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REVIEW OF OPERATION OF ULTRASONIC TIME OF FLIGHT METERS

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SUMMARY

The main objectives of this paper are to review Ultrasonic Time of Flight meter design concepts from a theoretical and practical view point. Reviewed are the basic equations used, a discussion of the signal detection problems, path formations and clamp-on meters and their limitations. The author also discusses some of his experiences with the practical operation of Ultrasonic meters, which while not necessarily directly in the oil and gas industry do highlight the practical difficulties of this type of metering.

1.0 INTRODUCTION

There are a number of very pertinent reasons for the current popularity of Ultrasonic Time of Flight techniques.

> The technique in various forms can be used on both gases and liquids, and in some cases mixtures, dependant on their format and the transducer and signal processing design.
>
> In general they present little or no obstruction to the flow
>
> They can be insertion or under some circumstances clamp-on, non invasive meters.
>
> They can be designed to a variety of specifications and costs, ie the small domestic gas meter costs around $60 with a 2% of range performance, whereas a 12" multi-path Fiscal meter would cost approximately $60000 with a 0.5% of actual flow performance.
>
> Finally the meter physics is such that many improvements in Electronics, particularly speed and processing power impact the performance and cost.

The basic principle for all of the meters described are basically the same, the modification of the time of flight of Ultrasound by the fluid velocity, along the line of the flight path.

2.0 BASIC PRINCIPLES

The ultrasound is usually generated by piezoelectric transducers. The crystals change size when an alternating voltage is applied to the terminal of the piezo material causing it to vibrate at the same frequency as the applied voltage. This produces longitudinal pressure waves in the adjoining fluid. A similar device when subjected to pressure waves has the reverse effect, in that it produces a voltage at the terminals of the piezo material.

The transducers are placed opposite each other, usually but not always, at an angle to the flow, Fig.1.

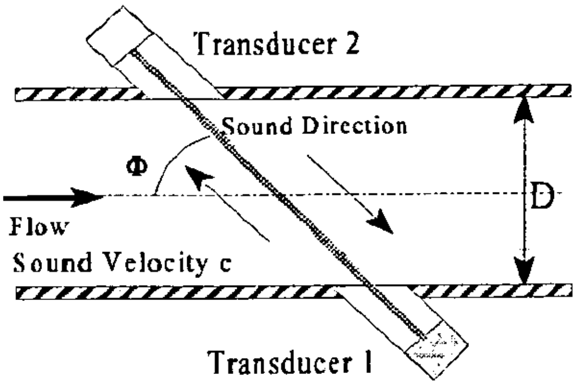

Fig.1 Time of Flight Set-up

The propogation velocity is the sum of the sound velocity, c, and the fluid velocity component in the direction of the transmission path, $v\cos\phi = c +/- v\cos\phi$

The time taken for the sound to travel from one transducer to the other depends therefore on the direction of transmission and fluid velocity and is given by :-

$$T_{12}=\frac{D}{\sin\phi(c-v\cos\phi)}$$

$$T_{21}=\frac{D}{\sin\phi(c+v\cos\phi)}$$

These two basic equations are used in a number of ways to obtain a fluid velocity that is independent of sound velocity.

2.1 SING AROUND (PULSE REPETITION)

This method was used for many years as a way of getting around the problem of the need for high resolution, nanosecond, timing. The basic equations when inverted, form a frequency, that is practically obtained by firing sound from one transducer to the other. When received another pulse is fired, and eventually a repetition frequency is obtained. This is repeated in the oposite direction and in theory the difference in frequency is directly proportional to the fluid velocity. This method is generally not used as the equation should also include the time delay for non-wetted parts and the associated electronics which becomes more significant as the flowrate decreases, causing a large zero offset. For direct timing methods this can be effectively removed.

2.2 DIRECT TIMING

The most common method now is to use direct timing. There are several variations of the above equation that can give flow velocity.

The two most usual forms are :-

$$\frac{1}{T_{12}} - \frac{1}{T_{21}} = \frac{2v\sin\phi\cos\phi}{D}$$

and

$$\frac{\Delta T}{T_{12}T_{21}} = \frac{2v\sin\phi\cos\phi}{D}$$

There are a number of other versions, but these generally contain the velocity of sound, which has to then be removed by some other measurement. **The above equations are essentially independent of velocity of sound, providing that the sound does not change during the flight in both directions**. This usually leads to designs in which the sound is transmitted in both directions at the same time. In both of the above equations the transit time has to be measured, and in the second equation the time difference also has to be calculated.

2.3 PHASE DIFFERENCE METHODS

Phase difference methods are less common than transit time, however there are a number of meters using this method of timing, particularly for "clamp-on" meter design. Instead of direct measurement of the transit time the phase angle of two continuous wave signals is determined. Usually to reduce the power consumption, rather than a continuous wave, packets of continuous wave signals are transmitted and the phase shift measured. In general with this method, the distortion of the signal during transmission is not as important as for the flight time methods, this can be an advantage for clamp-on meters. The measurement method is however fundamentally analogue and is dependant on the velocity of sound, which must be compensated for in the final calculation.

A variant of this type involves keeping the phase constant and vary the frequency, making measurement easier, however, again the velocity of sound of the fluid at rest is required to ensure that the output is directly proportional to fluid velocity.

3.0 SIGNAL DETECTION

The major error in timing derives from detecting the received signal. The transmitted pulse changes its form from the time the electronic pulse is converted into a mechanical pulse in the piezo-crystal. By the time it has reached the receiver it has become a series of pulses, ringing at the resonant frequency of the mechanical system comprising the transducer, its housing and the surrounding fluid, Fig. 2. The envelope of the signal is dependent on the properties and

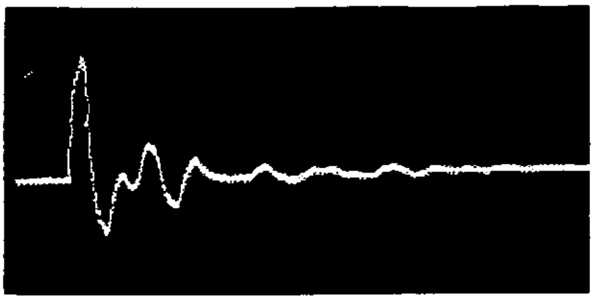

Fig.2a Transmitter Signal

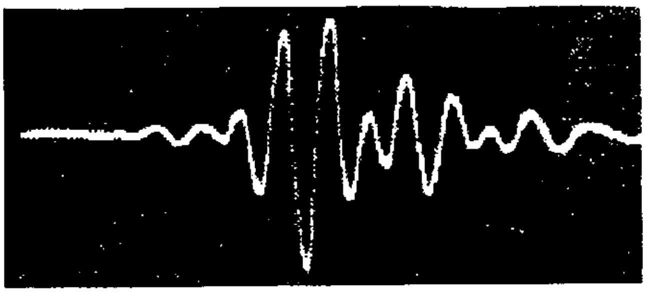

Fig.2b Receiver Signal

acoustic coupling of the various interfaces the signal passes through, as well as the design of the transducers. Generally to retain the shape of the signal the transducer design should have a wide band flat frequency response, as opposed to a high Q, resonant structure. The downside of this design criterion is the loss mechanical signal gain, requiring higher power electroncs. **The signal can be regarded as a gating mechanism to start and stop a timer. Obviously, therefore the rise time and consistency of the transmit and received pulses is essential to the accuracy of the meter**. The essential point of the received signal is the very start of the envelope. If the resonant frequency is, for example, 1MHz and if the measurement was out by half a cycle then the measurement error would be 500ns before any other errors are taken into account. It is, therefore, in the detection and correct identification of the received signal that much of the design work has progressed.

The design and connection of the transducers is critical to the signal quality, and hence the timing. As a rule, transducers for liquid measurement are operated at a higher frequency than for gases. Around 1MHz for liquid and 100KHz for gases, due largely to the impedance matching problems between gas and the transducers. An advantage of lower frequency operation is that the sound will go through most mediums, wheras the higher frequency signal is severely attentuated by gases. To protect the transducers they are normally potted, and often have a protective stainless steel or titanium cover over the face. Often mechanical amplification is used, such as quarter wavelength resonators , to enhance the signal.

The materials and design used are critical in a number of ways :-

> They have to be compatible with the process fluid if wetted. There have been many instances where potted transducers have "dissolved" due to the chemical content of the process fluid. Thus much effort is being put into the development of inert potting materials with the appropriate acoustic properties
>
> An obvious solution is to protect the potting with a material such as stainless steel, this presents two problems, the signal is additionally attenuated and there is always the possibility of the metal diaphragm separating from the potting under the action of temperature changes and the movement of transducers.
>
> The identity and quality of the received signal is very dependant on the stability of the materials used in the transducers. In most cases the action of temperature changes is to change the acoustic properties of the material and the boundaries. To a degree the problem is temperature range, rather than absolute temperature.

One immediate source of error that can be removed is sound either travelling around the pipe,

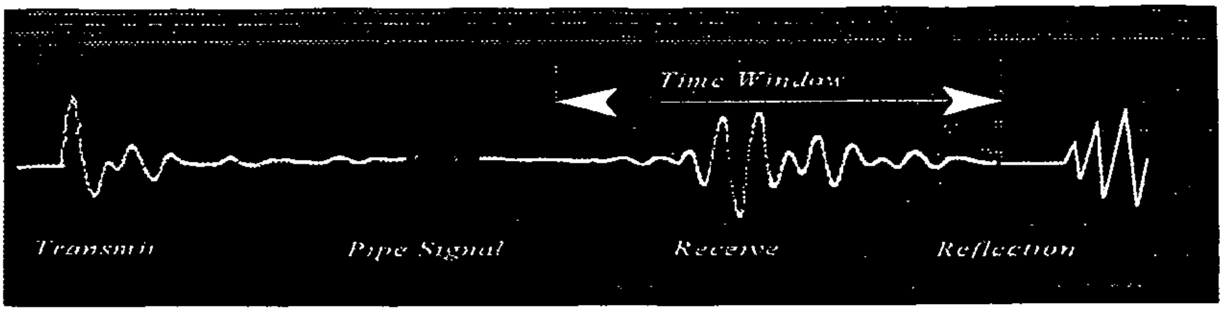

Fig.3 Signal Wndow

or being reflected in the pipe. This is carried out by ensuring that the receiver only scans the data within an expected time window, Fig. 3.

Correct matching of cable impedances and lengths also contributes toward improved performance.

The received signal is very low amplitude and in many cases buried in surrounding noise. Picking out the signal has produced a number of solutions. Essentially the requirement is to be able to ensure that the signal has as little distortion as possible, so that a position, cross-over point or relative amplitude can be chosen that has a fixed relation to the initial received signal point. The methods are either to set an acceptable trigger level and time from the first zero crossing point, or more successfully to chose a series of zero-crossing points on the most stable part of the signal, determine the period and work back to the first crossing. The alternative is to autocorrelate a burst of transmitted signal with it's received signal, and determine the time delay corresponding to the peak of the correlation function. Another method is to ensure that the shape of the received pulse is as stable and identifiable as possible. By careful design and using digital processing techniques this a very successful and reliable method, particularly using digital fingerprinting.

3.1 CLAMP -ON METERS

Obviously from the forgoing it would be expected that the problems of signal detection are made more difficult when transmitting and receiving the signal through a pipe wall. As one of the main features of a clamp-on system is that there is no requirement to cut the pipe to install the meter, the signal is bound by the vagaries of the pipe wall, its material, composition and any material forming on the inside. As the sound is transmitted it undergoes a series of reflections and refractions, shown at its simplest in Fig.4.

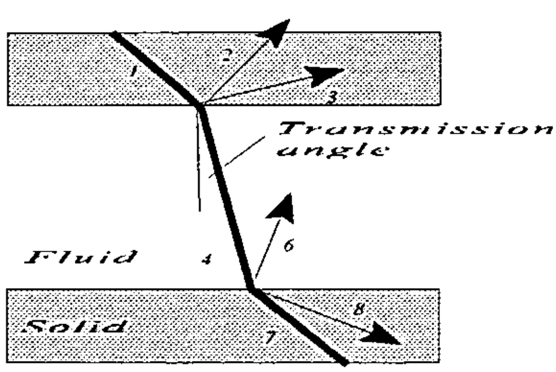

Fig.4 Sound Transmission Through Walls

The diagram describes the path of the signal for a single phase thick walled pipe material. Thin materials for pipe walls may cause waves to form in the pipe walls in plate mode, and longitudinal waves are produced in the fluid. The walls appear transparent to the sound. In the majority of cases the pipe wall is thick walled, and using Snell's law the maximum angle of transmission for different combinations of pipe and fluid materials can be obtained. Typically for stainless steel and water this will be 14.5° for longitudinal waves and 27° for transverse waves. These angles clearly limit the sensitivity of the transit time of flight meter, as the flight time equations show that the difference increases with increased angle. There is therefore often a higher minimum velocity than for wetted transducer meters.
A further problem results from the nature of the pipe material. Many materials attenuate the ultrasonic signal. Further, often there are layers of material that ensure that the signal is either heavily attenuated or is totally reflected.

4.0 VELOCITY MEASUREMENT

Much has been written about the way in which time of flight meters interpret the velocity along the path of transmission, and how this can be developed to produce a volume flow measuring device. In this paper the concepts will only be touched on as a guide to what is possible for practical measurement.
Essentially the final velocity determined along the path of the sound is a line integral of the varying velocities along that path. The beam width will obviously have some influence on the value of the velocities that go towards this final velocity Fig.5.

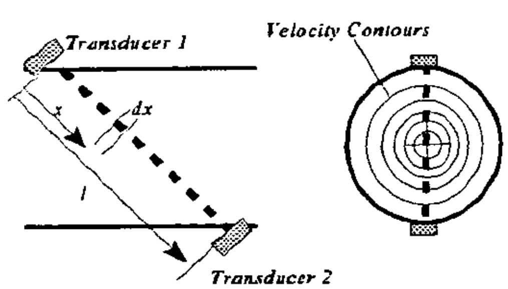

Fig.5 Velocity Averaging

The total transit time is given by :-

$$T_{12} = \int_0^l \frac{dx}{c + v(x)} = \frac{l}{c}\left(1 - \frac{v_{mean}}{c}\right)$$

Where v_{mean} is the average velocity in the direction of the beam along its length. This is not the same as the mean velocity over the complete volume. If as is common place the beam is fired across the centreline then the resultant velocity is weighted towards the centreline, and so reads high, relative to the volume weighted mean velocity. It can be shown theoretically that for a laminar flow the ratio of the ultrasonic mean velocity to the volume weighted mean is 1.33, that is it reads 33% high. For turbulent profiles it is approximately 1.05, that is 5% high dependant

on the profile. It can be shown that is of the order of 1% change per decade in the Reynolds number range of 10^3 to 10^6.
The implications of this are that the single path meter is not only installation dependant but has to be corrected for profile under ideal conditions if a reasonable level of uncertainty is to be maintained. The possible effect of installation is admirably demonstrated by the use of an eccentric orifice as the flow disturber, Fig .6. The effect on the calibration depends on the plane of the beam relative to the profile.

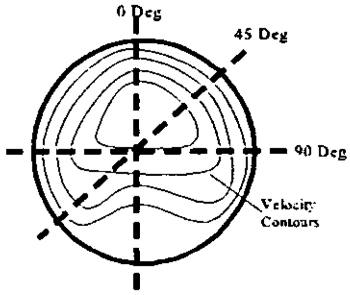

Fig.6 Path Positions

The changes in reading from the calibration under fully developed flow conditions are:-

0° -------- 16.3%
45° -------- 10.3%
90° -------- 5.2%

Detailed data is available for different combinations of installations in the list of references. The point at issue is that for single path meters, care must be taken with installation in relation to the fittings, further for gas measurement where the pipe is large it is common practice to fire the sound across an offset chord. There is data for the effect of installation on this method, but it is not as well documented as the centreline chord.
One method available to alleviate the effect of swirl flow is to reflect the signal from the opposite wall, the effect of rotational flow on the initial path is largely cancelled out on the reflected path. **The effect of distorted flow profile is not however removed**.

4.1 MULTI-PATH METERS

As with single path meters there are now a very detailed papers describing the basic concepts of the various multi-path meters. It is interesting that much of the basic data has been available for many years, the Westinghouse multi-path meter was successfully tested in 1970, and shown to have considerable benefits with regard to installation. Only in the last 10 years has technology caught up enough to make such meters a viable proposition.
There are currently two methods employed which take a fundamentally different approach to the problem of multi-path metering, both are shown in Fig.7. The more conventional approach is to use chordal paths, the positions of which are either obtained by experiment or by giving weighting factors to the various paths using a numerical quardrature method to obtain the least variation of calibration for a number of theoretical profiles. The other method is to use a series of paths, which by a combination of reflections can determine individual features of the flow.

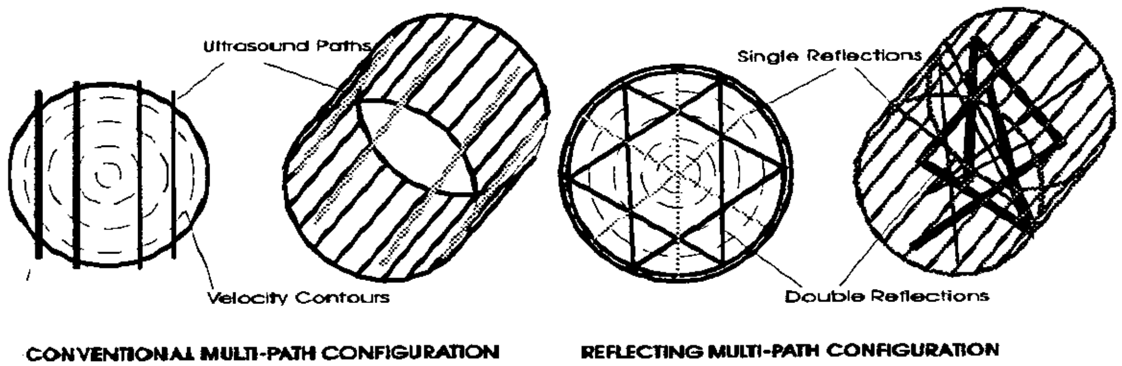

Fig. 7 Different Types of Multi-Path Configurations

For example the degree of swirl and the asymmetry can be estimated as a contribution towards the final answer.
Both methods have currently have their advantages and disadvantages:-

Method	Advantages	Disadvantages
Chordal	The information Required about the flow profile is fixed The weighting factors are fixed, reducing the computational requirements A loss of a path is easier to compensate for	The flow velocity is assumed as axi-symetric Additional information with regard to the flow is lost As the profile deviates from the theoretical errors occur
Reflecting	The close spacing of the paths gives high cross sectional coverage Measurement is insensitve to orientation for single phase fluids Paths are generally longer making timing resolution better More detailed data available for assessing the meter uncertainty	Much harder to manufacture Needs continuous update of algorithms for flow computation At present loss of certain paths causes larger uncertainties Concern over the reflection remaining stable in operation

In the following papers there will be a large amount of data provided on both meters for gas measurement. It is not clear whether it is possible to use reflecting methods for liquids successfully, as the acoustic mis-match between the liquid and the wall is generally low, thus reducing the reflectivity of the signal. Data shows that for small liquid meters there is an optimum design of two path chordal meter, that significantly reduces the effect of installation, although such a meter would struggle to meet fiscal levels of metering.
It worth making the point that the multi-path meters do have the possibility, particularly the reflecting path meters, of being true "smart" meters. It is feasible that in combination with such technology as neural networks that the meters can start to learn about the flow and improve with time. Further it very feasible to produce a meter that can give a good running estimate of its own uncertainty.

5.0 SOME PRACTICAL OPERATIONAL ASPECTS

The comments in this section are divided into application areas, with some notes from the authors experience on possible problems.

5.1 CLAMP-ON METERS

As previously described, clamp-on meters are generally used for liquid measurement either as a permanent installation or as a check meter.
Recently the author performed a series of eight meter checks of magnetic flow meter installations using a commercial clamp-on meter. It is probably one of the best designs, but of the eight installations only three worked fully and one intermittently. Two that worked well were with single phase plastic and the other a new steel pipe. An old cast iron pipe gave some results after thorough cleaning of the outer surfaces. The other pipes, multi-phase pipes with a liner and possibly internal build-up gave no results at all. The software was designed to cope with multi-phase materials, but no signal was ever found. Where results were obtained the best correlation obtained was of the order of 5%, with the magnetic flow meters. The errors in measurement of this type are very clear, the major uncertainty is usually the pipe diameter, which doubles when applied to volume. Practically, particularly within the confined spaces often available installation of the clamp-on meter is difficult to achieve with any degree of accuracy, in fact it was almost impossible to install single handed, with the problems of putting on the acoustic couplant, lining up the transducers and tightening them up.
With permanent installations life is marginally easier, as you can generally get someone else to install it. There are still a number of points of which to be aware :-

Always check the sound will go through the pipe walls and fluid before purchasing.
Do not assume that two nominally similar installations will work
Check that during operation the acoustic couplant does not deteriorate with time
For an uncalibrated installation the diameter of the calibration section can represent a large error

All of the above the author has encountered in recent audits of clamp-on installations. There is also a temptation, because of the theoretical ease of installation to mount the meters without regard to flow profile.
The uncertainty of clamp-on meters can be improved by on-site calibration, although for single path meters the calibration should be over the operational raqnge. Under such circumstances the good repeatability of the meters will give favouable results.

5.2 FLARE/ FLUE GAS METERS

The ultrasonic time of flight meter is almost the only meter capable of reliably metering Flare gas, there are however several problems encountered by the author for which potential users should be aware. Generally the gas for Flares is operating at a relatively low pressure. It becomes more difficult to send sound into the gas as the pressure reduces. This can be made worse if there is a large quantity of Carbon Dioxide present which attentuates signal. In several cases investigated by the author the presence of CO_2, has effectively killed the application. Sometimes it is possible to reduce the distance between the transducers by insering them into

the flow. This is done, however, at the cost of uncertainty, as the knowledge of the relationship between the path velocity and the fluid velocity is often unknown.
A further problem encountered is the presence of noise. This is a problem throughout Ultrasonic metering, particularly noise produced by fittings, such as pressure reducer valves that is in the frequency range of the transmitted ultrasound. This can effectively "kill" the received signal.

5.3 LIQUID METERS

In general high performance liquid meters have taken longer to achieve their full potential than Gas meters. This is due probably to the operational problems encountered when moving away from water measurement. Water is a relatively continuous medium, and does not in general carry gas, air, mixed in the fluid for very great distances. Oil on the other hand does form easily into emulsions of gas and liquid, which are almost impenetrable to sound. It has been the authors experience that the most destructive mixture of gas and liquid is the presence of contiuous small particles of gas, causing "Rayleigh" scattering.

5.4 REFERENCES

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