FUNDAMENTALS OF ULTRASONIC FLOWMETERS FOR NATURAL GAS

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The use of ultrasound in flow measurement began in the last century when, in 1928, Oskar Rütten patented this method and apparatus for measuring the volume of flowing liquids, gas, and steam. The first ultrasonic flowmeters were introduced in the 1950's, and in the 1960's different companies developed the first ultrasonic flowmeters using the differential transit time method. Around this same time the first clamp-on ultrasonic flowmeters were also launched onto the market. The first multi-path ultrasonic flowmeters for measuring gases were finally introduced at the start of the 1980's. However the main breakthrough in ultrasonic flow measurement has come in the last 10 to 20 years, which has seen the breakthrough of digital signal processing. With this highly precise method, exact recording and analysis of transit times has become increasingly accurate, which of course has made the measuring device extremely interesting to industry.

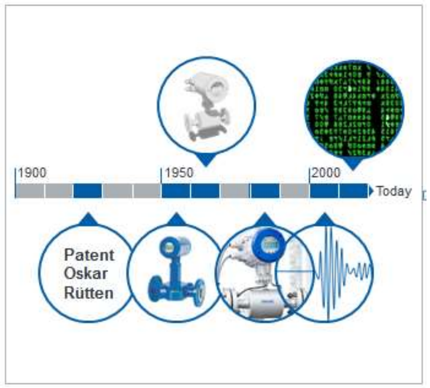

Figure 1 Historical Development

Today there are several different technologies on the market for ultrasonic flow measurement, with a wide range of applications. But how does ultrasonic flow measurement function? What should we know and what are the essential characteristics? In order to understand the measuring principle itself, we should first become acquainted with some basic terms which are important in ultrasonic measurement: frequency and velocity of sound.

Ultrasound, which is also called inaudible sound, consists of oscillations which move in a medium at a certain speed, frequency, and amplitude. For sound to propagate a medium is needed whose molecules can transport the sound. If we picture a vacuum, we know from experience that, since there are no molecules, there can be no propagation of the sound waves.

One of the properties of a medium is the speed at which sound propagates. At a specific temperature every medium has its own specific sound propagation velocity, which is also known as the speed of sound. The denser the molecular structure of a medium, the faster the sound waves propagate in the medium and the higher the velocity of sound of the medium. From this we can deduce that the velocity of sound of solids is greater than that of liquids, which in turn is greater than the velocity of sound of gases.

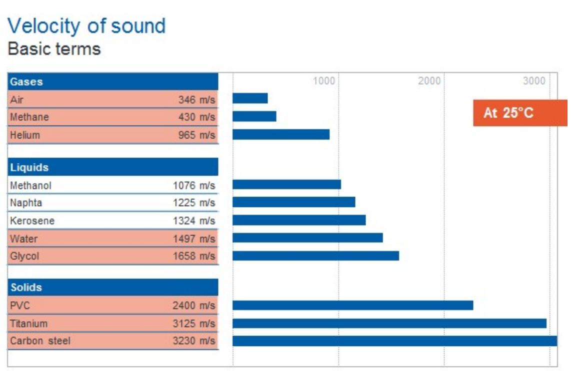

Figure 2 Velocity of Sound of different mediums

Let’s look at some examples at a temperature of 25°C. These examples only apply at 25°C because, when there is a change in temperature the density and hence the velocity of sound changes, too. At a temperature of 25°C air has a velocity of sound of 346 meters per second, Methane 430 meters per second and Helium 965 meters per second. As we have already seen, the velocity of sound in liquids is usually higher than in gases. Water has a velocity of sound of 1,497 meters per second, and glycol 1,658 meters per second. Solids and particulate materials have even higher velocities of sound: plastic or PVC 2,400 meters per second, Titanium 3,125 meters per second and carbon steel 3,230 meters per second.

Sound waves can propagate in media in different ways. We can start by looking at the longitudinal wave. This is a physical wave which oscillates in the direction of propagation. It always needs a medium in order to move. The best known example is sound in air or in water. Longitudinal waves are pressure waves. This means that in a medium, individual particles in the medium - atoms or molecules - oscillate in the direction of propagation. When the oscillation has passed the particles return to their rest position, the equilibrium position. No energy is lost when the oscillation is propagated, apart from the losses due to the friction between the particles. The counterpart to the longitudinal wave is the transverse wave which is also known as a shear or bending wave in solids. A transverse wave is a physical wave in which oscillation is perpendicular to the direction of propagation. In gases and liquids ultrasound propagates only as a longitudinal wave or in other words: longitudinal waves compress and decompress the medium in the direction of the propagation.

Another important term in ultrasonic measurement is frequency of sound.   As we have already seen, in a given material sound always propagates at the same speed at a certain temperature. According to the following equation, the wave length of sound is directly proportional to the velocity of sound and, inversely, proportional to frequency.

Wave length lambda λ is equal to the velocity of sound C divided by frequency f.

$$\lambda = \frac{C}{f} \qquad \textbf{\textit{Equation 1}}$$

The frequency of sound is measured in cycles per second, or Hertz. The human ear can hear up to a range of 18 to 20 kHz. Above 20 kHz we talk about ultrasound, which can no longer be perceived by the human ear. Some animals, however can hear higher frequencies, as we can see in the figure 3. Ultrasonic flowmeters operate in an even higher frequency range, since, from frequencies of 1 or 2 MHz, there is no longer any acoustic interference like that caused by valves or pumps in industrial plants. So we can apply the following rule of thumb: the lower the velocity of sound of a medium, the lower the frequency with which ultrasonic flowmeters work.

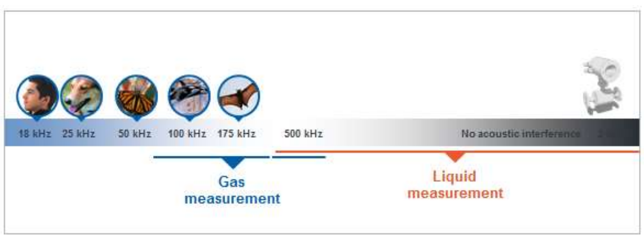

Figure 3 Ultrasonic Flowmeter operating frequencies

Now we have got to know some of the basic terms needed to understand ultrasonic flow measurement, we can move on to the measuring principle itself. There are two different technologies in ultrasonic flow measurement: Doppler effect and determining the flow using Transit time difference.

The Doppler Effect is the change perceived or measured in the frequency of any kind of wave when the source and the observer approach or move away from each other, in other words, when they move relative to one another. One example from everyday life is an approaching train. When observer and source approach each other, the frequency perceived by the observer increases, but then drops again when they separate. One well-known example of this is the change in pitch of an ambulance siren, where only a frequency shift takes place. A Doppler ultrasonic flowmeter works on this principle. The transmitter frequency changes when it is reflected by moving particles and gas bubbles in the flowing medium. The net result for the Doppler ultrasonic flowmeter is a frequency shift between the Doppler signal transmitted and the signal received. This difference in frequencies is proportional to the velocity of the moving particles or gas bubbles and can be used to infer the mean flow velocity. When the nominal diameter of the pipe is known we can also calculate the volume of the flow. This measuring principle requires a minimal amount of solid particles or gas bubbles, called reflectors, in the medium to achieve optimal measurement results.

Ultrasonic flowmeters which measure according to the Doppler Effect are typically of the clamp-on type and are particularly suited to applications with very dirty liquids or slurries. However, they never measure as accurately as ultrasonic flowmeters using the differential transit time method. So we should move on to this method which is very widely-used in various industries, particularly for highly accurate measurement of Natural Gas.

Ultrasonic flow measurement using the transit time difference is based on one simple physical fact. Imagine two canoes crossing a river diagonally on the same line: one in the direction of the flow and the other against it. The canoe moving in the direction of the flow will be carried by the flowing river and needs considerably less time to reach the other riverbank than the canoe moving against the direction of the flow. If we transfer this concept to the measuring principle, we can see that ultrasonic waves sent along a diagonal path behave in exactly the same way. A sound wave propagates in the direction of the flow of the medium, such as a liquid or a gas, more quickly than a sound wave propagating against the flow direction of the medium. The difference in the transit time is directly proportional to the flow velocity of the medium.

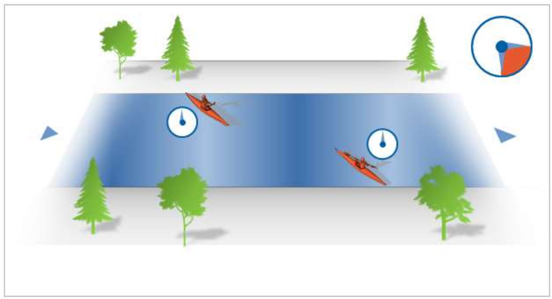

Figure 4 differential Transit Time principle

In order to understand the technical background we can look at the most important features: The transducers, which are always in pairs and mounted under an angle, consist of a transmitting, and a receiving transducer, which we can call transducer A and transducer B.

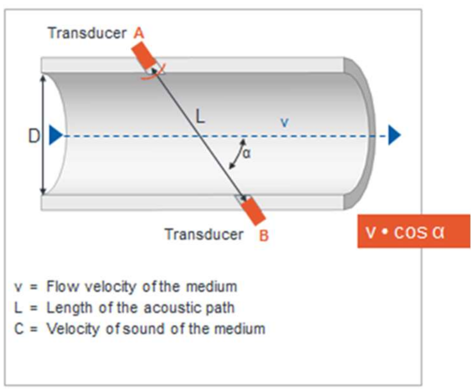

Figure 5 Key components of ultrasonic flowmeter

The two transducers act both as signal transmitters and signal receivers. The time an acoustic wave needs to travel from transducer A to transducer B, that is in the flow direction of the medium, is known as transit time T_{AB} and from transducer B to transducer A, that is against the flow direction, T_{BA}. The transit times T_{AB} and T_{BA} are measured continuously. The difference between transit times T_{AB} to T_{BA} is directly proportional to the average mean flow velocity, v_m of the medium.

Let's see why ultrasonic flow measurement is completely independent of the medium. As we can see in equation 2, the transit time of a signal is the distance between transducer A and transducer B, also known as the acoustic path length L, divided by the mean velocity, v_m which the acoustic signal needs to travel from one transducer to the other.

$$Transit\ Time\ (T) = \frac{Distance}{Velocity} = \frac{L}{v_m} \qquad \textbf{\textit{Equation 2}}$$

Although the signal travels in a straight line over the acoustic path length (L) at the speed of sound C, it is travelling at an angle, alpha(α), to the pipe axis. Equations 3 and 4 define the transit times between transducer A upstream and B downstream.

$$Transit\ Time\ of\ the\ signal\ from\ A\ to\ B = T_{AB} = \frac{L}{C_{AB} + v_m \times \cos\alpha} \qquad \textbf{Equation 3}$$

$$Transit\ Time\ of\ the\ signal\ from\ B\ to\ A = T_{BA} = \frac{L}{C_{BA} + v_m \times \cos\alpha} \qquad \textbf{Equation 4}$$

The transit time from A to B is shorter when the acoustic signal is transmitted downstream, that is in the direction of the flow of the medium, than when it is transmitted upstream from B to A that is against the direction of the flow. These transit times are measured in rapid succession, tens of times a second.

The Velocity of sound, C will vary with changes in the fluid density or composition, but that occurs over a much longer time periods than does each individual measurement pair, roughly 40 times per second. In practice we can assume that since neither the temperature, nor the pressure, nor will the composition of the medium change in these very small time intervals that are within milliseconds of each other that they remain constant for each measurement pair. So, during the transit time period, the velocity of sound can also be seen considered constant.

For each pair of transit times, $C_{AB} = C_{BA}$ **Equation 5**

Assuming that temperature, pressure, nor composition of the medium change in such a short time period, the resulting flow velocity of the medium can be shown as follows by solving equations 3 and 4:

$$Average\ Mean\ Flow\ Velocity = v_m = \frac{L}{2 \times \cos\alpha} \times \frac{T_{BA} - T_{AB}}{T_{BA} \times T_{AB}} \qquad \textbf{Equation 6}$$

This represents the average mean flow velocity. When multiplying the average mean flow velocity with the cross sectional area of the pipe A, of diameter D, we get the flow rate Q.

$$Cross\ Sectional\ Area\ of\ a\ Pipe = A = \frac{\pi D^2}{4} \qquad \textbf{Equation 7}$$

Therefore, the volume flow Q, of an ultrasonic flowmeter with a diameter D and transducers which are welded into the spool piece at a fixed angle alpha α, is given by equation 8.

$$Volume\ Flow = Q = \frac{\pi \times D^3}{4 \times \sin(2\alpha)} \times \frac{T_{BA} - T_{AB}}{T_{BA} \times T_{AB}} \qquad \textbf{Equation 8}$$

These formulas confirm what we have already seen, that is, that the characteristics of the medium do not affect the measurement. These characteristics include density, temperature, pressure and the velocity of sound of the medium. If we rewrite the formulas a little, we can see that the velocity of sound C can also be calculated using differential transit time. During calibration, the path length L is very accurately defined and is therefore known and fixed. The velocity of sound C is the distance traveled or twice the path length L, divided by the total time which is the sum of the two transit times T_{AB} and T_{BA}:

$$Velocity\ of\ Sound = C = \frac{2 \times L}{T_{AB} + T_{BA}} \qquad \textbf{Equation 9}$$

This gives ultrasonic flow measurement a unique feature, the velocity of sound is available as a measured value. The velocity of sound of a medium can be used for diagnostic purposes, for example, to identify different products such as different API oil grades.

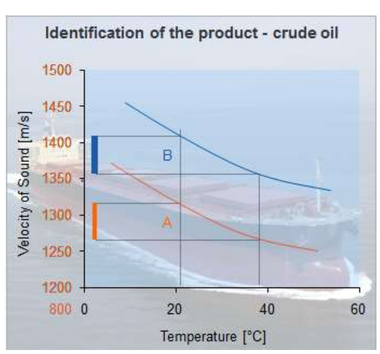

Figure 6 Velocity of sound for product identification

The diagram in figure 6 shows the identification of different types of crude oil by their corresponding velocity of sounds. These oils can differ according to their source. This means that crude oil can have different velocities of sound, Crude oil A for example, with a velocity of sound of 1,330 meters per second at 20°C, is being unloaded into tank X. As soon as the ultrasonic flowmeters measures a velocity of sound of 1,420 meters per second, the control room knows that crude oil B is flowing through the pipe and the valve can be switched.

For natural gas applications the measured velocity of sound can be used to determine the composition of the gas. The relationship between composition of natural gas and the corresponding velocity of sound is very well known and documented. This gives a way to compare the measured velocity of sound from the meter with the results from a Gas Chromatographer which precisely determines the composition.

Ultrasonic flowmeters operate with different frequencies and this affects the penetrating power in the media, the shape of the acoustic beam and the divergence of the acoustic beam. The excitation voltage and the pulse length of ultrasonic sensors can also vary. In applications to measure liquids, the frequency used by ultrasonic flowmeters is from 2 MHz down to 500 kHz. Among other things, this also depends on the viscosity of the medium being measured. Frequencies between 500 kHz and 80 KHz are used in applications which measure gases.

The acoustic signal is generated by a piezo electric material that has two unique properties. When a voltage is applied to them they oscillate at ultrasonic frequencies and generate the acoustic signal into the flowing medium. Once this acoustic energy reaches the opposite side of the meter it vibrates the opposing transducer. When piezo electric material is oscillated, it generates a voltage. This voltage is sensed on the receive transducer to stop the timer for that transmission time. The process is then repeated in reverse and the differential transit times measured and used for calculation of flow.

While ideally 100% of the acoustic signal generated by the transducer travels straight through the flow and is entirely received on the other side, there are losses that reduce the received signal strength. Some of the signal travels around the flow sensor metal walls, this is called ring-around, and can arrive at the receive transducer at the same time as the signal through the flow stream to be analyzed, potentially causing errors.

In liquids, due to their relatively dense nature, the signal through the fluid is much larger than the ring-around signal and interference is mitigated. This allows the use of transducer holders that are securely welded into the flow sensor. Because gases are less efficient at transmitting the acoustic signal, the transducer holders cannot be welded to the flow sensor body as the ring-around signal would be too large and create errors in the measurement. Therefore the use of 'De-Coupled' or often referred to as 'Wetted' transducers are commonly used to isolate the signals from travelling through the pipe wall reducing or eliminating the parasitic ring-around. These typically utilize O-rings to achieve this decoupling.

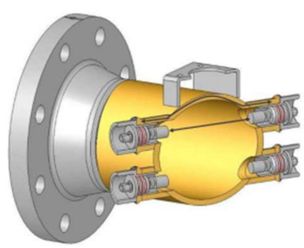

Figure 7 Ring-around signals via flow sensor wall

A common problem can occur when measuring wet gases, if liquid droplets form at the O-rings, then they can act as a short circuit for the sound and the majority of the signal drains to the flow sensor wall, usually causing a path failure alarm from the meter. By using special designs, this loss of signal due to wet gases can be overcome and measurement continued.

Figure 8 Decoupled transducer with isolation grooves

Since the primary measurement of an ultrasonic transit time flowmeter is differential time, which has been shown to be directly proportional to the mean flow velocity and the calculation of volumetric flow is done by way of the flowmeter cross sectional area. It is imperative that the cross sectional area of the measurement section remain constant after calibration and for years of service in the field. This is achieved by using very strong materials such as forged stainless steel. Since the meters are non-intrusive and are not subjected to wear and tear there should be no geometry changes over time and therefore can operate for many years of stable performance.

Figure 9 Forged stainless steel flow sensor for dimensional stability

However, there are processes conditions which may alter the cross-sectional area of the measurement section, liquids flowing through the bottom of the meter for instance will change the area the gas is flowing through and cause errors in the measurement. Additionally hydrates may migrate through the meter, clinging to the walls. To identify this is occurring, many meters now have acoustic paths oriented to ‘see’ these obstructions and provide alarms that the meter performance is being affected.

Figure 10 Process conditions which can affect meter performance

Why do we need multi-path ultrasonic flowmeters? Although the measurement of a single path is very linear to the velocity occurring along that path, flow velocity is not linear across the pipe, it varies from near zero at the pipe wall in a parabolic type distribution, peaking at the centerline and then returning again to near zero at the opposite pipe wall. This is known as the flow profile.

Since each acoustic path measures only part of the flow profile, selecting the optimum number and location for the acoustic paths is important to achieving the highest accuracy. An ultrasonic flowmeter measures only parts of the flow profile and has to integrate the acoustic paths to achieve the correct mean flow velocity. There are two options for choosing the correct location of the acoustic paths.

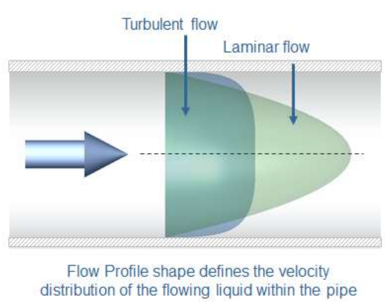

Figure 11 Flow velocity distribution across a pipe

One method is to assume the flow profile follows mathematician’s description, i.e. Gaussian distribution to apply the correct integration to achieve the true mean flow velocity. These meters are based on the Westinghouse patent from 1968 still applied in parallel 4 path design flow meters.

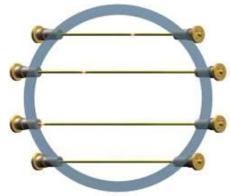

Figure 12 Westinghouse 4 path design

A second approach is to use computational fluid dynamics and investigate the true flow profile shape. With this information the optimum number of paths and positions can be selected with the least sensitivity to flow profile distortions and can be accurately integrated to achieve the best measure of the true mean flow velocity. Many variations are seen in meter designs as each attempts to attain the highest accuracy and least sensitivity.

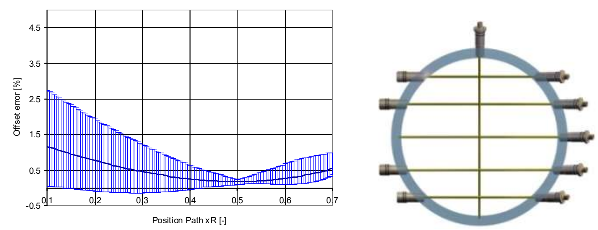

Figure 13 Computational Fluid Dynamic 5 (+1) path meter design

Now that we've looked at the design considerations for ideal flow profile conditions, how is this achieved in a field installation? According to AGA 9, the meter should have a total of 20D (D = nominal pipe diameters) of straight unobstructed pipe before the meter with a flow conditioning plate installed at 10D, an additional 5D straight unobstructed pipe downstream of the meter to ensure a uniform, symmetric, flow profile.

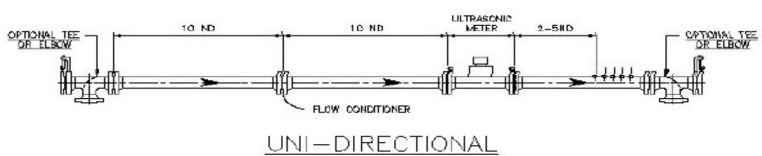

Figure 14 AGA 9 installation recommendation

Even when these conditions are met, due to the very low viscosity of gases (i.e. the pipe wall roughness does little to slow them down) and many out of plane elbows typically installed upstream of the meter run, some non-axial flow velocities may persist, these are referred to as swirl.

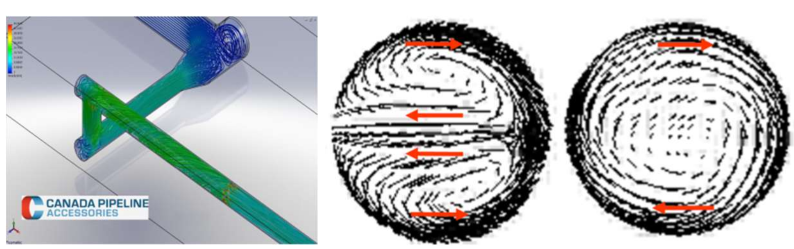

Figure 15 non-axial flow velocities (swirl)

A meter design that uses a single direct path across the flow stream may over or under register as a result of swirl.

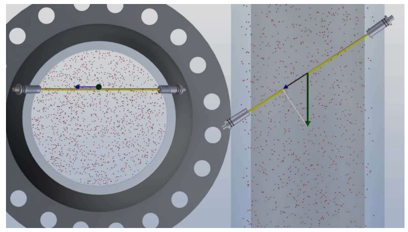

Figure 16 Direct path meter, prone to errors with swirl

Two designs have been introduced to eliminate the effect of swirl, in plane cross path and reflect path. By crossing direct paths in plane, any swirl in the pipe will affect the paths equally and oppositely so that the average of the crossed paths will represent the pure axial flow velocity without the influence of swirl.

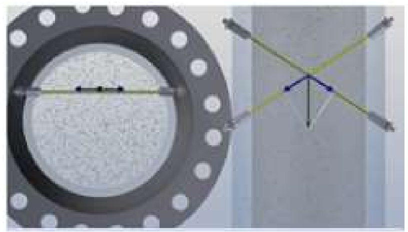

Figure 17 In plane cross path design, immune to swirl

The in plane reflect path design achieves the same result, by bouncing the signal off the meter wall (or when off center line, by reflectors to keep the path in plane) the acoustic path is going first in the direction of the swirl, and then against it, and in the end cancels out the swirl effect and again provides the pure axial flow velocity.

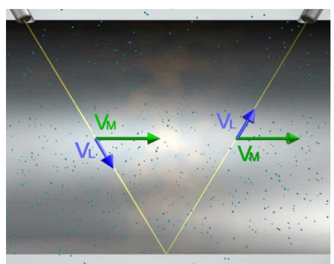

Figure 18 In plane reflect path design, immune to swirl

Testing has shown this swirl compensation to be suitable for reduced straight pipe runs without compromise to accuracy. Consult with vendors for specific make and model recommendations.

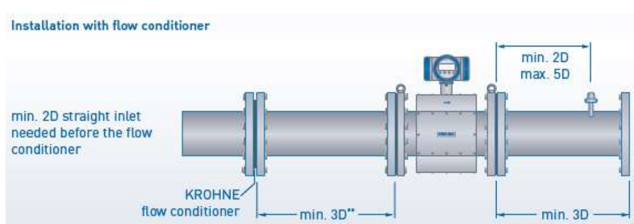

Figure 19 Straight run reduction possibilities with swirl immune designs