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ULTRASONIC DOMESTIC GAS METERS – A REVIEW

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Abstract: *There are many designs of ultrasonic domestic gas meters but all the main ones use the measurement of the transit time of an ultrasonic signal through the flowing gas to estimate its velocity. The shape of the duct and devices to control the waveform of the signal passing through it are significant parts of the design. The transducers used to produce the signal, reciprocal operation and the main techniques to time the transit of the signal to several nanoseconds are discussed. The acceptance of these meters has been restricted and their possible future is discussed.*
Keywords: ultrasonic, domestic, gas, meter, flow, transducer, transit time, reciprocity

1 INTRODUCTION

The purpose of the domestic gas meter is to charge the customer for heat used and this is done by assuming that this is proportional to the quantity of gas used. The best measurement of quantity is mass, but as mass is difficult to measure for gases, the volume has been the traditional quantity metered. Sometimes temperature corrections are made but not pressure, except in an average way. The usual meter uses a bellows that fills and empties to achieve a measurement of flow rates from a pilot flow of 0.015 m^3/h to a maximum of 6 m^3/h. With a turndown ratio of 400, operation from (at least) –10°C to 50°C, an uncertainty over most of the range of 1.5% and a production cost of about $20, this meter is the culmination of a century of development. However, for at least some systems, a large fraction of the gas consumed is due to pilot flows that have been difficult to measure with the bellows meter. Further development of it seems unlikely to improve its performance.

Due to market resistance to this rather bulky and unattractive traditional diaphragm meter, a competition was set up by British Gas in the 1980s for the development of a more compact gas meter. In the end, the successful designs were mostly ultrasonic. During the last decade several ultrasonic domestic gas meters have been developed to the commercial stage and there has been much activity in the patent literature [1, 2, 3, 4, 5, 6].

All of the meters seriously developed have used the transit-time principle of operation. A pulse of ultrasound is transmitted through the flowing gas and its passage timed over a length L. It will have a different time in the direction of flow T_d to that in the opposite direction T_u and the equation

$$v = \frac{L}{2}\left(\frac{1}{T_d} - \frac{1}{T_u}\right) = \frac{L(T_u - T_d)}{2T_d T_u} \qquad (1)$$

allows the velocity v to be calculated. From this velocity the flow may be obtained and, by integration, the volume passed in a given time.

For a meter that is about the size of a common house brick, the path length for the ultrasound is about 175 mm. This gives a transit time of 500 µs, varying of course with temperature and the nature of the gas. The stream velocity cannot be too high or the pressure drop will exceed the normal specification. For a velocity of 22 mm/s that might be typical of pilot flow, the difference between the upstream and downstream times is 57 ns. Thus a resolution of a few nanoseconds is needed for reasonable uncertainty. In the laboratory context this is not a difficult task using a high speed timer. For low power battery operation that is required for independence from the electricity mains, this solution is not feasible as high speed oscillators and timers use high power. Various solutions to this problem have been found and will be discussed.

Though the times measured allow a velocity to be measured this is not necessarily proportional to the flow. The correct determination of the flow from the velocity is a problem for all ultrasonic flow meters. In the large ultrasonic meters, based on the work of British Gas, multiple beams are used to allow the flow profile to be measured and hence the flow to be estimated. This technique is not currently feasible in a small battery operated device costing $20 but other techniques are used and these are described.

Ultrasound propagation in a flowing gas is not straightforward. Transducers normally used in ultrasonic work are made from piezo-ceramic materials that have a high acoustic impedance. The acoustic impedance of gases is low and this impedance mismatch makes it difficult for ceramic transducers to put energy into gases, or at least the process is inefficient. The characteristics of the received signal also depend on whether the direction of travel of the beam is with the flow or against it. Various meters handle these problems in different ways.

2 TRANSMISSION AND RECEPTION OF SIGNALS USING TRANSDUCERS

The traditional approach [1] uses a very low density composite material on the surface of the transducer, which is usually a piezo-ceramic material, to provide a matching of the different impedances. This layer may have stability and construction problems but the coupling can be considerably improved using this technique. To reduce the ringing of the transducer, that is to reduce the Q, an absorptive backing may be added. These transducers usually have a frequency range of from 140 kHz to 180 kHz.

Polyvinylidene fluoride (PVDF) film has a naturally lower acoustic impedance and can be made to have piezo-electric properties by stretching and poling it. One transducer developed using it [7] consists of a strip of metal-coated PVDF film 25 μ thick, held in a smooth “M” shape. The curvature assists some of the modes of vibration of the film when it is excited by a signal applied across the thickness of the film. The result is a transducer of low Q and with a frequency of about 115 kHz that operates with low voltage excitation, and can be used either as a transmitter or as a receiver, in a reciprocal manner. A disadvantage is that the sensitivity depends on the temperature and so the gain of the electronics must be varied to allow for this.

A commercially available transducer that operates at the low end of the ultrasonic range, at about 40 kHz, has also been used in gas meters [2]. It uses a piezo-ceramic element and coupling to the gas is enhanced by a small speaker cone attached to it. This transducer has a large Q and so it rings a lot in use. A technique mentioned later is used to achieve the precise timing required.

One of the operational difficulties that the transducers must face is that of dust. In all reticulation systems there is some dust but in old systems there can occur what are known as dust storms. The dust is composed mainly of iron oxides and silica and gets picked up by the flowing gas when there is a change in the distribution pattern or some other disturbance. It can be very upsetting for the operation of the transducers for mechanical reasons, for reasons of abrasion and for loss of linearity in performance.

Linearity in transducers is important for the accuracy of the meter at low flows. Non-linear behaviour can cause the timing to be different in the two directions even with no flow present. As a result there will appear to be a flow when really there is not. The need for good linearity occurs because when transmitting the amplitude of vibration of the transducer is orders of magnitude greater than when it is receiving. Dust on the surface of an otherwise linear transducer can adhere differently at different amplitudes of vibration of the transducer giving non-linear performance.

Some gases at some frequencies absorb the ultrasound energy much more than others. Gases with a simple molecular structure such as argon and diatomic molecular gases such as nitrogen and oxygen have low absorption. Gases such as methane and carbon dioxide as well as mixtures of these and water vapour with simpler gases can cause much higher absorption. A mixture of methane with 6% carbon dioxide is often used as a test gas because it is especially absorptive. The signal loss will depend on the frequency of operation as well as the path length but can be around 30 db.

3 DUCTS, FLOW AND ULTRASOUND

In the construction of a gas meter, the gas must flow through a duct and the ultrasound must pass through the flowing gas. When ultrasound propagates in a duct it generally does so as a series of modes. The exact nature of these modes depends very much on the geometry of the duct, but they travel at speeds that decrease as their complexity increases. The plane wave mode is the simplest and always propagates. Other modes have a cut-off frequency and they will not propagate in a given duct, below this frequency. As a mode approaches its cut-off frequency, its speed approaches zero

The waveform that is received after travelling through a duct is comprised of the combined signals from many modes and this has the effect of prolonging the signal seen. The use of a transducer with a large Q also prolongs the signal. This is of importance in the pulse repetition method of timing.

The presence of flow in the duct changes the shape of the received waveform. This can be illustrated for a cylindrical duct such as that shown in Figure 1, by the waveforms shown in Figure 2.

Here the relative peak heights of the signal transmitted with the flow are different from those transmitted against the flow. This is very inconvenient for timing based on a particular zero crossing of the received waveform. If this crossing is being detected using an electronic threshold, illustrated by the heavy horizontal line in Figure 2, then it will select a different crossing depending on the direction of transmission. This causes a very serious timing error.

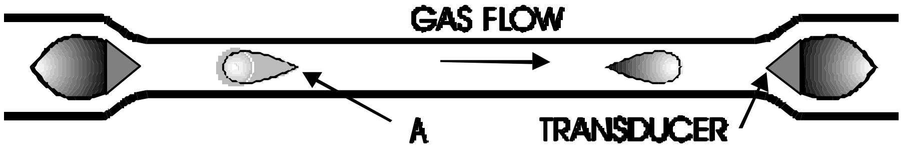

Figure 1. A cylindrical metering tube with transducers and mode control devices (A).

A solution to this problem has been to modify the flow path by inserting mode control devices [3] into the duct. These are shown in Figure 1. Other meters use an element down the axis of the tube. Sometimes the transducer is made considerably larger than the duct to avoid the generation of modes other than the plane wave [5].

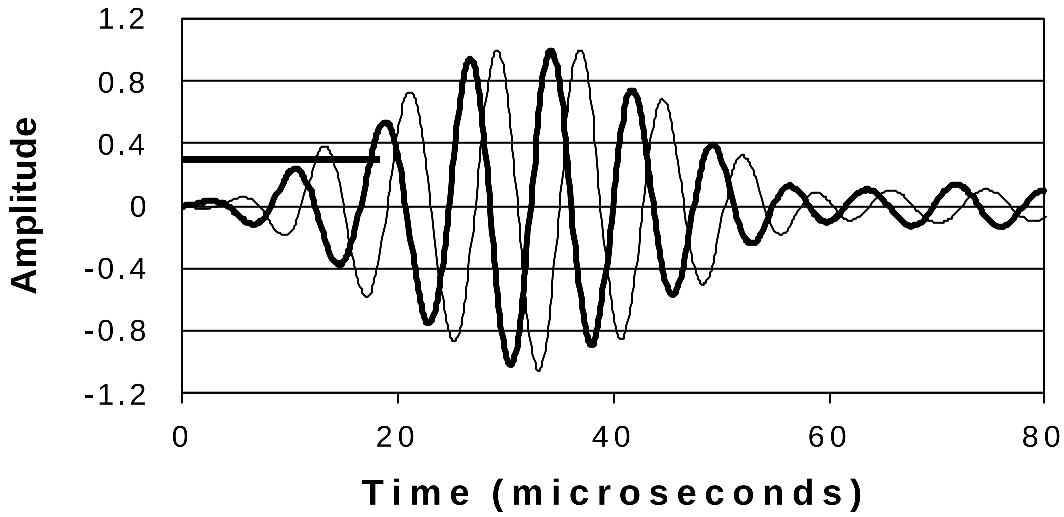

Figure 2. Upstream (light trace) and downstream waveforms, with gain adjusted to make them of equal height. The origin of the time axis is arbitrary. The heavy horizontal line represents a threshold.

4 TIMING TECHNIQUES

The timing of the signal in the two directions must be done with an uncertainty of about 3 ns if the specification is to be met for the uncertainty at low flow rates. This is quite difficult to achieve when the restriction of low power consumption is applied. A timing clock of even 10 MHz will allow direct timing to only 100 ns. An advantage is the very large number of measurements made in the billing period. If these measurements are truly random a high single measurement uncertainty can be tolerated while still achieving a low uncertainty in the mean value. The meters developed so far do not rely on this averaging to achieve their required uncertainty. This is probably because they must show their performance ability over a much shorter period during the calibration and testing part of their operation.

4.1 Pulse repetition

In this technique [3], a low frequency clock is used and the time to be measured is increased by sending the signal down the tube a number of times. A timer is started as the first pulse is sent down the tube. When it arrives it is detected and another pulse is immediately sent down, in the same direction, and so on for, say 100 pulses. When the 100^{th} pulse arrives the timer is stopped. Thus the time that is measured is 100 times that for one pulse and so a clock frequency 100 times less may be used. This works well and allows resolutions of a few nanoseconds with a clock period of 100 ns. There are, however, some drawbacks detailed in section 5.

4.2 Phase methods

Another method [8] of timing uses a special drive signal of 24 cycles of a sinusoid with a phase reversal built into it two thirds of the way through. The drive signal is generated from a 1.44 MHz clock by counting down to 180 kHz so that it is phase locked to it. Members of a group of eight capacitors are switched in turn by the clock to sample the received signal. During the 16 cycles before the phase switch they form a good average of the incoming waveform. A phase detector is used to compare the incoming wave with this average and hence the reversal is detected and the sampling stopped. This measurement establishes the time to one clock pulse but this is not nearly accurate enough. The phase of the stored waveform on the capacitors is then investigated. The voltage on each of the eight capacitors is read by an analogue to digital converter. If the phase reversal stopped the data collection at exactly the start of the phase of the received signal then the received signal and the driving signal (and the clock) would be in phase and an integral number of clock pulses would correspond to the transit time to be measured. Usually there is a phase difference that needs to be determined by the curve fitting procedure used. It is claimed that this can be done to one thousandth of a period of the signal thus achieving an accuracy of several nanoseconds.

In a similar technique [2], the transducer is excited with a tone burst of 8 cycles at 40 kHz. The received waveform is sampled at 320 kHz to give the data set $y(t_i)$. The phase is given by

$$f = \tan^{-1}\left[\frac{\sum_{1}^{n} y(t_i)\sin(2p40{,}000t_i)}{\sum_{1}^{n} y(t_i)\cos(2p40{,}000t_i)}\right] \quad (2)$$

which is more easily calculated than might appear since the sine and cosine values for eight samples per period are constrained to be either zero or ±1 or ±1/√2. It can only be determined between 0 and 2π. To remove the phase ambiguity (or to do "phase unwrapping") a separate, direct measurement of the time of flight is done using a threshold and comparator, exciting the transducer with a single pulse.

4.3 Clock period interpolation

A portion of the received waveform is digitised at a rate equal to the clock rate and these data are stored. If timing is done to a zero crossing it is easy to find the integral number of clock pulses that finish just before that crossing. Then an interpolation is done to determine that fraction of a clock period to the crossing.

It is also possible to interpolate by using a fast voltage ramp lasting one clock period with a circuit that samples this voltage at the instant of the event being timed. The voltage sampled divided by the maximum voltage for the ramp, is the fraction of the clock period required.

5 PULSE REPETITION TECHNIQUE PROBLEMS

This technique enables timing to be done with sufficient precision but it introduces some additional problems that have to be dealt with before a satisfactory meter can be made. In a graph of the velocity measured by the meter against the flow rate there are systematic cyclical variations from a straight line relationship. The reason for this behaviour lies in the manner of propagation of the acoustic pulse in the duct.

The plane wave mode arrives first at the receiving transducer but during the reception of the second such signal the modes from the first transmission that travel at half its speed, will also be arriving. During the reception of the third plane wave pulse the modes of one-third speed from the first transmission and half speed from the second transmission will be simultaneously arriving, and so on.

The timing of the pulses is done using a zero crossing and the presence of another signal can change the exact time of this crossing. This would not matter much if everything stayed constant but the flow changes the phase relationship of the modes to the plane wave. For example for a mode of velocity c_m, the velocity of the gas increases the effective downstream velocity to $c_m + v$ and the change in arrival time, *DT*, is given by

$$\Delta T \approx \frac{Lv}{c_m^2} \quad (3)$$

The value of *DT* varies with flow from 0 to many times the period of the signal thus changing the phase relationship of the mode to the main signal and producing a cyclical effect on the timing error and the deviation from the straight line.

If a particular mode interacts with the plane wave mode to shift the time of a particular zero crossing by $\delta\tau$ then if we could invert the plane wave mode the time shift would be $-\delta\tau$. If we could add these two errors, they would cancel. This can be arranged to happen since we are able to transmit both normal and inverted pulses. It is, however, not quite straightforward because we would like to cancel the effect of more than just one mode. The principles on which the error cancellation scheme works are:

- a timing error occurs when the main signal is combined with a much smaller signal (slower mode),
- this error has the same magnitude but opposite sign if either the main signal or the smaller signal, but not both, are inverted,
- the error has the same magnitude and sign if both are inverted,
- the principle of superposition applies, that is the signals act independently in the presence of each other.

The error in the timing can be cancelled if we can generate equal numbers of errors of opposite sign. This can be achieved by transmitting an inverted pulse once in every four transmissions. A more detailed explanation of this scheme is in [9].

6 THE RELATIONSHIP OF VELOCITY TO FLOW

The meter calculates the velocity of the gas, but exactly what velocity is this? In a duct of flowing gas there is a range of gas velocities forming what is called the flow profile. For laminar flow the velocities form a parabolic shape, for turbulent flow this flattens, and the exact shape varies with the Reynolds number. The maximum Reynolds number for most of the gas meters is about 10,000 and so the meters span the regimes of turbulent and laminar flow. The maximum velocity v_{max} for both cases is that along the axis. The mean velocity for laminar flow is $0.5v_{max}$ and approximately $0.75v_{max}$ for turbulent flow but in this case the exact relationship varies with Reynolds number. Hence, if the velocity measured is that along the axis then a different relationship will be obtained in the two flow regimes. It is even worse than this since the turbulent regime will have a profile that depends on the Reynolds number.

It has been shown [10] that a plane wave can sample equally over the whole diameter of the tube and so the velocity calculated from the transit times for a plane wave is the mean velocity of the gas. Usually there are other modes present, however, and these will sample preferentially from different parts of the cross section of the tube. The extent of this error depends on the relationship of the wavelength to the tube diameter. If the tube is large compared with the wavelength rather than filling the tube the ultrasound travels down the centre in a beam-like manner. In this case the velocity obtained will be closer to v_{max} and will thus have a different relationship to the mean velocity depending on whether the flow is turbulent or laminar.

For one design the wavelength of the signal used is sufficiently large compared with the diameter of the tube that it tends to spread rather than propagate as a beam down the axis. Comparing the velocity

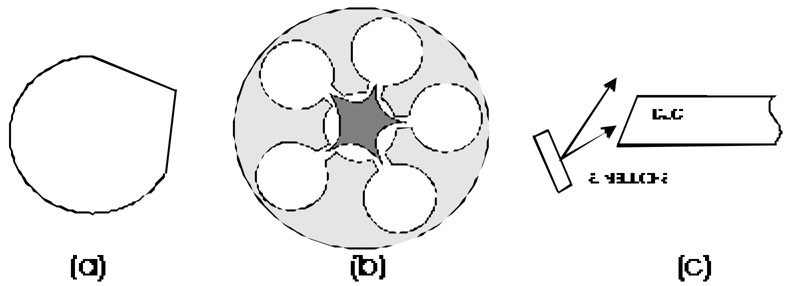

Figure 3. Three duct designs to reduce the effect of modes.

measured with the velocity calculated from the mean flow, shows it is closer to the mean than to the maximum velocity. Experimentally the ratio of the slopes of the lines of best fit for velocity versus flow in the turbulent and in the laminar regions is 0.989 whereas the ideal value would be unity. If the velocity measured were that along the axis, the result would be approximately 1.5. For meters such as this a velocity of sound dependent correction algorithm can be used to reduce further the error.

There are some designs that make a special effort to ensure that only the plane wave mode propagates. They do this sometimes by dividing the duct into small units so that all other modes are cut off at the frequency of the transducer. This has the disadvantage of increasing the pressure drop since this goes as the inverse fourth power of the diameter. Some designs try to recover some of the velocity head using the usual technique of slowing the gas down in a controlled manner by slowly increasing the diameter of the tube.

Alternative tube designs try to make propagation of the higher modes difficult by using a tube design that is not symmetrical such as that shown in Figure 3a [11]. Another example of duct design [12] to suppress mode propagation is shown in Figure 3b. Here the slots tend to bleed off the energy of the modes more than the plane wave. An off-axis beam can preferentially generate higher order modes and this can be at least partly prevented by inclining the end of the tube as shown in Figure 3c [12].

An alternative technique to produce a better average over the velocity profile is to use a beam-like signal but to direct it across the flow profile. Sometimes this is done in a circular duct with a diagonal crossing but in a commercial version [1] of this type of meter, the duct is rectangular with the long side about five times the length of the short side. As shown in Figure 4 the beam is reflected in a “W” shape from the sides of the duct using a special reflector in the middle to refocus the beam. There is a quarter wave plate to avoid the “V” reflection.

7 RECIPROCITY AND DELAYS

The time for the transit of a pulse of ultrasound in the tube when there is no flow present should be the same in both directions. For this to happen the time delays for the transducers in the presence of the medium must act with identical delays whether they are acting as transmitters or as receivers.

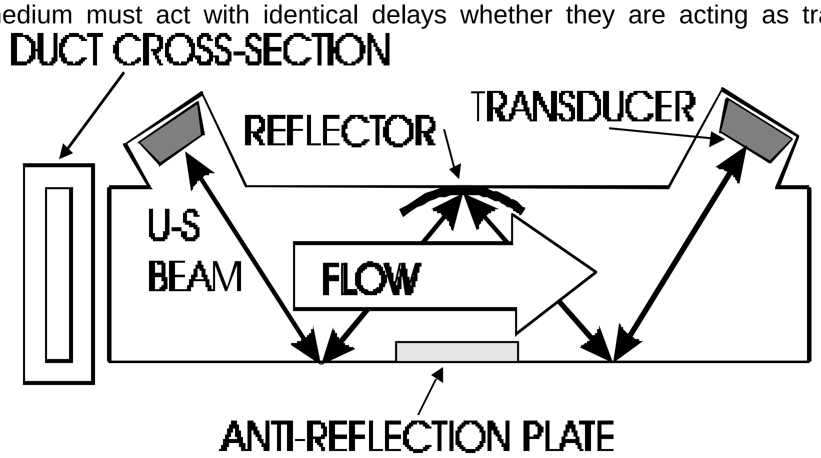

Figure 4. Rectangular duct with ultrasonic beam.

According to the reciprocity theorem in acoustics, the transmission properties will be independent of the transducers and the properties of the medium, if the transducers are linear and if the impedance of the circuit that the transducers are connected to is zero, or alternatively infinite [10]. Whilst strictly speaking, neither of these conditions can be met in practice, it is possible to design circuits that have impedances that achieve the required degree of reciprocity. It is also desirable to have the transducer see the same impedance whether it is transmitting or receiving.

Because the difference in transmission times between the two directions must be small when there is zero gas flow, it is important that the circuits used for upstream and downstream transmission do not differ in their time delays. The maximum time difference that is acceptable is 2 ns. For a signal of 130 kHz when a zero crossing is used for timing, this corresponds to a phase stability of 0.1° which for two separate amplifiers working over a wide temperature range is hard to maintain. It is better to have as many parts of the circuit in common as possible, to avoid the time delay differences that lead to a poor measurement of the zero velocity.

The transit time measurements at zero flow may be equal but still in error because of electronic delays and delays caused by the transducers by an amount DT. Then there is an error in the measured velocity of $2DT/T_0$ where T_0 is the transit time in still gas. This would not be serious if it remained constant but the value of T_0 varies with the gas type and the temperature. For DT of 2µs this gives an error of about 1%. Due to a change in the velocity of sound from air to hot gas, this will change by about one quarter giving a change in the measurement of 0.25%.

A means to eliminate the delays caused by the transducers and associated electronics is to use the second form of equation (1) that has the term T_u–T_d in the top line. This difference cancels the delays since they are common. The bottom line contains the term T_u T_d and this does not eliminate the delays. However, this can be written as

$$T_u T_d = \frac{L^2}{c^2(1-v^2/c^2)} \tag{4}$$

so that a knowledge of the velocity of sound, *c*, and an approximate knowledge of *v* enables it to be calculated quite accurately since *v/c* is small. The velocity of sound is found from a separate measurement using a third transducer [8] or a peripheral signal from the gas velocity measurement transducers [6]. These measurements are based on multiple reflections using only time differences that cancel the delays.

8 CONCLUSION

Domestic ultrasonic gas meters face design problems due to the requirement for small size and low power consumption. The various techniques used to achieve the operational specifications needed have been described. The acceptance by the market of these devices has been limited to the United Kingdom and there it has been muted due to the higher cost of manufacture of the meters compared with the traditional diaphragm meter, and some difficulties implementing the designs. These difficulties are associated with the sophistication of the design for a harsh environment that demands timing to nanoseconds, a measurement protocol that requires a computer to run, and all for a very low cost. Since the meters are replacing a proven technology they have been given a specification that places greater requirements on them than is currently placed on the traditional meters. With a computer on board, it is easy to lock into the modern "connected" world and to implement, for example, several billing rates for different times of the day and easy communication with the outside world to report consumption or fault. These features have not yet become important in the market. It would be foolish to suppose that development of ultrasonic domestic gas meters should stop. With electronics becoming more sophisticated and cheaper then perhaps ultrasonic correlation, or multiple beam meters will become economically feasible. It may well be that ultrasonic technology will be superseded in the future. However, as the cost of production continues to fall and with the increasing move towards integration of billing systems for water and energy reticulation, it seems likely that some form of electronic meter, probably ultrasonic, will find increasing acceptance in the future.

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