ULTRASONIC DOMESTIC GAS METERS

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ABSTRACT: Different ultrasonic domestic gas meters and the transducers used are discussed. They all measure a gas velocity with a transit time method. Time measurement techniques include repeated transmission and phase measurement. The propagation of the acoustic energy in the duct of the meter is in the form of modes and these can cause waveform changes and timing errors, which are discussed. The relationship of the velocity measured to the flow is not simple and various means are used to determine the flow from the velocity. The significance of delays and proper reciprocal operation is discussed.

1. INTRODUCTION: THE TASK OF A GAS METER

During the last few years there have been several ultrasonic domestic gas meters developed [1-8] and much activity in the patent literature. This paper attempts to explain some of the more interesting features of these meters and to draw together the many common threads that they have.

The purpose of domestic gas metering is to measure the heat used by the consumer and this is done by assuming that this is proportional to the quantity of gas. The ideal measurement of the quantity of gas would be its mass but it has traditionally been its volume; this assumes that the temperature and the pressure or their average values are known. The traditional diaphragm gas meter measures the volume of gas that passes through it by filling and emptying a bellows with the gas. The usual range of flows to be measured is from pilot flow of 15 L/h to 6000 L/h. Some capacity to measure flows outside this range is also needed. Pressure corrections are not usually done but sometimes a temperature correction is made to 15°C.

The ultrasonic gas meters that have been developed do not measure the heat of the gas nor its mass nor its volume but attempt to measure the volume flow rate by measuring a velocity in the flow. The relationship between the measured velocity and the flow rate is discussed later in this document. They are all sampling meters with a measurement being made every several seconds. They are called inferential meters because it is possible to infer the volume of gas that has passed by integrating the flow rate with respect to time.

All of the ultrasonic domestic gas meters developed so far are powered by lithium cells that usually operate for about 10 years. They need to function over a temperature range of at least -10°C to 50°C. The measurement uncertainty for most of the flow range is 1.5% but this is larger at low flows. The meters also need to work with a range of gases from air to methane.

2. TRANSIT-TIME ULTRASONIC GAS METERS

All ultrasonic domestic gas meters use a measurement of the transit-time of an ultrasonic pulse in a duct through which the gas is flowing to determine the velocity of the gas. The geometry of the duct varies so that sometimes the ultrasound is parallel to the flow and sometimes it makes an angle to it. In the latter case, it is the component of the flow velocity in the direction of the ultrasound that is measured. By measuring the times of travel of the signal upstream and downstream in the duct the velocity, v, can be calculated from the equation

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

where T_d is the time downstream, T_u the time upstream and L is the distance between the transducers. For the arrangement shown in Figure 1, of transducers in a tube of diameter 15 mm, the velocity of the gas at 15 L/h is about 20 mm/s and at 6000 L/h about 10 m/s.

The time for the pulse to travel the length of the tube is L/c where c is the velocity of sound. For a tube of 175 mm this has a value of approximately 500μs which is a typical value for most of the existing meters. The difference between the upstream and downstream transit times for a velocity of 20 mm/s is 57 ns so a resolution of a few nanoseconds is needed for reasonable uncertainty. To do this by direct timing using a fast clock is certainly possible but a lot of power is required to run such a clock. For a gas meter expected to operate from a battery supply that should last for ten years, this direct timing method is not feasible.

3. TRANSDUCERS

The main problem with transducers that must work in gases is that the acoustic impedance of the gas is much less than that of the transducer. This has been overcome in three ways. A traditional approach is to use a matching layer on the face of the transducer that has an acoustic impedance intermediate between the gas and the transducer material which is usually a piezo-ceramic. The materials that are suitable for this are very light composite materials that have to be specially made. To reduce the Q an absorptive backing may also be used [2]. The frequency of operation is usually about 180 kHz.

Another transducer used in some gas meters [3] operates at 40 kHz and uses a small loudspeaker cone attached to a piezo-ceramic element to couple to the gas. This transducer has a larger Q and so is not particularly suitable for impulse timing.

A third solution is the transducer developed by CSIRO/AGL [9] that uses a strip of metal coated, polyvinylidene fluoride (PVDF) film of 25 μm thickness and curved in a smooth "M" shape. The PVDF is prepared by poling and stretching to give it piezoelectric properties. The curvature assists some of the modes of vibration of the film when it is excited by signals applied to either side. The result is a transducer of low Q and with a frequency of 120 kHz, that operates with low voltage excitation and can be used either as a transmitter or as a receiver in a reciprocal manner. Due to the properties of the PVDF the output of the transducer depends on temperature and so the gain of the system must be varied to allow for this. An automatic gain control system is used in all meters to allow for the changes in the transmission properties of the gases, and changes in the transducers and electronics.

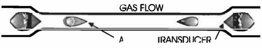

Figure 1. Transducers in a metering tube with mode control devices (A).

4. PROPAGATION OF ULTRASOUND IN DUCTS

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 depend on their complexity, with the simpler modes travelling the fastest. The plane wave is regarded as the simplest mode. Other modes have a cut-off frequency for the conditions involved, that is, they will not be propagated in a given duct below this frequency. Many modes can propagate in ducts that are somewhat larger than the wavelength.

The received waveform in a gas meter is due to the arrival of a number of modes and this has the effect of prolonging the arrival time of the signal. The signal is also prolonged by the natural oscillation of the transducer as an oscillator with a particular value of Q. It is thus to be preferred that the transducer have a low Q so that this effect is not enhanced. This long signal is of great significance to the pulse repetition timing method.

The modes also behave differently in the presence of flow and this leads to changes in the received waveform depending on whether it has been transmitted upstream or downstream. This change of waveform can have serious consequences for the timing of the signals as explained in the next section. The simple duct is usually modified to try to control these changes. An example of this is the device shown as "A" in Figure 1 [11]. Other configurations use an element down the axis of the tube [5]. Some designs use very small ducts that allow the propagation only of the plane wave mode [7]. This also has the effect of increasing the pressure drop across the meter since this varies as the inverse fourth power of the diameter of the duct. Some of this pressure drop may be able to be recovered since it is a velocity head and some meter designs [6] use a conical recovery section to do this. Sometimes the transducer is made considerably larger than the duct to try to avoid the generation of these modes [6].

5. WAVEFORM AND TRIGGERING

The time interval that needs to be measured is from the time of the excitation of the transducer to the arrival of the signal. The first is known very precisely but the arrival time of the signal is not. The reason for this is that the signal starts at a very low level as is shown in Figure 2. It is necessary to select some part of the signal capable of greater precision for the second timing marker. A zero crossing in the middle of the signal is suitable or a deliberately introduced phase reversal.

It is essential that the same zero crossing be chosen consistently for the timing as the time difference between one negative-going zero crossing and the next is far more than the uncertainty that is required in the timing. One common technique uses a comparator, one input of which is the signal and the other a reference or threshold level. The comparator produces an output when the signal passes the threshold. The next zero crossing (perhaps in a particular direction) can then be identified for the timing marker. To ensure that the correct zero crossing is chosen it is preferable to have a signal that rises rapidly. This means that a low Q transducer should be used. For a system that depends on selecting the same zero crossing in the waveform by its relation to peaks of particular heights, changes in the envelope of the received signal must be small. This is not so for propagation in a flowing gas.

This change in peak heights due to flow is illustrated in Figure 2 where two waveforms are shown. One is for transmission upstream into a flow of $4 m^3/h$ in a 15 mm diameter tube and the other is for transmission in the opposite direction. They have been adjusted to have the same peak height. The individual peaks in the two waveforms have quite different heights however, so that a threshold, such as represented by the thick line from the left, and a comparator combination would select different zero crossings. The upstream waveform is almost the same as the zero flow waveform but the downstream can be very different. Because of the flow profile the wavefront bends to the outside giving a pumping of the (0,2) mode. This is also seen when the tube wall is colder than the gas. The exact effect depends on the phase relationship between the plane wave and the (0,2) modes. Sometimes the second part of the waveform can be larger than the first with obvious detrimental consequences for the triggering and selection of a particular zero crossing.

6. TIMING

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.

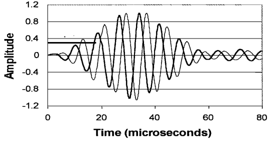

Figure2. Received waveforms from transmission downstream (heavy trace) and upstream (light trace) made to have the same maximum value.

6.1 The pulse repetition technique

In this technique [4], 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 as detailed in section 7.

6.2 Phase techniques

Another method [8] of timing uses a special drive signal of 24 cycles of sinusoid waveform with a phase reversal built into it two thirds of the way through. The drive signal is generated from the 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 [3], 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

$$\phi = \tan^{-1}\left[\frac{\sum_{1}^{n} y(t_i)\sin(2\pi 40{,}000 t_i)}{\sum_{1}^{n} y(t_i)\cos(2\pi 40{,}000 t_i)}\right] \quad (2)$$

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 $\pm 1/\sqrt{2}$. 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 method with single pulse excitation of the transducer.

6.3 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.

7. 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 the graph of Figure 3 the velocity measured by the meter has been fitted to a straight line and the differences from this line have been plotted against the flow rate. There are systematic cyclical variations from the straight line. The reason for this behaviour lies in the manner of propagation of the acoustic pulse in the duct. Because it travels fastest the plane wave mode arrives first at the receiving transducer but during the reception of the second signal the modes from the first transmission, that travel at half its speed, will also be arriving.

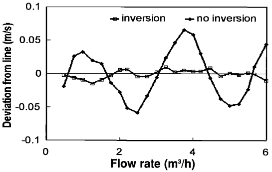

Figure3. Cyclical deviations from the line of best fit.

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 downstream propagation, the velocity of the gas increases the effective velocity of the mode to $c_m + v$ and the change in arrival time, ΔT, is given by

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

where c_m is the velocity of the mode. The value of ΔT varies with flow from 0 to many times the period of the signal and so there is a cyclical effect on the timing error. This is the cause of the oscillation seen in Figure 3.

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 [10]. It is able to correct substantially for the timing error caused by the slow modes in the tube with the result shown in Figure 3.

8. 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 turbulent flow is normally regarded as occurring for flows with Reynolds numbers above 2200. Thus the meters span the two flow 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.

It has been shown [1] 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 the CSIRO/AGL gas meter measurements of the mean flow and the velocity show that the velocity measured is closer to the mean than to the maximum velocity. The ultrasonic signal used is of sufficiently large wavelength compared with the diameter of the tube that it tends to spread. 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. A velocity dependent correction algorithm is used to reduce the error.

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 [2] 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.

9. RECIPROCITY AND DELAYS

The time for the transmission 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. 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. Whilst strictly speaking, neither of these conditions can be met in practice, it is possible to use impedances sufficiently low to achieve the required degree of reciprocity. It is also desirable to have the transducer see the same impedance whether it is transmitting or receiving. Linearity in the transducers is a significant requirement since they operate with very different signal levels when they are transmitting to when they are receiving.

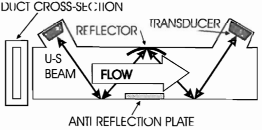

Figure 4. Rectangular cross section duct with "W" acoustic path.

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 time difference, that is the maximum 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 ΔT. Then there is an error in the measured velocity of $2\Delta T/T_0$ 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 ΔT 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. 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]. This measurement is based on multiple reflections using only time differences that cancel the delays.

10. CONCLUSION

Domestic ultrasonic gas meters face 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. An electronic meter permits several billing rates for different times of the day and has the inherent advantage of allowing easy communication with the outside world to report consumption or fault. These features have not yet become important in the market. As the cost of their production continues to fall and with the increasing move towards integration of billing systems for water and energy reticulation it seems that they will be more used in the future.

REFERENCES

1. J. Hemp, "Theory of Transit Time Ultrasonic Flowmeters" J. of Sound and Vibration **84**, 133-147 (1982)
2. A. von Jena, V. Magori and W. Russwurm, "Ultrasound Gas Flow Meter for Household Application" Proc. Eurosensors **VI** (1992)
3. L. Beneteau, R De Vanssay, B. Froelich, and J.M. Pietrzyk, "A Domestic Ultrasonic Gas Meter Based on Differential Phase Measurement" Proc. Int. Gas Research Conf. (IGRC98) (1998)
4. N. Bignell, et al "An Ultrasonic Domestic Gas Meter" Proc. 6th Int. Conf. Flow Measurement. (FLOMEKO '93) 403-409 (1993)
5. B. Huang and G. Marquette "Dispositif de measure ultrasonore d'une quantité volumique d'un fluide à propriétés acoustiques améliorées" Intl Pat. Applic. WO 96/06333 (1996)
6. M. L. Sanderson and A. R. Guilbert, "Ultrasonic Flow meter" U.K. Patent App. GB 2 301 186 A (1996)
7. J. D. Y. Collier et al "Fluid Flow Meter" UK Patent App. No. GB 2 275 108 A (1994)
8. M. J. Gill "Flowmeter Eliminating Transducer Delay Errors" UK Patent App. GB 2 259 571 A (1993)
9. B. J. Martin "Ultrasonic Transducer" United States Pat. No. 5,434,830 (1995)
10. N. Bignell "Mode Suppression in Fluid Flow Measurement" Aust. Pat. No. AU-B-21728/92
11. N. Bignell "Mode Suppression in Fluid Meter Conduits" Int. Pat. Applic. WO94/20821 (1994)