# Paper 10

# The Transit Time Difference Ultrasonic Gas Meter - A Reassessment

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# The Transit Time Ultrasonic Multi-path Gas Meter
# A Reassessment

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## INTRODUCTION

When fiscal ultrasonic gas meters first came to market, about 1988 (Ref 1), they held great promise with claims like:
1) No moving parts. 2) No obstruction to the flow. 3) No pressure loss. 4) No calibration required. 5) Large turndown ratio. 6) Bi-directional flow measurement. 7) Velocity measurement independent of gas properties. 8) Installation requires minimal pipe work. 9) No periodic maintenance required. 10) Long life and stability.

It seems appropriate after 15 years to pose the questions - Have these promises been fulfilled? – Have other advantages been found?

## FLOW METERS

The ultrasonic meter is not a bulk flow meter, in the sense of current fiscal meters like the orifice and turbine, but rather a sampling device. With bulk meters all the flow passes through the sensing element to produce a signal related to the total flow; differential pressure for the orifice, and angular velocity for the turbine. The ultrasonic meter samples the velocity on several discrete chords. To obtain the bulk flow requires additional information about the location of the samples and a suitable integration technique, adding further uncertainty from three sources instead of just one. The sample is taken with a very sensitive ultrasonic pulse and is the reason for the relatively poor short-term repeatability (0.2%), because the pulse responds to the turbulent fluctuations in the flow. With a turbine meter all the flow is accelerated through the rotor, which also has inertia, to give much better repeatability (0.02 – 0.05%).
One might question whether the ultrasonic meter was such a good idea. However, remember there is no perfect way of measuring flow rate; otherwise such a large variety of meters would not exist. All meter selection requires compromise to best fit the particular application. The ultrasonic meter has the immediate advantage of 1) No moving parts, 2) No obstruction to the flow, 3) No pressure loss, 6) Bi-directional flow measurement, 9) No scheduled maintenance required, and potentially other benefits over the turbine meter.
A common way of classifying flow meters is either as “energy extractive “or “energy additive”. The orifice and turbine are energy extractive, while the ultrasonic is energy additive. The energy extractive meters have problems at low flow, because there is too little energy to generate a reliable signal. The ultrasonic meter adds the same energy at all flow rates to overcome this problem and does better at low flows. This improves turn down, because getting closer to zero flow approaches an infinite turn down. Much higher flows are also possible because there is no obstruction or pressure loss. Thus achieving 5) Large turndown ratio.

## METER DEVELOPMENT

The first commercial meter was from Daniel (Ref 1 & 2) with 4 chordal paths, next came Instromet (Ref 3) with 5 bounce paths, FMC (Ref 4) with 6 chordal paths, and most recently ABB (Ref 5) have returned to 4 chordal paths. Not only has the number and arrangement of paths changed, but so has the basic concept. From making the meter itself less sensitive to profile effects, to measuring swirl and asymmetry and using them in an effort to improve the flow measurement accuracy.

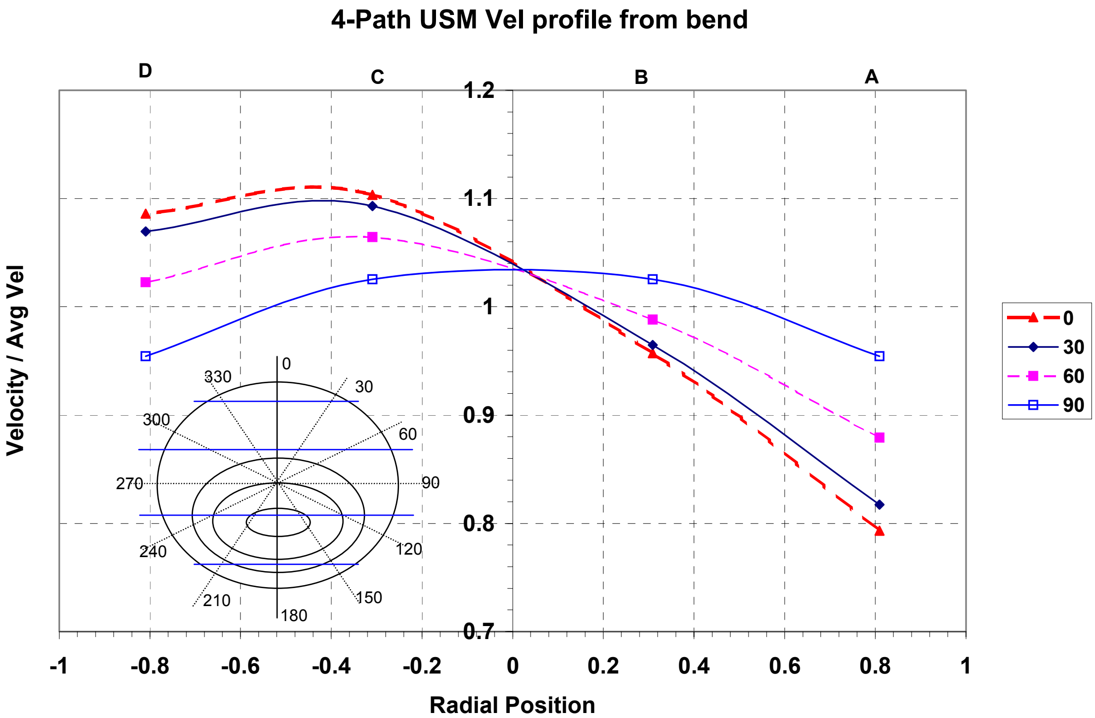
Liquid ultrasonic meters have been around much longer than gas ultrasonic meters, mainly because of simpler transducers. It is relatively easy to couple a piezoelectric crystal to a liquid, but not to a gas. Gases have very much lower acoustic impedance ($z = \rho c$) than liquids, and furthermore it changes with the gas pressure (density $\rho$). Westinghouse made some important contributions to liquid meters that are valid for gas meters. In 1971 (Ref 6) they introduced the idea of multi-path meters, and in 1976 (Ref 7) proposed accurate numerical integration techniques to obtain the average pipe flow velocity $\bar{V}$ from the chord velocities $V_i$. They give the radial position of the chord $X_i$ and a weighting factor $W_i$ to use in the numerical integration $\bar{V} = \sum V_i W_i$. It is interesting to recall the Westinghouse values for 2, 3, 4 & 5-path chordal meters:

| | Radial Position | | Centerline | Radial Position | | Sum Wi |
|---|---|---|---|---|---|---|
| X2 | | 0.5000 | | -0.5000 | | |
| W2 | | 0.5000 | | 0.5000 | | 1.0000 |
| | | | | | | |
| X3 | | 0.7071 | 0.0000 | -0.7071 | | |
| W3 | | 0.2500 | 0.5000 | 0.2500 | | 1.0000 |
| | | | | | | |
| X4 | 0.8090 | 0.3090 | | -0.3090 | -0.8090 | |
| W4 | 0.1382 | 0.3618 | | 0.3618 | 0.1382 | 1.0000 |
| | | | | | | |
| X5 | 0.8660 | 0.5000 | 0.0000 | -0.5000 | -0.8660 | |
| W5 | 0.0833 | 0.2500 | 0.3333 | 0.2500 | 0.0833 | 1.0000 |

Note that $\sum W_i = 1$ for all path locations. This is important because $W_i$ can be interpreted as the area associated with $V_i$ and the total area = 1. In addition if the velocity is uniform $V_1 = V_2 = V_i = V$ ($Re \rightarrow \infty$) then $\sum V_i W_i = V \sum W_i = V$, giving the correct answer.
Note that all the paths are symmetrical about the center, and with an odd number of paths (3 & 5) one path is on the centerline. The centerline path reads about 5% higher than the average flow velocity (Ref 8), because the line integral is larger than the area integral. Another disadvantage with the centerline path over reading is that other paths must be closer to the pipe wall to compensate: the 3-path meter is at 0.7071 compared to 0.500 for the 2-path, while the 5-path meter is at 0.8660 compared to 0.8090 for the 4-path. Close to the wall is good for the integration but not for the acoustics, due to shear, turbulence, refraction and reflection. Another advantage of the 4-path meter is that the inner chord velocity is above the average (1.042), while the outer chords are below the average (0.89), allowing better compensation for asymmetry. Hence British Gas (BG) considered the 4-path meter to be the optimum design.

Westinghouse had all 4-paths in one plane, BG alternated them in two planes at right angles, to improve performance in cross flow (Ref 8), FMC doubled up on two paths, to improve performance in swirl (Ref 4), While ABB reverted to the original Westinghouse design. All these designs are aimed at locating the paths and assigning weights to achieve immunity to disturbed flows and are reasonably successful (Ref 1, 4, 5 & 8). There have been some recent attempts to further improve the integration (Ref 9), lending credence to claim 8) Installation requires minimal pipe work.

Patent 5,546,812 (Ref 3) took an alternative approach; it does not use the Westinghouse direct chordal paths, but bounce (reflective) paths from the pipe walls. The paths are arranged to measure asymmetry and swirl. It is assumed that with this knowledge of asymmetry and swirl it is possible to make a more accurate flow measurement even in disturbed flows without any flow conditioning. The difficulty with this approach is that it demands an intimate knowledge of fluid mechanics, or limitless experimental data, to succeed in every conceivable disturbed flow. To illustrate the dilemma, we show the velocity profiles when a Daniel 4-path meter is rotated relative to an asymmetrical flow profile Each profile is different, yet the bulk flow is the same, so how would one adjust the integration of each profile to yield the same, but better answer? This seems unnecessary when the Westinghouse integration gives less than 0.2% variation in all these cases.




Others (Ref 10, 11 &12) are recommending the use of flow conditioners.

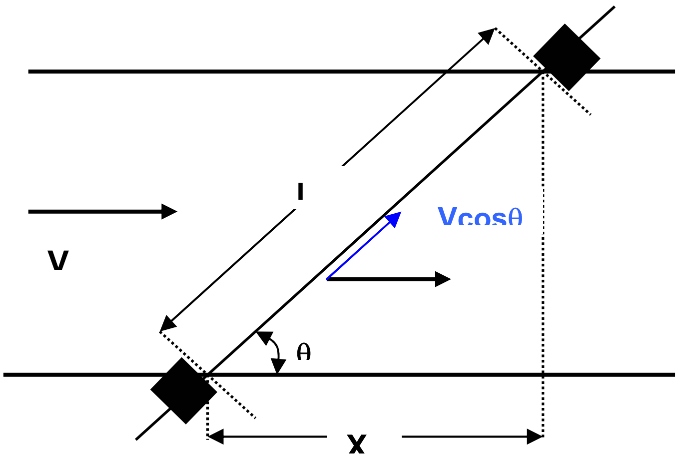
The current trend to use flow conditioners to correct profile effects and not rely on the meter has the disadvantage of introducing loss and obstruction, loosing claims 2) & 3), and casting doubt on claim 8). If a flow conditioner must be used, more advantage would be gained using it additionally as a check meter (Ref. 13), by measuring the differential pressure across the flow conditioner.

Another design trend, (Ref 10 & 14), is to place the USM at the throat of a Venturi, using the acceleration as a flow conditioner. Thus further suggesting that flow conditioning is necessary.

Some more fundamental difference between direct chordal paths and bounce paths are that the pipe wall becomes part of the bounce path; the bounce path length is difficult to measure directly, and the bounce path cannot detect thermal stratification. Another problem with centerline bounce paths is that they read high (1.05), so need correction even in ideal flow. The centerline path can only be corrected with a Reynolds number in ideal flow, but not in disturbed flow, another reason for needing a flow conditioner.
A more recent development is the use of clamp-on transducers, but these can only fire through the centerline and suffer from the same problem of reading 5% high in good flow and being poor at compensating for distorted flow profiles. Daniel offers centerline bounce paths, but not for custody transfer applications.

## THEORY

The simplest theory assumes the acoustic path is the geometric path directly between the transducers.




Where:
L = distance between transducers
X = axial distance in the flow
θ = angle of path to the flow
Cosθ = X/L
C = speed of sound SoS
V = velocity of the fluid
$\Delta t = t_1 - t_2$

We can then write equations for the transit time of an ultrasonic pulse $t_1$ against the flow and $t_2$ with the flow:

$$t_1 = \frac{L}{C - V\cos\theta} \quad or \quad C - \frac{VX}{L} = \frac{L}{t_1} \qquad \text{Eq. 1}$$

$$t_2 = \frac{L}{C + V\cos\theta} \quad or \quad C + \frac{VX}{L} = \frac{L}{t_2} \qquad \text{Eq. 2}$$

There are two equations and two unknowns C & V, as L & X are fixed geometry, and the meter measures the transit times $t_1$ and $t_2$, so they can be solved:

$$C = \frac{L}{2}\frac{(t_1 + t_2)}{t_1 t_2} \qquad \text{Eq. 3}$$

$$V = \frac{L^2}{2X}\frac{(t_1 - t_2)}{t_1\, t_2} = \frac{L^2}{2X}\frac{\Delta t}{t_1\, t_2} \qquad \text{Eq. 4}$$

Eq. 4 shows that the velocity V is independent of the speed of sound C. It is C that depends on pressure, temperature and gas composition. So this justifies claim 7) Velocity measurement independent of gas properties.

Eq. 4 also shows that $V \propto \Delta t$, the basis of a linear transit time ultrasonic flow meter.

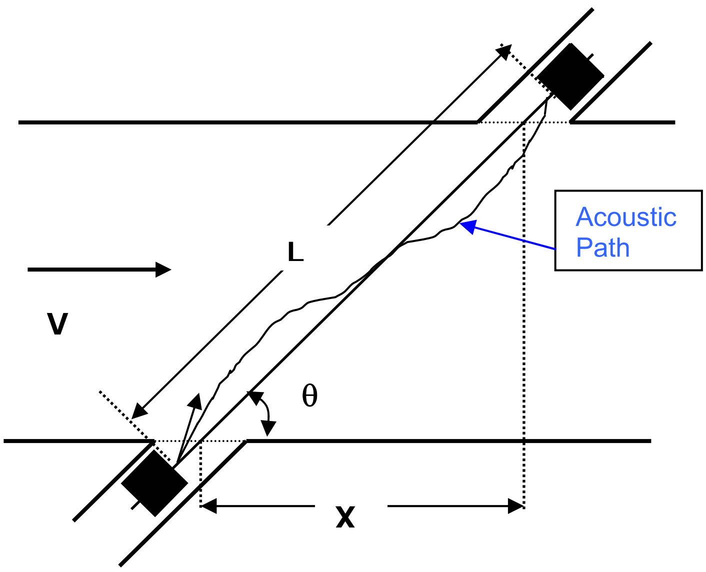
Eqs. 3 & 4 can be combined to give some useful information:

$$V = \frac{L^2}{2X}\frac{\Delta t}{t_1\, t_2} \approx \frac{C^2 \Delta t}{2X} \quad or \quad \Delta t \approx \frac{2XV}{C^2} \qquad \text{Eq. 5}$$

Eq. 5 shows that an error in C of say 0.1% will give an error of 0.2% in V.

A common misconception is that a long path L gives a larger transit time t and hence improved accuracy. However, Eq. 5 shows it is X that generates Δt, and not L. Providing the timing resolution is sufficient for Δt, more length will not improve the accuracy.

The simple theory is obviously incorrect, as a pulse traveling directly to the other transducer would be swept downstream by the flow. To get there it must head off into the flow at a steeper angle than the direct path. Another problem is that the transducers are normally recessed in a port. Both of these concerns are addressed in ISO TR 12765 (Ref 15)

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Eq. 4 for the velocity is still correct when using the same definition of L & X, with the assumption that there is no flow in the transducer port recess.
The derived speed of sound has a correction (from Eq. 3) for the actual acoustic path length

$$C = \frac{L}{2}\frac{(t_1 + t_2)}{t_1 t_2}\left[1 + \frac{M^2}{2}\frac{X^2}{L^2}\tan^2\theta\right] \qquad \text{Eq.6}$$

Where M = V/C = the Mach number. For M = 0 this reverts to Eq. 3, which is a reasonable approximation for low M.

The speed of sound can be calculated from gas composition, pressure and temperature using AGA 10 (Ref 18) to about 0.1%, and compared with that measured by the meter. This can confirm that the meter is making a reasonable measurement of L & t. However this does not ensure such a reasonable measure of V (0.2%). Taking for example a 12" meter with t = 1000 μs, then 0.1% in C is 1 μs. However there is no guarantee that the much smaller Δt (Δt = 50 μs at 50 ft/s) is measured accurately. Further more, the speed of sound (Eq. 3) does not check the value of X, which appears in Eq. 4 for the velocity.

It is quite common to hear that the calculated speed of sound can check the stability of the clock (Ref 12). However the accuracy of C is 0.1% while the stability of a crystal clock is typically 10 - 100 ppm. Further more, if the same clock is used to measure the velocity (V = L/t) and to integrate the volume Q = ∫A*Vdt, then any drift in the clock cancels. If a separate flow computer is used for the volume integration then the accuracy of both the meter and computer clocks matter.

The meter measures Velocity = Length/Time, where length and time are fundamental units, but this does not automatically allow them to be measured very accurately. We know the distance between the transducers L, but not the actual acoustic path length. The distance X is difficult to define, because the transducer is not a point source, and difficult to measure directly. When measuring time it is not obvious where to stop the clock, especially when the signal becomes distorted, and the actual time spent by the ultrasonic pulse in the gas is not measured directly by the electronics. Several corrections are made to account for these effects, but it is doubtful that they could achieve 0.5 % uncertainty, loosing claim 4) No calibration required. However, when this claim was first made in 1988 BG was aiming to achieve 1.0 % uncertainty.

Another point often made is that the $t_1$ and $t_2$ measurements should be simultaneous, or at least in rapid succession, to avoid changing conditions. This leads to practical problems because each transducer has to switch rapidly from transmit to receive mode, and is likely to still be ringing from the transmit pulse while trying to receive the next signal. We can show that this is not necessary by considering Eqs. 1 & 2 with velocity $V_1$ during $t_1$ and $V_2$ during $t_2$, then Eq.2 – Eq.1 gives:

$$V_2 \frac{X}{L} + V_1 \frac{X}{L} = \frac{X}{L}\left(V_2 + V_1\right) = \frac{L}{t_2} - \frac{L}{t_1} = \frac{L\left(t_1 - t_2\right)}{t_1\, t_2} = \frac{L\Delta t}{t_1\, t_2} \qquad \text{Eq. 7}$$

So $$\frac{L^2}{2\,X} \frac{\Delta t}{t_1\, t_2} = \frac{\left(V_2 + V_1\right)}{2} = \overline{V} = \textit{The Average Velocity} \qquad \text{Eq. 8}$$

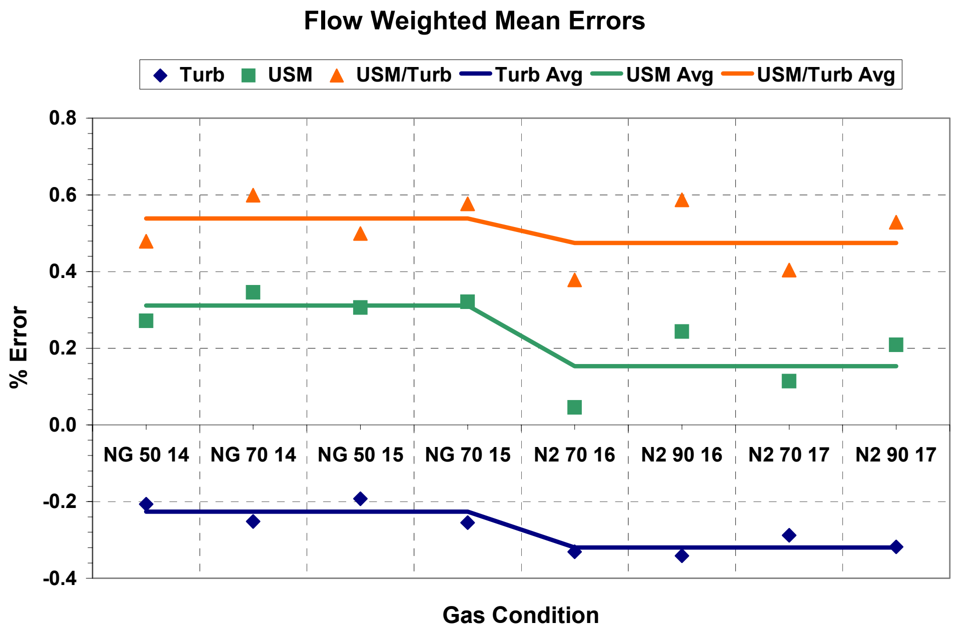
Thus if the velocity is changing during the upstream and downstream transit time measurements, the meter actually measures the average velocity, which gives the correct answer for flow measurement. This gives complete freedom of choice for the transducer firing sequences, allowing optimization of batch processing times, and reduction of noise.

## CALIBRATION

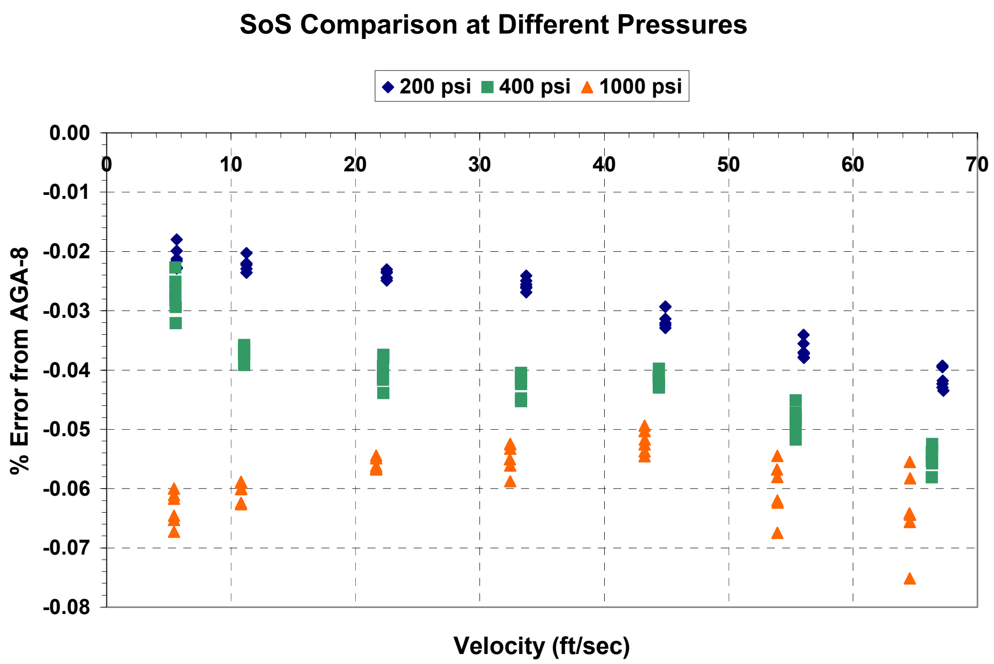
Early meters claimed about 1% uncertainty without calibration. Because of the value of natural gas passing through large high-pressure meters, present fiscal demands are closer to 0.1%, which cannot be met without calibration. However large high-pressure gas calibration facilities can only achieve 0.2 – 0.3% absolute uncertainty. There is a current debate on whether other gases and lower pressures could be used to calibrate meters. Recent work on using air or nitrogen (Ref. 5, 16 & 17) has shown that this might be possible, but some doubts remain about "pressure or gas effects".
For example with the nitrogen/natural gas tests (Ref 16.) Some results are shown for the calibration of a 12" USM in series with a 12" turbine meter against a reference bank of sonic nozzles. The key to the Figure is:
N2 = nitrogen, NG = natural gas, 50-70-90 = Temperature $^{o}$F, and 14-15-16-17 = day.

The USM shifts 0.2% from NG to N2 when compared to the sonic nozzles, which provide a mass flow reference.
The Turbine meter shifts 0.1% from NG to N2 when compared to the sonic nozzles
The USM shifts 0.1% from NG to N2 when compared to the Turbine, where both meters respond directly to the actual volume flow.
It is also notable that the day-to-day repeatability is ~0.1%, the temperature effect is ~0.1% and the uncertainty of the reference sonic nozzles is ~0.2%.

So it is reasonable to conclude that there is no significant gas effect.

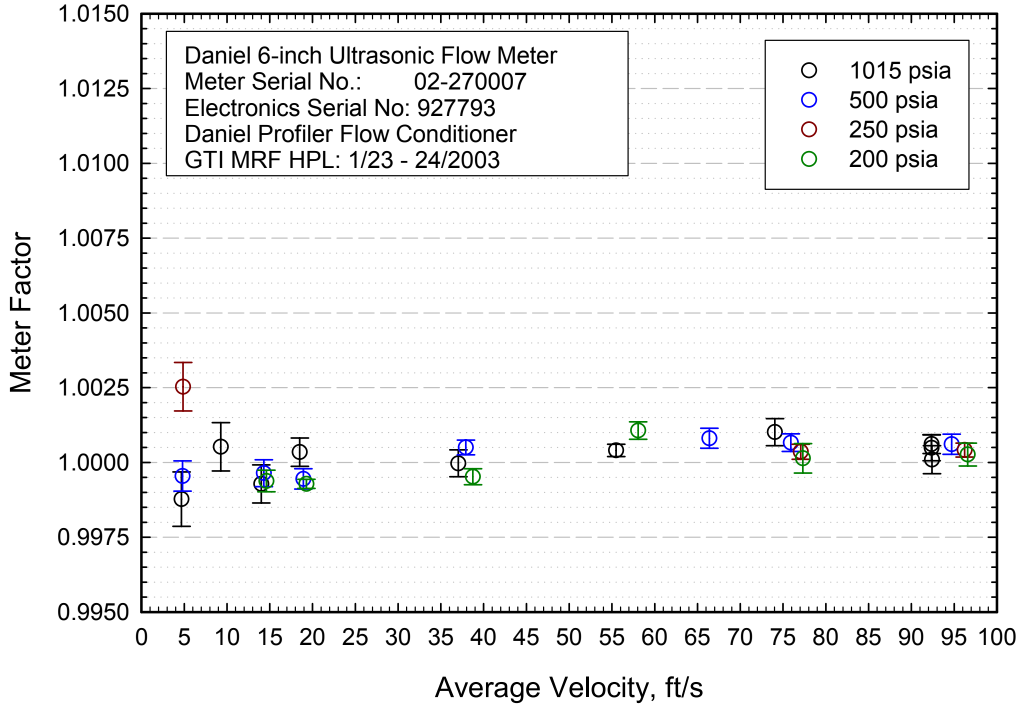


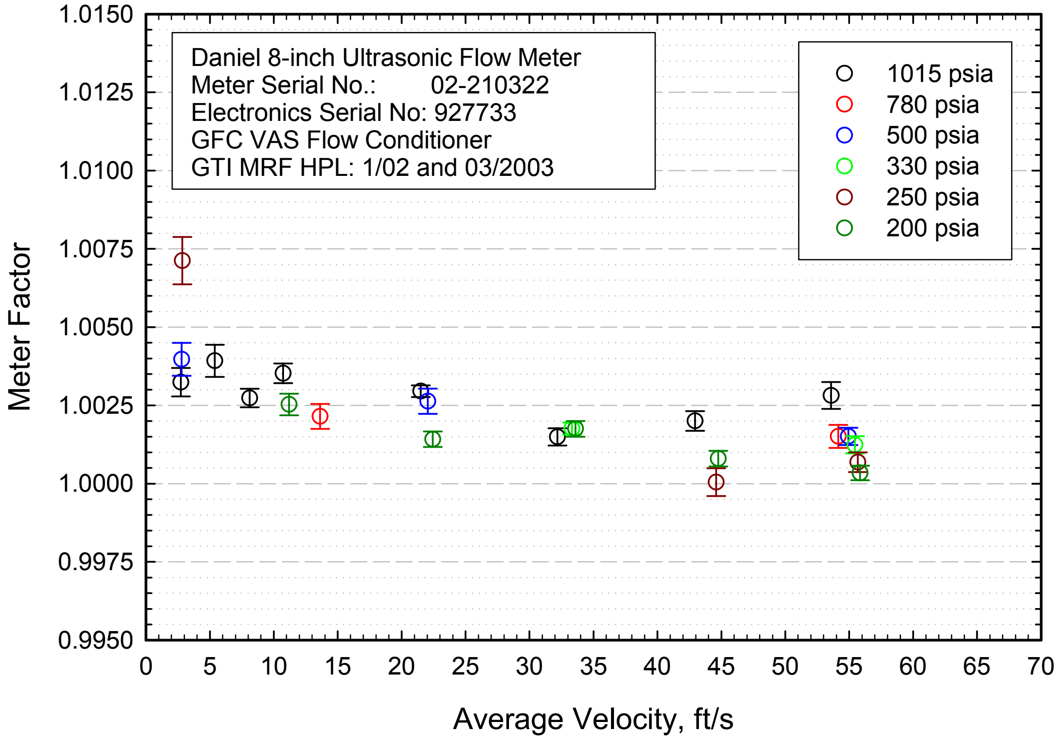

There have been conflicting reports of pressure effects on meter accuracy.
However, during these tests the speed of sound measured by the USM was compared with that calculated using AGA 10:




. While the calibration showed 0.3% shift the SoS shows only 0.03%, an order of magnitude less, and well within the 0.1% accuracy of the calculation. This indicates that there is nothing wrong with the basic transit time measurement.

Recent tests with an 8” & 6” USM, found very small (<0.1%) pressure effects and they were in opposite directions for the two meters. This again shows that there is no pressure effect.



These “pressure and gas effects” fall within the uncertainty of the lab (0.2 – 0.3%), and much recent work (Ref. 5, 16 & 17) has shown that it should be possible to calibrate with different fluids and pressures. The advantage of nitrogen over natural gas is that the properties are less variable and better known and should thus improve accuracy. Together with reduced pressure they should reduce cost, thus making research economically attractive.

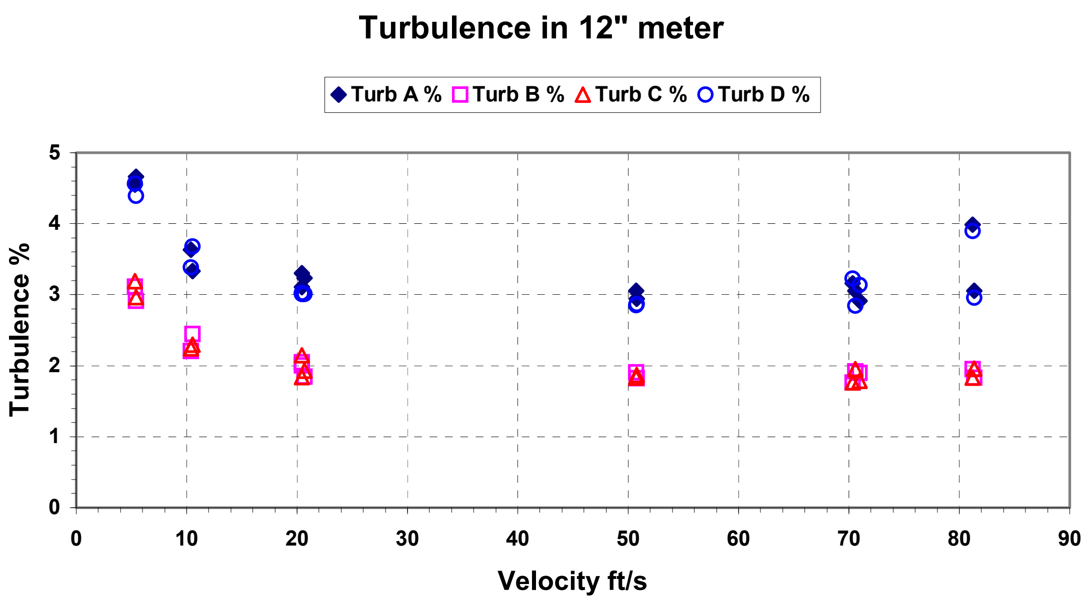
## DIAGNOSTICS

One advantage of the meter that was not recognized early on, and has not been fully exploited, is its diagnostic ability. As a sampling device it produces an abundance of data, which can be converted into useful diagnostic tools (Ref 19). This could then lead to conditional maintenance and re-calibration, instead of relying on routine maintenance and statutory re-calibration intervals.

Repeatability and sampling were considered a disadvantage of the ultrasonic meter over the turbine meter. However, the ability to measure turbulence and use it as a diagnostic is more important than the short term repeatability, which is not relevant for hourly, weekly, monthly or yearly totals. It is the sampling that yields the diagnostic data, which is an advantage over a bulk flow meter that has a single output.

If all the internal diagnostic parameters are normal, one can have complete confidence that the meter is working correctly. This confidence is very important, because one can then look for external problems in other parts of the metering system. Typically distorted velocity profiles, pulsating flow, temperature stratification (at low flows) and noise.

Typical turbulence levels for good flow are shown below

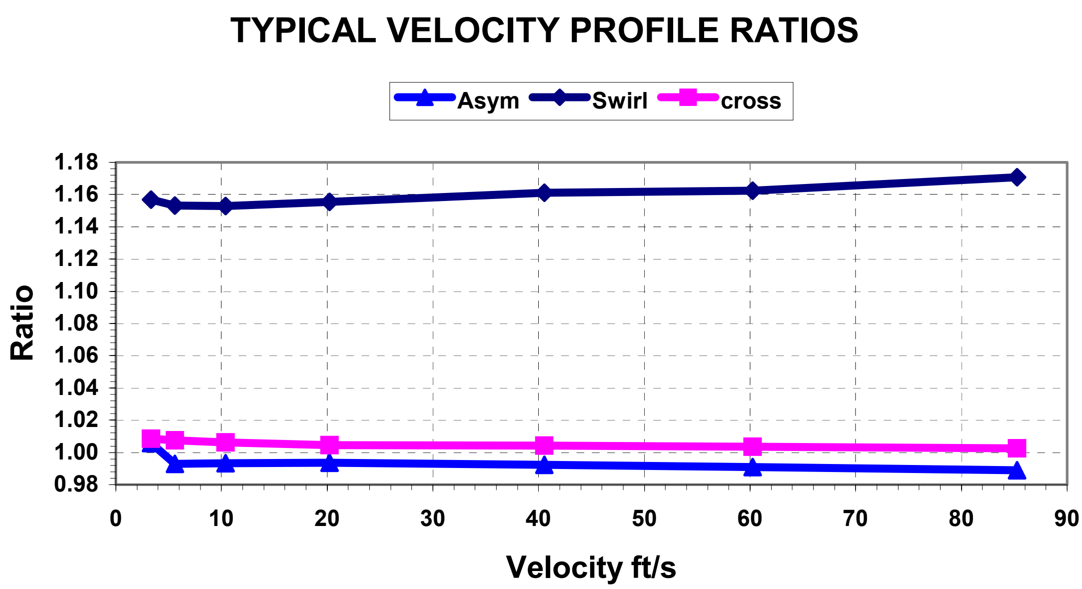


Variations in flow, fluctuations and pulsations will increase the turbulence level.

The meter compensates for asymmetry, cross flow and swirl, but it can also measure them. The four chordal velocities give an indication of the velocity profile in the meter, established by the flow through the upstream pipe work. Three helpful ratios can be defined as: **Asymmetry = $(V_A + V_B)/(V_C + V_D)$, Cross flow = $(V_A + V_C)/(V_B + V_D)$** and **Swirl = $(V_B + V_C)/(V_A + V_D)$.** The **asymmetry** compares the flow in the top half of the pipe with that in the bottom half; in good conditions it should be close to 1. The **cross flow** compares the chords in one plane with those in the other plane at right angles: in good conditions it should be close to 1. The **swirl** compares the inner chords to the outer chords and it is an indicator of swirl due to both the different radial locations and planes. In good conditions the **swirl** should be close to 1.042/0.89 = 1.17

In general, four paths are not sufficient to resolve any arbitrary 3-dimensional flow field containing asymmetry, swirl and cross flow. However, fiscal flow measurement practice attempts to establish good flow conditions, which can certainly be verified by these ratios. Never the less, if the ratios differ significantly from their ideal value they can give a reasonable indication of the type of disturbance, especially if only one of the ratios has changed significantly.

Actual measured ratios are shown for a 20" meter.




Because of tolerances in the manufacture of the ultrasonic meter and the difficulty of achieving ideal fully developed flow, the actual ratios are never exactly at their theoretical values, and give the meter a unique fingerprint. However they are usually within ±2%, which is sufficient to say that the flow profile is near perfect, which is not surprising since this example came from a lab calibration.

If a meter fails, the diagnostics can quickly reveal the problem, which then leads to a solution.

The range of decline between perfect performance and complete failure is more difficult to quantify. Trending the diagnostic parameters will certainly show if changes are occurring, but knowing how much change is tolerable, before intervention is necessary, is at present very much a judgment call. However, this leaves ample scope to improve diagnostics in the future, to make them more user friendly, and apply them to automatically self tune the meter for optimum performance.

**OTHER ADVANTAGES**

The high flow capacity, large turndown, lack of pressure loss, no moving parts and small foot print make ultrasonic metering systems very attractive economically for both low capital and running costs.

The ultrasonic meter is considered the most accurate gas meter especially when handling large flows of high-pressure natural gas. Because of the value of the natural gas, the meters are calibrated in facilities with an uncertainty of typically 0.2 – 0.3%. Performing a 10-point calibration and using piece wise linearization to maximize the value of the calibration can further enhance the accuracy.

The diagnostic ability of the meter can check that the calibrated accuracy is being maintained in the actual field application.

**CONCLUSIONS**

Of the original ten promises four remain unchallenged: 1) No moving parts, 5) Large turndown ratio, 6) Bi-directional flow measurement, 9) No periodic maintenance required.

For the other six we can say:

4) No calibration required, was associated with an acceptable 1% accuracy in 1988. Today with the expectation closer to 0.1% accuracy, calibration is necessary.

2) No obstruction to the flow, 3) No pressure loss; have been lost by insisting on using flow conditioners. Not all ultrasonic meters and not all applications require a flow conditioner. The user could benefit by being more selective.

8) Installation requires minimal pipe work. This has also been negated by the use of flow conditioners, but again it is not necessary with all ultrasonic meters. Some of the first ultrasonic meters were supplied to offshore platforms because of space limitations.

7) Velocity measurement independent of gas properties. Some work with different gases and pressures has raised questions. But the most recent work shows that 7) is basically true. This holds out the possibility that a low-pressure nitrogen or air calibration might be more accurate and certainly less expensive than a high-pressure natural gas calibration.

10) Long life and stability. This is still an open question as not many meters have been re-calibrated, but preliminary results are encouraging. The transducers can still be a limiting factor with extremes of pressure, temperature and corrosion.

Meter concept and design does affect performance, all ultrasonic meters are not created equal.

We have challenged some commonly held USM myths:

Increased path length improves accuracy.
SoS can check the clock stability.
Velocity = L/t, as L & t are basic units, they can be measured very accurately.
$t_1$ and $t_2$ should be measured simultaneously or in rapid succession.
High-pressure natural gas calibration is essential.
Flow conditioners are always required.

Other advantages of the ultrasonic meter that have become recognized are high accuracy and low cost.

The full benefits of meter diagnostics have still to be realized, and no doubt this will be where future efforts are focused.

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