Clamp-On Measurements of Fluid Flow in Small-Diameter Metal Pipes Using Ultrasonic Guided Waves

Steve Dixon, Zhichao Li, Matt Baker, Xhorxh Bushi, and Luke Smith

***Abstract*— Clamp-on ultrasonic transit time difference is used extensively to calculate the volumetric flow rate of a fluid through a pipe. The operating principle is that waves traveling along a path that is generally against the flow direction take longer to travel the same path than waves traveling along the same path in the opposite direction. The transit time difference between the waves traveling in opposite directions can be used to calculate the flow rate through the pipe, by applying suitable mathematical correction factors. The approach is non-disruptive and noninvasive and can be retrospectively fit to pipes and easily relocated to different positions. When ultrasonic clamp-on transducers are attached to pipes with diameters of less than 30 mm and a wall thickness of less than a few millimeters, the resulting guided waves can appear confusing and produce very different signals to those observed on larger diameter pipes. The experimentally observed behavior of these guided waves in fluid-filled, small-diameter pipes is analyzed, modeled, and explained. Experiments are performed in copper pipes of sizes that are commonly used in buildings, and accurate measurements of water flow rates are taken down to a few milliliters per second. This technique presents new possibilities for smart metering of water supplies, where the positioning of the small clamp-on transducers is not sensitive to the variations in water temperature, and low-power electronics can be used.**

***Index Terms*— Clamp-on, transit time difference, ultrasonic flow measurement.**

I. Introduction

MANY different types of flowmeter using a number of different physical principles are used to measure fluid flow rates through pipes [1]. For pipe diameters less than 30 mm, potential flow meters could include turbine and rotary meters, inline ultrasonic meters, fluidic oscillators, and pressure differential meters and Coriolis meters [1], all of which require cutting the pipe to fit the meter. Thermal differential methods can also be used to measure flow from the outside of a thin-walled metal pipe [1], but produce poor accuracy quantitative flow measurements. The existing ultrasonic clamp-on flowmeters measure the rate of flow in large-diameter metal and plastic water pipes using relatively large and expensive transducers [1]–[4]. Their accuracy can be further degraded by a number of factors, including variability in the electronics and transducers and changes in the temperature of the liquid: the transducers need to be located at very specific positions for optimal accuracy, and these positions will change for different water temperatures [2]–[7]. While some commercial flowmeter sales literature claim operation on pipes less than 20 mm diameter, their operation principles are unclear and their claimed accuracies can vary significantly, and there are no journal publications that appear to be related to any such devices.

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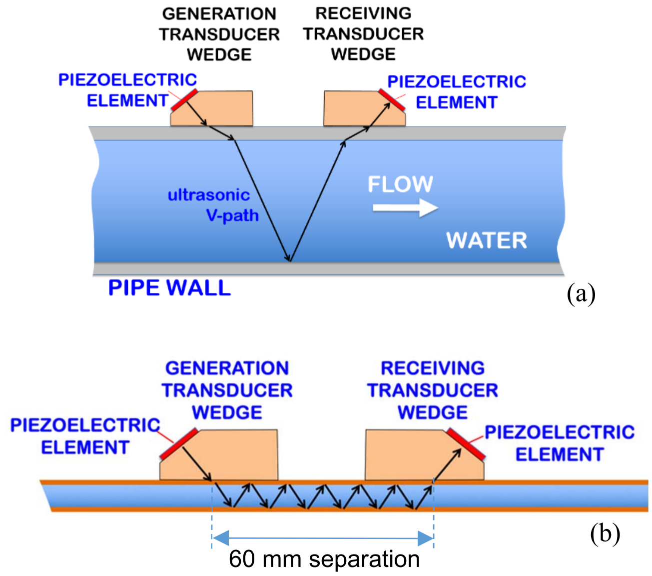

Fig. 1. (a) Schematic ray tracing diagram for ultrasonic bulk wave V-path in conventional clamp-on flow measurements on a large-diameter, thick-walled metal pipe and (b) ray tracing path one might assume on a smaller diameter pipe, where the wave arrives at the detector as a series of multiple V-paths.

In the ultrasonic transit time difference method on a relatively large-diameter metal pipe, a piezoelectric transducer introduces a compression wave to a pipe wall at a specific angle, which mode converts to a shear wave in the wall and then mode converts back to a compression wave in the liquid. The ultrasonic wave travels across the liquid in the pipe at an angle to the net flow velocity or axial direction of the pipe. After one or more transits across a diagonal path, the ultrasonic waves are coupled back through the pipe wall as a shear wave, and into the receiving ultrasonic transducer as a compression wave, where it is then detected when arriving at the piezoelectric element as shown in Fig. 1(a), inducing a voltage in the piezoelectric. The average component of the flow velocity vector along the ultrasonic path will cause the ultrasonic wave to have a shorter transit time when the flow velocity is generally in the direction of the traveling wave, and a longer transit time when the flow velocity is generally opposed to the direction of the traveling wave. The method measures the average flow along one particular path through the liquid, meaning that non-axisymmetric flow profiles are not properly measured. Low flow rates are also difficult to reliably measure, due to the variations in transducer responses and the small, sometimes sub-nanosecond time differences that need to be measured for very low flow rates. The conventional clamp-on approach can be difficult to implement on small-diameter and thin metal wall pipes due to the complicated and sometime confusing ultrasonic wave arrivals that are observed.

II. Experimental Results on Metal Pipe

The ultrasonic transducers reported here are constructed using 30 mm long, 6 mm wide PEEK (polyether ether ketone) wedges, which can be injection molded. The size of the 0.5 mm thick, 4 MHz PZT piezoelectric element used in these transducers is

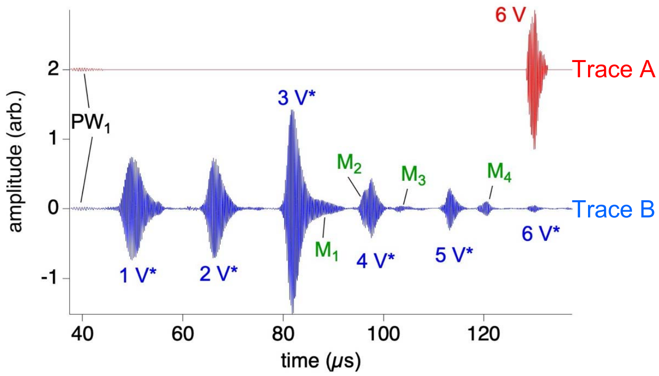

Fig. 2. Top Trace A in red is a simulated waveform of what one might expect to see on a 15 mm diameter, 0.7 mm wall thickness copper pipe if the wave propagated as a simple multiple number of V-paths, as would be the case for a larger diameter pipe. Note that for the separation of transducers used here [60 mm as defined in Fig. 1(b)], one also expects to observe a wave that travels directly along the pipe wall (PW_1), followed by the multiple 6 V path signal. The lower Trace B in blue shows the actual waveform measured on the 15 mm copper pipe, where one can see multiple guided wave modes, which in terms of time spent propagating in the liquid are equivalent to one V-path (1 V*), two V-paths (2 V*), and so on. Note that on this pipe several additional modes are observed and are denoted as M_N, for $N = 1, 2, 3\ldots$ These wave modes are other guided wave modes that arise in the three-dimensional cylindrical geometry of the pipe.

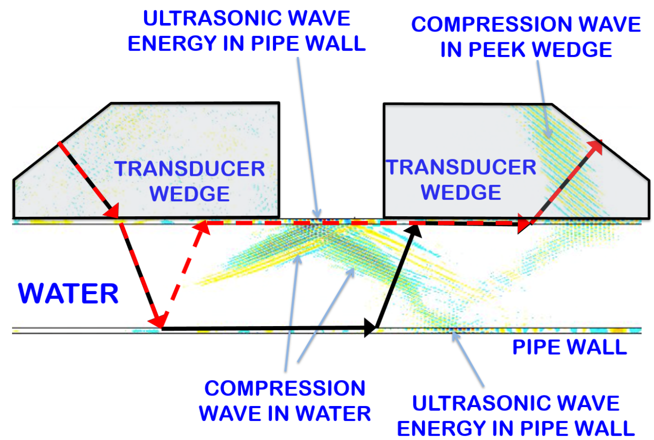

Fig. 3. FE models show that any combination of ray tracing paths consisting of two transits across the pipe at the correct angle and two transits along the pipe wall are possible for this particular geometry of transducers and liquid-filled pipe, to give rise to the 1 V* mode (and similar for higher order modes). The ultrasonic waves that arrive at the detection transducer average across the face of the piezoelectric to give one effective guided wave mode arrival that has traveled the equivalent of one V-path through the liquid in the pipe. The two possible ray tracing diagrams above show that ultrasonic energy can arrive at the detection transducer, taking paths shown by the black or red-dashed arrows, where both these paths have the same transit time and both are perfectly valid paths for ultrasonic energy to take. An infinite number of such paths could be drawn for each guide wave mode arrival.

5 mm × 10 mm, with a PEEK wedge angle of 38° [5]. The transducers are driven by a four-cycle, 10 $V_{pk\text{-}pk}$ sinusoidal wave pulse. A preamplifier is used to amplify the data before they are 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 the signal to noise, but to average out any potential variations due to turbulent flow and trigger jitter. Treating the ultrasonic waves traveling along the ray tracing path shown in Fig. 1(b) as bulk waves, one might expect to observe an ultrasonic waveform similar to the simulated one shown in Fig. 2 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 labeled here as V* modes, traveling along the pipe, as shown in Trace B of Fig. 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.

Guided waves have been reported previously in the transit time difference clamp-on flow measurements [6], where the guided wave that propagates along the pipe is equivalent to a single V-path measurement and is 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 article are not reported previously for flow measurement. For small-diameter plastic water pipes, the conventional multiple V-path measurements can be used to measure the flow rate, as plastic pipes due to the higher ultrasonic attenuation in the polymer wall.

A 2-D finite element (FE) model was constructed, using PZFlex (Onscale), as memory limits meant that it was not possible to run a full 3-D model on the machine available to us. The response and behavior of the 2-D FE model are almost identical to the results obtained in the real cylindrical pipes and specially constructed rectangular cross section pipes of the same diameter, explaining the nature and appearance of the experimentally measured waveforms. The cylindrical pipes do have some extra features (M_N modes) that arise as they can support additional guided wave modes. The results of FE modeling show how energy propagates along the pipe-water system, with energy being constantly exchanged between the pipe wall and water within it. The angles of the pressure wavefronts in the PEEK and in the water obey Snell's law, despite the pipe wall being thin compared with the wavelength. The waves in the water generate ultrasonic disturbances in the pipe wall, which then are re-radiated into the water together with direct specular reflections. The experimental and modeling results show that the arrival labeled as 1V* in the lower waveform of Fig. 2 can be thought of as a combination of ray tracing diagrams through the system, such that either path shown in Fig. 3 is an allowable path for ultrasonic energy. Therefore, the energy that propagates along the pipe has an infinite number of paths that one could draw, all arriving simultaneously at the detection transducer, adding together to produce a signal that corresponds to a wave that has effectively traveled a distance of one V-path through water. This particular guided wave mode has averaged the properties of the material through which it has traveled along the pipe, which is advantageous as an average flow velocity through the turbulent liquid is measured along the length of liquid between the two transducers. Looking down the pipe in the direction of flow, the ultrasonic beam would also spread across the cross section of the pipe to some extent. For the transducers used here, the contact between the PEEK wedge and the outer pipe wall is linear, causing sound energy to diverge across the cross section of the flow on entering the pipe. This gives rise to some of the additional features labeled as the M_N modes, noting that there may actually be modes arriving earlier than the M_1 mode, which are not always clearly distinguishable from the V* modes.

To further demonstrate that the interpretation of the source of the guided wave modes is correct, a transit time difference measurement (upstream–downstream) was performed on the 2 V* mode, with water flowing through the 15 mm diameter pipe. The water flow was supplied by a header tank at a constant pressure, using a valve close to the end of the pipe to control the flow rate. A volume of water was measured over a time period to calculate the true flow rate of the liquid through the pipe to an accuracy better than 0.25%. The

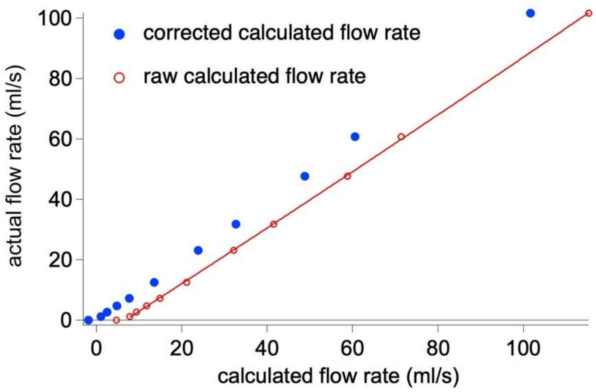

Fig. 4. Raw calculated flow rate is shown together with a linear fit of the data giving a gradient of 0.94+/−0.6%. This factor is used to provide a correction factor for the data that take into account the fact that the flow velocity across the pipe cross section is not uniform and that the ultrasonic wave is not uniformly distributed across the entire flow profile as it travels along the pipe. Using the correction factor of 0.94 yields the corrected, calculated flow rate data shown in blue.

plot of the measured actual flow rate against the calculated flow rate from the ultrasonic data is shown in Fig. 4, where the transit time difference is obtained by cross-correlating upstream and downstream time-domain data [10] for the 2 V* mode, captured on a digital oscilloscope at a sampling rate of 31.25 MHz. Note that the time difference calculated from correlating the upstream and downstream 2 V* signals at zero flow is 0.64 ns and is lower than is usually observed in such systems [7]. This "zero flow offset error" is always observed in such measurements and is often compensated for by deducting it from the time differences measured during flow. There are a number of different sources of measurement error that can contribute to the zero flow offset error and errors during flow measurement [6]–[9].

In the graph of Fig. 4, the corrected data do not quite pass through time = 0, because the correction factor is obtained by fitting all the experimentally measured data to the true flow at each measurement point and discovering that all the ultrasonically obtained data fit the measured flow data simply by multiplying it by a constant correction factor. This was felt to be more reliable as the trigger jitter on the oscilloscope would have been at least 0.5 ns for each waveform captured and acknowledges that for such a small zero flow transit time difference, the zero flow offset value is more accurately determined from the gradient of the line across a broad range of flow rates.

The relationship between the calculated flow and the actual flow appears to be linear across the entire flow range, from laminar to turbulent, with a gradient of 0.94+/−0.6%. In larger diameter pipes, one might expect the correction factor of 0.75 in the laminar region to 0.94 for the turbulent region [10]. In our case, the way that the ultrasonic guided wave energy is distributed through the pipe cross section appears to produce a different dependency. This correction factor is liable to change for different guided wave modes, transducer separations, and for different contact areas between the PEEK wedges of the transducer and the pipe wall, as both these will affect the way that ultrasonic energy diffracts and spreads out through the cross section of the pipe. Examining other modes, one obtains the same type of dependency, where there are no other modes interfering with the main V* modes.

III. Conclusion

For higher order V* modes, the transit time difference flow measurement scales exactly in line with the hypothesis that all the V* modes spend an equivalent amount of time propagating through water as the equivalent V-path mode would have done when using simple ray tracing diagrams. The behavior clearly demonstrates that our understanding of the origin of the guided wave modes is correct, and that they can be used to measure flow. The time between upstream and downstream measurements here was in the range of nanoseconds. Water temperature between upstream and downstream measurements of 0.01 °C can shift the measured time difference by 1.2 ns, equivalent to approximately 1 ml/s. This can be mitigated by taking upstream and downstream measurements simultaneously, as will be described in future publications.

As the separation of the transducers is increased along the pipe, the general appearance or the number of observed V* wavemodes stays the same, only time shifted with some small amplitude variations, and the number of visible modes does not significantly increase above six or seven modes. There are modes other than the V* modes present in the time-domain data, and preliminary calculations have shown that the arrival times of these modes are consistent with them taking paths that are equivalent to taking a helical-like path down the bore of the pipe. These modes can be suppressed or enhanced by different transducer designs which will be the subject of future papers. Because several modes can be used in the calculation of flow rate simultaneously, more accurate flow rate results can be obtained using all the data available. Later arriving modes have larger transit time differences between upstream and downstream propagating waves, but they also tend to be of lower amplitude and can potentially have interference from other modes, and so care must be taken in calculating the flow rate. Nevertheless, the example provided in Fig. 4, where only the 2 V* mode is used, gives accurate results of the flow rate to within 1%, even for flow rates down to 1.25 ml/s. The guided wave signals reported in this article are relatively large amplitude, providing high SNR levels for drive voltages of only a few volts. The approach reported in this article enables accurate flow rate measurements on small-diameter liquid-filled, thin-walled metal pipes by cross correlation of guided wave mode signals. This is achieved using small and low-cost ultrasonic transducers that are easily integrated into a single push-fit clamp, with the transducers in a fixed position.

References

[1] R. C. Baker, *Flow Measurement Handbook: Industrial Designs, Operating Principles, Performance, and Applications*. Cambridge, U.K.: Cambridge Univ. Press, 2016.

[2] A. Bailleu, "Ultrasonic transducer positioning system for clamp-on flowmeter applications," in *Proc. IEEE Sensors Appl. Symp. (SAS)*, Apr. 2016, pp. 122–127.

[3] S. Mass and M. Laukner, "Ultrasonic time delay difference estimation with analytic signals and a model system," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 67, no. 10, pp. 2234–2238, Oct. 2020.

[4] D. V. Mahadeva, R. C. Baker, and J. Woodhouse, "Further studies of the accuracy of clamp-on transit-time ultrasonic flowmeters for liquids," *IEEE Trans. Instrum. Meas.*, vol. 58, no. 5, pp. 1602–1609, May 2009.

[5] Z. Li, L. Smith, and S. Dixon, "Design of miniature clamp-on ultrasonic flow measurement transducers," *IEEE Sensors Lett.*, vol. 5, no. 6, Jun. 2021, Art. no. 2500604.

[6] M. Aanes, R. A. Kippersund, K. D. Lohne, K.-E. Frøysa, and P. Lunde, "Time-of-flight dependency on transducer separation distance in a reflective-path guided-wave ultrasonic flow meter at zero flow conditions," *J. Acoust. Soc. Amer.*, vol. 142, no. 2, pp. 825–837, Aug. 2017.

[7] F. Schneider, F. Peters, and W. Merzkirch, "Quantitative analysis of the cross-correlation ultrasonic flow meter by means of system theory," *Meas. Sci. Technol.*, vol. 14, no. 5, pp. 573–582, Mar. 2003.

[8] B. Iooss, C. Lhuillier, and H. Jeanneau, "Numerical simulation of transit-time ultrasonic flowmeters: Uncertainties due to flow profile and fluid turbulence," *Ultrasonics*, vol. 40, no. 9, pp. 1009–1015, Nov. 2002.

[9] E. Sritham *et al.*, "Similarity model for estimating the error of clamp-on ultrasonic flowmeter: Flow in water supply piping system," *Eng. Lett.*, vol. 25, no. 3, pp. 239–246, 2017.

[10] H. Zhang, C. Guo, and J. Lin, "Effects of velocity profiles on measuring accuracy of transit-time ultrasonic flowmeter," *Appl. Sci.*, vol. 9, no. 8, p. 1648, Apr. 2019.