.

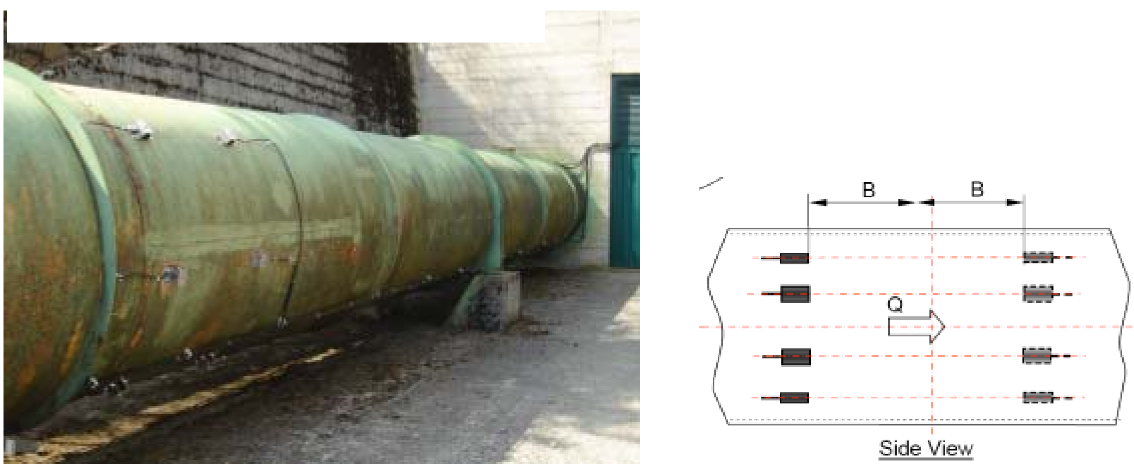


Figure 9. Multipath Clamp-On System Providing Turbine Output Control.

b) **<u>Insertion Type or Wetted Transducer Type:</u>**

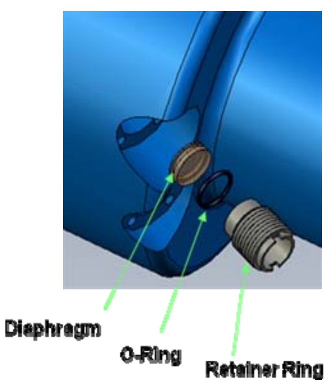
Insertion type or wetted transducer type flow meters are more accurate as the transducer actually sees the fluid and hence the pipe properties do not come into play. There are two types of insertion type transducers that are typically in use.

In one type, the insertion transducers stick into the flow. These transducers are either field mounted if the pipeline is too big or are preassembled in a spool with flanges and sold to customers. The insertion type transducers are typically fitted with a ball valve allowing the transducers to retract in and out without stopping the flow. The flow meter using insertion type transducers can also be single path or multiple paths. In the multipath configuration, the transducers are usually arranged in a chordal arrangement where each chord is weighted based on its location to provide accurate readings. Insertion type chordal meters can be used also to measure flow in open channels and also pipes that are not full.

Figure 10. A Multipath Insertion Type Transducer System.

Figure 11. An Open Channel using Transit Time Technology to Measure Flow.

In the second type, the transducers are recessed and do not interfere with the flow. These transducers are fitted on a spool with ports. The ports are sealed with a diaphragm that retains the pressure and acoustically couples the transducer to the medium of measurement. These flow meters are also available in single path or multipath construction.



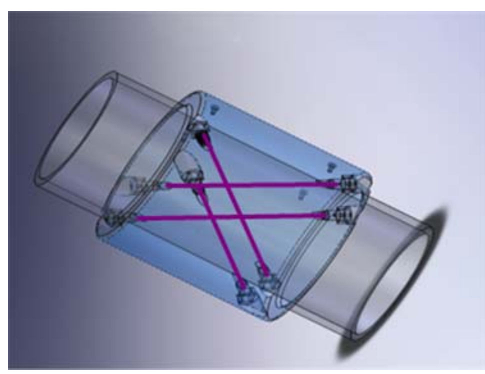


Figure 11. Sealing Arrangement for Recessed Type Transducers and Arrangement of Multiple Paths for a Multipath Flow Meter with Recessed Transducers.

<u>Conclusion:</u>

Ultrasonic flow meters are gaining popularity for their ease of installation and extensive diagnostic capabilities. The absence of any moving parts and near zero pressure drop is helping the technology gain popularity for high viscosity liquid measurements. As with any technology, there are a lot of options and the user needs to make the right choice for the application.

References:

- "Ultrasonic Meters for Liquid Measurement," by Chris B. Laird, Cameron Measurement Systems, Proceedings from ISHM 2009
- "Ultrasonic Meters for Liquid Measurement," by Douglas Baumoel, Controlotron Corporation, Proceedings from ISHM 2008
- EngineeringToolBox.com