FLOMEKO 2022

High accuracy, low cost ultrasonic clamp-on flow metering of small diameter, thin walled pipe

S. Dixon, D. Greenshields, Z. Li, R. Burton, T. Burton and L. D. Smith

Department of Physics, University of Warwick, Coventry, UK
E-mail (corresponding author): S.M.Dixon@warwick.ac.uk

Abstract

A new, miniature design of a clamp-on ultrasonic transit-time difference flow meter for use in liquids is presented, with particular application to small diameter, thin walled metal pipes, opening up new areas of application, including smart water metering. The particular embodiment of the hardware is low cost and can be installed by unskilled users, and uses a type of guided wave mode that is significantly different to previous examples of clamp-on flowmeters that have used a leaky guided wave in the pipe to generate compression waves in the liquid. In the example presented in this paper, the entire liquid-pipe system acts as a wave guide, providing large amplitude ultrasonic signals with outstanding signal to noise, even from a drive voltage of just a few volts. The flowmeter is capable of measuring flow rates down to a few millilitres per second, with an accuracy better than 0.5 millilitres per second. The results presented mainly focus on 15 mm diameter copper pipes of wall thickness 0.7 mm, but the same approach works well on pipes with larger diameters and slightly thicker walls, up to around 30mm diameter in the current embodiment, In many instances, in previous work, the presence of the guided wave modes has prevented clear interpretation of the ultrasonic signals that are detected.

1. Introduction

1.1 Conventional clamp-on flowmeters

Clamp-on transit time difference flowmeters have been used successfully for several decades in the process industry and water utility sectors. Their main advantage is that they can be retro-fitted to pipes, and easily moved around to different locations. Like all flowmeters, they have their limitations, with the a key one being that the ultrasound takes what is effectively a single path across the flowing fluid inside the pipe. This means that the average flow velocity might be affected by asymmetric flow profiles, that are common in realistic pipes.

The equation used to calculate flow velocity in the pipe is of the form

$$V = \frac{L}{2\cos(\alpha)} \frac{t_U - t_D}{t_U \; t_D} = \frac{L}{2\cos(\alpha)} \frac{\Delta t}{(t_{AV})^2} = \frac{c^2 \; \Delta t}{2\,L \; \cos(\alpha)} \tag{1}$$

Where V is the average velocity of liquid along the sound path, L is the distance travelled in the liquid, t_U is the transit time in the liquid in an upstream direction, t_D is the transit time in the liquid in a downstream direction, α is the angle between the path of the sound and the velocity vector of the liquid, to a good approximation t_{AV} is the average of t_U and t_D and c is the speed of sound in the liquid. There are correction factors that need to be applied to this equation to account for the fact that the velocity is the average along a linear path that cuts across part of the cross section of the flow. The correction value varies from 0.75 for laminar flow through to 0.94 for turbulent flow [1]. The conventional set-up of an ultrasonic clamp-on transit time difference flowmeter is shown in Figure 1 below.

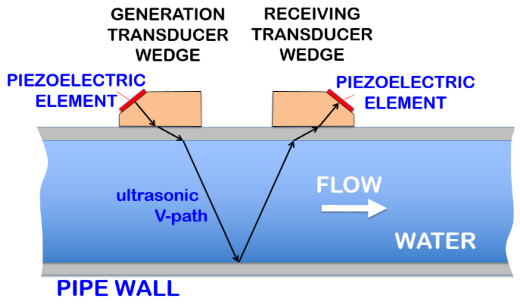

Figure 1. Schematic ray tracing diagram for ultrasonic bulk wave V-path in conventional clamp-on flow measurements on a large diameter, thick-walled metal pipe

In the arrangement of Figure 1, the transducers are usually multiplexed so that a transit time upstream and then downstream can be measured. Often, because of the difficulty in defining what at ultrasonic wave arrives, the usual approach is to store the upstream and downstream measured waveforms, and then use an algorithm such as cross-correlation to calculate the difference between them (Δt), as appears in Equation 1.

When the same transducers are attached to a smaller diameter pipe, one might expect to have to perform a measurement similar to that shown in Figure 2, where multiple reflections of the wave within the pipe give rise to a discreet signal that has propagated via several internal bounces inside the pipe. However, the results that are observed when performing measurements shown in Figure 2, can look very different to those observed on larger diameter, thicker walled pipes, as will be explained in section 2.

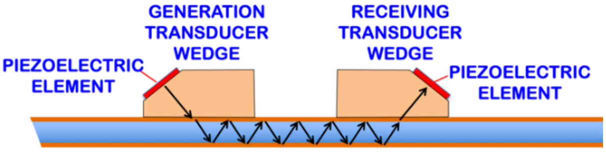

Figure 2. Schematic diagram of a ray tracing path one might assume on a smaller diameter pipe, where the wave arrives at the detector as a series of multiple V-paths.

1.2 Flowmeters for small diameter pipes

For pipe diameters of 28 mm or less, a range of different flow meters can be used including turbine and rotary meters, inline ultrasonic meters, electromagnetic meters, fluidic oscillators and pressure differential meters [1], all of which require costly and disruptive installation, switching off the supply and cutting into the water pipe to fit the meter. These meters have parts that are in contact with the water and their performance can degrade with time, particularly for turbine meters. There is also the potential for these meters to be damaged by sudden changes in pressure or flow rate. Coriolis meters have been successfully used to measure mass flow through very small diameter pipes with high accuracy, making them an excellent tool for multiphase flow measurement, but they also require fitting inline with the pipe and have a limited dynamic range of measurement compared to ultrasonic methods [1].

Thermal differential methods are also used to measure flow from the outside of a thin walled metal pipe, by attaching a heat source and one or more thermal sensors to the pipe and measuring how flow affects the temperature distribution on the outer wall of the pipe [2,3]. This method can yield a crude measurement of flow, and reliable quantitative measurements of flow rate are not possible, but it does have applications in water supply management where measurement accuracy is not vital, such as pathogen control [4].

Existing ultrasonic clamp-on flowmeters measure the rate of flow in large diameter metal water pipes and plastic water pipes [1], but these are severely limited in terms of their size, cost accuracy and measurement range, massively limiting their applicability and usefulness. For small diameter metal water pipes, the minimum measurable flow rates for these water pipes using state of the art technology [5,6] is in the range of 32 ml/s which equates to 114 litres of water per hour, or over 2700 litres per day could be lost without being measured. The accuracy of the flow rate measurement decreases with flow rate and it would not be unusual for clamp-on flow meters to have inaccuracies the order of 20% to 50% when approaching their minimum detectable flow rate.

2. Measurements on small diameter pipes

2.1 Waveforms observed on pipes

Treating the ultrasonic waves travelling along the ray tracing path shown in Figure 2 as bulk waves, one might expect to observe an ultrasonic waveform similar to the simulated one shown below in figure 3 as Trace A, which is typical of what is seen in larger metal pipes. On small diameter thin walled pipes, one actually observes a number of guided wave modes labelled here as V* modes, travelling along the pipe, shown in Trace B of figure 2. An air space or solid object inserted into the pipe under either transducer will have relatively little impact on the appearance of the waveform in Trace B, because the wave propagates as a guided wave, constantly exchanging energy between the liquid and the pipe wall as it propagates along the composite system.[7]

Guided waves have been reported previously in the transit time difference clamp-on flow measurements [8], where the guided wave that propagates along the pipe is equivalent to a single V-path measurement, and are best described as a guided wave that leaks energy into the fluid which travels through the fluid as a bulk wave. The guided wave modes described in this paper, are not reported previously for flow measurement. For small diameter plastic water pipes, conventional multiple V-path measurements can be used to measure flow rate, as plastic pipes due to the higher ultrasonic attenuation in the polymer wall.

The ultrasonic transducers reported here are constructed using 30mm long, 6mm wide PEEK (polyether ether ketone) wedges, that can be injection moulded. The size of the 0.5 mm thick, 4 MHz PZT piezoelectric element used in these transducers is 5mm x 10mm, with a PEEK wedge angle of 38° [7,9]. The transducers are driven by a 4 cycle, 10 V_{pk-pk} sinusoidal wave pulse. A preamplifier is used to amplify the data before it is captured by a digital oscilloscope. Using more drive cycles will eventually cause the observed pulses to overlap. The waveforms were averaged 16 times each, not to improve signal to noise, but to average out any potential variations due to turbulent flow and trigger jitter.

3. Results

For water at room temperature in smooth pipes, one typically takes the average velocity measured ultrasonically across the diameter and multiplies it by a factor of 0.75 for laminar flow which increases through the transitional region, through to 0.94 for highly turbulent flow, to obtain the average velocity of liquid across the entire area of the pipe. This of course assumes that the flow profile is circularly symmetric. However, on analysing the second pulse in the blue waveform of figure 4 (2 V* at ~70 μs), we find that the results indicate that only one correction factor is required across the entire range of flow. Figure 4 below shows the measured transit time difference with flow rate from the 2V* mode shown in figure 4 [9]; it is linear across the entire flow range, where for this copper pipe with an inner diameter of 13.6 mm and an outer diameter of 15 mm, the laminar to turbulent flow transition should occur at around a flow rate of 20 ml/s.

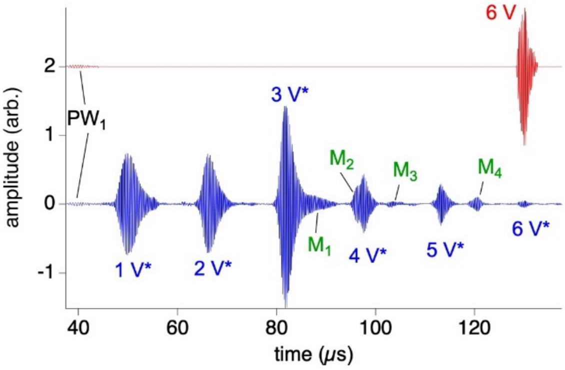

Figure 3. The top Trace A in red is a simulated waveform of what one might expect to see on a 15 mm diameter, 0.7mm wall thickness copper pipe if the wave propagated as a simple multiple number of V-paths, as would be the case for a larger diameter pipe. Note that for the separation of transducers used here (60 mm as defined in Figure 1(b)), one also expects to observe a wave that travels directly along the pipe wall (PW1), followed by the multiple 6 V path signal. The lower Trace B in blue, shows the actual waveform measured on the 15mm copper pipe, where one can see multiple guided wave modes, that in terms of time spent propagating in the liquid are equivalent to one V-path (1 V*), two V-paths (2 V*) etc. Note that on this pipe several additional modes are observed and are denoted as MN , for N=1,2,3… These wave modes are other guided wave modes that arise in the three dimensional cylindrical geometry of the pipe.

However, for this particular guided wave mode in this arrangement, a single correction factor of 0.94, perfectly corrects the ultrasonically measured value to the actual average flow velocity across the entire cross section of the pipe. The accuracy of the measured flow rate data is better than 0.5 ml/s, and flow rates down to 1.25 ml/s were measured using this approach.

This is a surprising and tantalising result, that requires further research to carefully analyse all of the key ultrasonic wave arrivals that can be seen in figure 4, and explain why this is the case. Speculatively, this is probably related to a combination of the actual ultrasonic beam width within the pipe combined with focusing effects of the curvature of the pipe wall. Half-radius chordal ultrasonic paths have been proven to do something similar [20] for wetted transducers in meter bodies, in direct contact with the liquid. This is almost certainly a related effect, where in a small diameter pipe the ultrasonic beam spreads out across a relatively large cross-section of the pipe, and is a beautiful natural coincidence in the physics of the flow and the wave propagation within it.

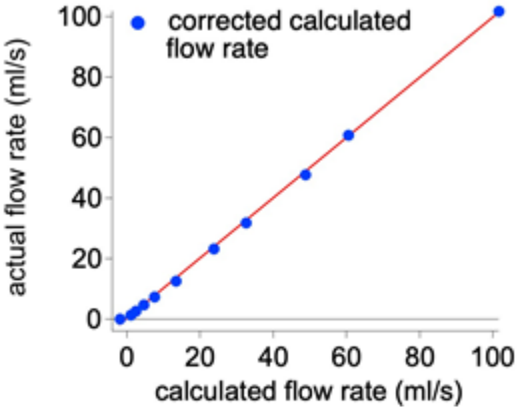

Figure 4. Ultrasonic transit time difference, calculated for the second pulse (2V*) in the guided wave observed in figure 3, using a single value to correct the flow rate.

The miniature transducers used in these measurements can also be applied to larger diameter pipes and used in the same way as any other clamp-on transducer, but there are several interesting features of the ultrasonic signal on metal pipes of less than 30mm diameter, including a linear relationship between transit time difference and flow across the entire range of flow speeds (no change in flow profile correction factor), and the ability to use different ultrasonic wavemodes to simultaneously measure flow speed. The transducers can also perform self-calibration for the speed of sound in liquids and have been driven in a way that provides further improvements in accuracy compared to some methods currently used. Affordable and accurate smart metering is now possible, and some of the approaches described in this paper will have wider benefits to clamp-on ultrasonic flow measurements.

4. Discussion

In conventional clamp-on ultrasonic measurements one assumes that the path of the ultrasonic beam is adequately viewed as a single ray path, cutting across the pipe diameter, through the liquid within the pipe. More sophisticated models do take some consideration of ultrasonic reverberations within the pipe wall, but essentially the only ultrasonic path considered is the same as that shown in Figure 1.

In reality, the width of the ultrasonic beam will always have some effect, and the curvature of the pipe wall will to some degree focus the ultrasound back into the liquid in the pipe. For large diameter pipes, it has been shown that the correction factors can adequately relate the average measured flow velocity across the pipe diameter to volumetric flow rate. The average ultrasonic velocity effectively puts equal weight on every point across the diameter of the pipe, but there is of course relatively more liquid travelling at larger radial positions away from the pipe centre.

Conventional analysis of the system requires a factor called a correction factor, to account for effects of changes in flow profile, assuming that the flow profile is circularly symmetric about the centre of the pipe. The correction factor can also account for effects of pipe roughness, liquid temperature and liquid viscosity. However in this case the data needed only on value of correction factor to produce the result shown in figure 4.

7. Conclusion

Using the miniature PEEK wedge transducers described provides a very small and compact measurement head for this clamp-on flow measurement. Combining the small transducers with the guided wave approach, operating at 4 MHz enables us to make flow measurements down to 1.25 ml/s on a 15mm diameter copper water pipe, with an accuracy better than 0.5 ml/s. This is all done with a single correction factor across the entire flow range, probably indicating that the ultrasound insonifies effectively the entire cross sectional area of the flowing water in the pipe. The transducers can also be used on small diameter plastic pipes, but in that case the guided wave in the pipe wall is heavily supressed, such that the ultrasonic transit path is behaves as shown in Figure 2 and produces a signal similar to the red trace shown at the top of Figure 3.

The data generated by this approach can be analysed either by analysing signals that have been digitised (using analogue to digital conversion), as was done here using an oscilloscope to collect the data, or can equally be analysed by a time-to-digital measurement, where the difference in upstream and downstream ultrasonic transit times is measured by detecting zero crossing points in the ultrasonic wave pulse or similar.

Like all ultrasonic transit time difference techniques, this approach it limited by the similarity of the ultrasonic response of the transducer. Fortunately, the design of miniature transducer that we use is very reproducible from transducer to transducer, and can also be tuned to some extent by changing the pressure on the PZT element.

The patent pending solution described in this paper using guided waves and miniature transducers offers the potential for low cost IoT smart metering type applications. The high signal to noise ratio obtained in measurements when driving the ultrasonic transducers by only a few volts, means that battery operation of such a system is now viable.

References

[1] Baker RC, “Flow Measurement Handbook: Industrial Designs, Operating Principles, Performance, and Applications”, Cambridge University Press, 2016

[2] Han IYet al.,m “Study on the transient characteristics of the sensor tube of a thermal mass flow meter”, Int. J Heat Mass Tran., **48**, pp2583-2592, 2005

[3] Glatzl T et al., A Thermal Flow Sensor Based on Printed Circuit Technology in Constant Temperature Mode for Various Fluids, Sensors **19**, 1065, 2019

[4] van der Kooij Det al., “Biofilm formation and multiplication of Legionella in a model warm water system with pipes of copper, stainless steel and cross-linked polyethylene”, Water Research **39**, pp789-2798, 2005

[5] https://www.streamlabswater.com/monitor (accessed 22/07/2021)

[6] 8. https://restechtoday.com/guide-5-modern-leak-detectors (accessed 22/07/2021)

[7] Dixon S et al., “Paper title in full”, *IEEE Trans. Inst Measure*, **70**, 7504403, 2021

[8] Aanes M.et al., “Time-of-flight dependency on transducer separation distance in a reflective-path guided-wave ultrasonic flow meter at zero flow conditions”, J. Acoust. Soc. Am., **142**, pp825-837, 2017

[9] Li ZC, Smith L and Dixon S, “Design of miniature clamp-on ultrasonic flow measurement transducers”, IEEE Sensors Letters **5**, 2500604, 2021 .

[10] Jackson GA et al., “A three-path ultrasonic flow meter with fluid velocity profile identification”, Meas. Sci. Technol. **2**, pp635-642, 1991