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Design of miniature clamp-on ultrasonic flow measurement transducers

Zhichao Li[1], Luke Smith[1] and Steve Dixon[1,2]

[1] *Department of Physics, University of Warwick, Coventry, CV4 7AL, UK*

[2] *School of Engineering, University of Warwick, Coventry, CV4 7AL, UK*

Abstract— Clamp-on ultrasonic transit-time difference measurements of liquid flowrate are widely used in industry for both flow metering and heat metering applications. However, the sensors used tend to be relatively large, hindering their use on small diameter pipes, and using more material in the transducer wedge than is strictly necessary. The accuracy of the technique depends on a number of factors, and particularly on the accuracy of the compression wave speed in the liquid that is used in the calculations to obtain flowrate or heat transfer rate from the liquid in the pipe. Many flow meters either assume a value for the wave speed or obtain it using thermocouple measurements of the pipe exterior with a look-up table or simple equation. An error in the liquid ultrasonic velocity relates directly to errors in the calculated flowrate. It is highly beneficial if the ultrasonic wave speed in the liquid can be accurately measured in real time for flowrate calculations, especially for temperature and pressure varying conditions. A new type of small clamp-on ultrasonic transducer is reported, using a 6mm wide PEEK wedge that contains two piezoelectric elements, one of which generates sound normal to the flow direction, yielding the measurement of ultrasonic wave speed in the liquid. The new transducers were tested on a small rig with a 15mm diameter copper pipe and a 70mm diameter stainless steel pipe, yielding accurate measurements of liquid ultrasonic velocity and flowrates.

Index Terms—Mechanical sensors, flow measurement, clamp-on ultrasonic transducers, injection moulding.

I. INTRODUCTION

Clamp-on ultrasonic flow metering is used extensively for measuring liquid flow rates in pipes. The technique is truly non-invasive and non-disruptive with low installation and maintenance costs, and is reliable and accurate over a wide range of flowrates. [1]. Transit-time [2], Doppler [3] and cross-correlation [4] are three general types of clamp-on ultrasonic flowmeters. This paper focuses on transducers used for transit-time ultrasonic flow metering, where two or more transducers are clamped to the outside of the fluid filled pipe (Fig.1). In this configuration, the transducers are positioned such that the ultrasonic velocity has a component aligned with the flow velocity. The transducers are repeatedly switched between generator and receiver to take upstream and downstream measurements. The transit time difference between the ultrasonic waves travelling in the downstream and upstream directions are used to calculate average flow velocity along the ultrasonic path, and correction factors are applied to the time difference measurement to yield the volumetric flowrate of fluid in the pipe [5].

Fig. 1 shows a schematic diagram of a transit-time clamp-on flowmeter with a Z-path configuration, where two transducers are placed on opposite sides of the pipe with a specific separation along the axial direction. The transducer TR1 generates an ultrasonic wave which travels though the transducer wedge, pipe wall and then through the liquid along the red solid line (downstream path). After passing through the pipe wall and into the wedge of the second transducer TR2, it is received as a voltage signal induced on the piezoelectric element. Then, the process is reciprocated, where TR2 generates an ultrasonic wave travelling along the blue dashed line (upstream path) which is eventually received by TR1. The angles of the transducer wedge are usually designed for a particular pipe material, such that the compression wave in the wedge mode coverts to a shear wave in the pipe wall. The wave is compressional in the fluid and mode coverts again into a shear wave at the opposite pipe wall, before generating a compression wave in the receiving wedge. This approach minimizes the number of wave modes present in a thick walled pipe to simplify waveform analysis. However, this does not happen when the pipe wall is of a similar thickness to the ultrasonic wavelength, and guided waves rather than bulk waves are generated in the pipe wall.

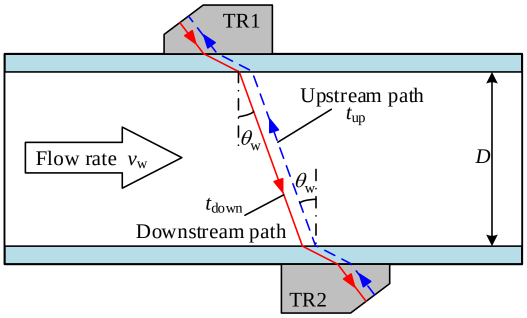

Fig. 1. Schematic diagram of the transmission path of ultrasonic waves between two transducers in a *Z*-configuration.

The transit times of ultrasonic waves along downstream and upstream paths are t_{down} and t_{up} respectively. For sub-sonic flows, the liquid flowrate v_w can be calculated from the time difference

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$\Delta t = t_{\mathrm{up}} - t_{\mathrm{down}}$ [5, 6],

$$v_{\mathrm{w}} = \frac{k_{\mathrm{h}} c_{\mathrm{w}}^{2} \Delta t}{2D \tan \theta_{\mathrm{w}}} \tag{1}$$

where k_h is the flow profile correction factor which depends on the Reynolds number [2, 7]; c_w is the ultrasonic velocity in the liquid; D is the inner diameter of pipe and θ_{w} is the refraction angle in the liquid. Further correction factors can also be introduced for internal pipe roughness [8].

Normally, the clamp-on ultrasonic transducers use machined polyether ether ketone plastic (PEEK) as the wedge material, because the semi-crystalline PEEK polymer offers a wide range of advantages such as resistance to chemicals, wear, fatigue and creep, favorable elasticity and low ultrasonic attenuation. A significant component of the cost of a flowmeter is the cost of the ultrasonic transducers. A conventional transducer design usually comprises a PEEK wedge of several centimeters size in each dimension, which is expensive in both material and CNC manufacturing costs. Injection moulding of pure PEEK to yield good quality ultrasonic wedges is possible at high manufacturing rates, using heated moulds and provided the component is thin enough. Making smaller PEEK transducers can result in lower cost sensors without any compromise on performance.

In this paper, a new design of clamp-on ultrasonic transducer is presented which uses a small PEEK wedge. It has two piezoelectric elements: one performs the flow measurement whilst the other, oriented to generate ultrasound normal to the flow, measures the ultrasonic velocity in the liquid and the pipe wall thickness. This is important for both flow metering and heat metering, where an error in the ultrasonic velocity of the liquid relates directly to errors in the calculated flowrate, as is evident from equation (1).

II. Design of the clamp-on ultrasonic transducer

Fig. 2 shows the geometry of the design of the clamp-on ultrasonic transducer, which includes a PEEK wedge and two piezoelectric ceramics PT1 and PT2. The contact area between the transducer and the pipe wall is narrow, as the wedge surface is flat while the pipe wall is curved. Without any couplant and for a rigid transducer face and pipe wall, this would be a line contact. Through the use of an ultrasonic couplant, the contact area can be made wider than the infinitesimally thin line or Hertzian type contact that would be expected for dry coupling. However, it is still narrow, especially on small diameter pipes with a sensible amount of couplant. Therefore, there is little benefit in having a wide bodied transducer if the contact area is narrow. Conventional PEEK transducers are typically 15-25 mm wide. The new transducers are designed to be much narrower, resulting in lower material costs. Designing thinner transducers lends itself to injection moulding, where the PEEK wedge could be between 12mm and 4mm wide, which is ideally suited to low cost, high volume manufacturing. As the wedge width decreases, one has to use smaller sizes of pieozoelectric sensors, which will generally have lower sensitivity than wider sensors. However, the limiting factor is the size of the contact area between the wedge and the pipe wall. The width of the PEEK wedge in this paper is 6mm and experiments have been conducted to show that these new small sensors produce excellent ultrasonic performance on large pipes and are very convenient and beneficial for use on smaller pipes, where the physical size of transducers can be a limiting factor in performing a flow measurement.

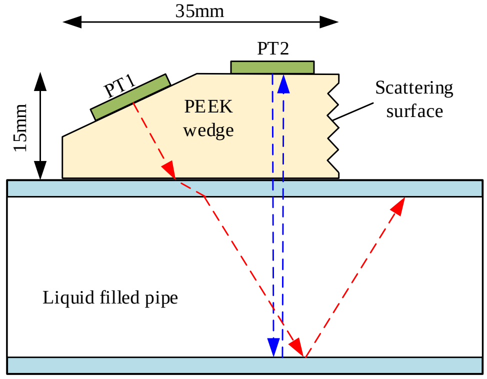

Fig. 2. Schematic diagram of the new clamp-on ultrasonic transducer, illustrating components and direction of wave propagation (not to scale). In this case, the piezoelectric elements are 0.5mm thick (4 MHz), 6mm wide, and 10 mm long PZT − 5H piezoelectric ceramics that are coupled to the PEEK wedge by means of a thin layer of silicone grease.

The piezoelectric ceramics are modified PZT-5H plates with a 4MHz through thickness resonant frequency (PI ceramic [9]), although the only requirement for the piezoelectric is that it has suitable sensitivity and is of a consistent quality. The piezoelectric elements are attached to the wedge surface using silicone grease as a couplant. PT1 is used to generate an inclined ultrasonic wave (path shown by the red dotted line), which is the typical type of path that ultrasound would take in a clamp-on transducer. A scattering surface is machined on the side opposite to PT1 to dissipate any reflected waves within the wedge. The additional piezoelectric element, PT2, is designed to send ultrasound vertically (blue dotted line) into the pipe and through the liquid so that with knowledge of the pipe material and dimensions, the ultrasonic velocity in the liquid can be measured and used in the calculation of the flow velocity, or used to calculate the temperature of the liquid. The same can be done using the transit time of the ultrasonic waves following the red path, but the accuracy of that measurement is more limited by other material property parameters (temperature, pressure and density etc.), in which the ultrasound propagates.

The new transducer design has been tested on two different diameter pipes, which will be illustrated in next section. The piezoelectric elements can also easily be replaced for ones operating at different frequencies for different measurement requirements.

III. Experimental results and discussion

A. Experimental setup

A schematic diagram of the experimental setup used to test the new clamp-on ultrasonic transducers is shown in Fig. 3. Two transducers were positioned on the pipe wall. Here, only one transducer (TR1) was fabricated with two piezoelectric elements and the ultrasonic velocities in pipe and liquid are measured using this transducer. An arbitrary function generator (Tektronix AFG3052C) generates a gated 4MHz sine wave pulse (amplitude 10V, 5 cycles) to the generation

PT1 and the other transducer's PT1 served as a receiver. A dual input, dual output switch was used to multiplex these two transducers to measure the downstream and upstream flows respectively. PT2 in TR1 worked as a transceiver by using a duplexer to connect the function generator and pre-amplifier. The amplified signals were recorded by a digital oscilloscope (Tektronix DPO2024, 1GS/s sampling rate) with 64 times averaging and then transferred to computer for post-processing. The function generator and oscilloscope could easily be replaced by low voltage, low power microcontroller based electronics that can also perform the time difference calculation and handle data communication.

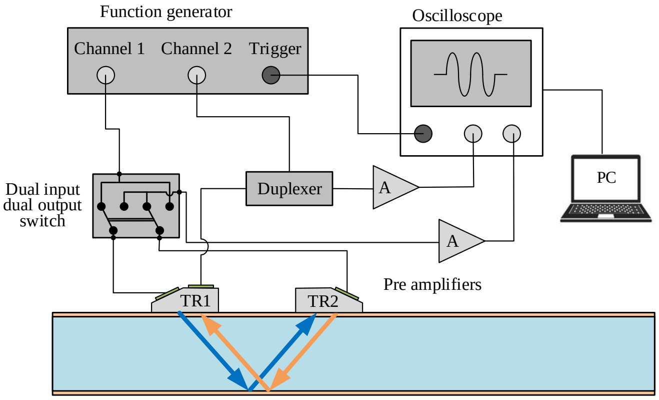

Fig. 3. Schematic of the experimental setup for the new clamp-on ultrasonic transducers.

B. Test on a 15mm diameter copper pipe

A simple flow rig was constructed with a 40 litre header tank providing water at a constant pressure through the 15mm outer diameter, 0.7mm wall thickness copper pipe (roughness 0.0013mm), with the flowrate varied by a tap. Volumes of water were captured over various time periods to provide accurate actual flowrate measurements. The maximum flowrate tested was 101.6mL/sec, which corresponds to a Reynolds number of 1.065×10^4.

Fig. 4 shows the ultrasonic waveform measured by the vertical piezoelectric element (PT2), which includes a main initial drive voltage signal, some reflections in the PEEK wedge and more reflections within the copper pipe.

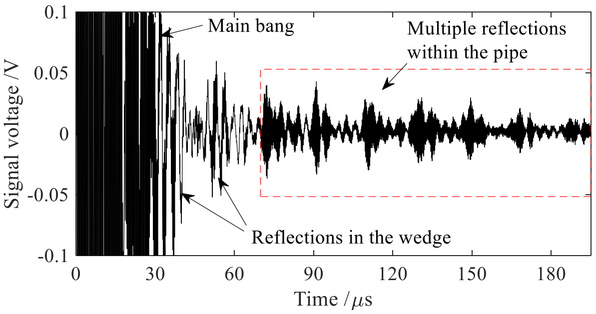

Fig. 4. A-scan waveform received by PT2 in TR1 on a 15mm copper pipe filled with water.

Some reflections within the copper pipe are masked by the initial generation voltage pulse and wedge reflection signals, but this is not actually limiting. The data after 65μs is used to calculate the ultrasonic compression wave velocity in the liquid using a magnitude fast Fourier transform [10]. The design of the transducer could be modified with backing materials, but it is unnecessary since the information required can readily be obtained. The ultrasound velocity in the liquid c_{w} can be calculated from the spectrum as

$$c_{\mathrm{w}} = \Delta f / 2D \tag{2}$$

where Δf is the frequency spacing of the spectrum peaks and D is the internal pipe diameter.

Fig. 5 shows the spectrum of the A-scan waveform in Fig. 4, with the peaks used to determine Δf. The maximum peak was selected first, which was used as a reference point to find the other peaks at specific spacing steps. A threshold was used so the peaks above this value are averaged, yielding a value for the ultrasonic wave speed in water of 1485 m/s using equation (2), which is close to the nominal value of 1482 m/s at room temperature [11].

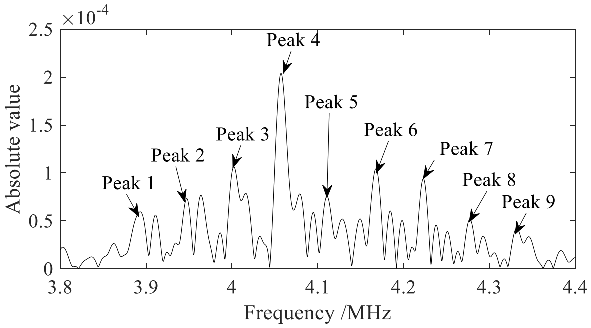

Fig. 5. Frequency spectrum of the signal in the red dotted box of Fig. 4.

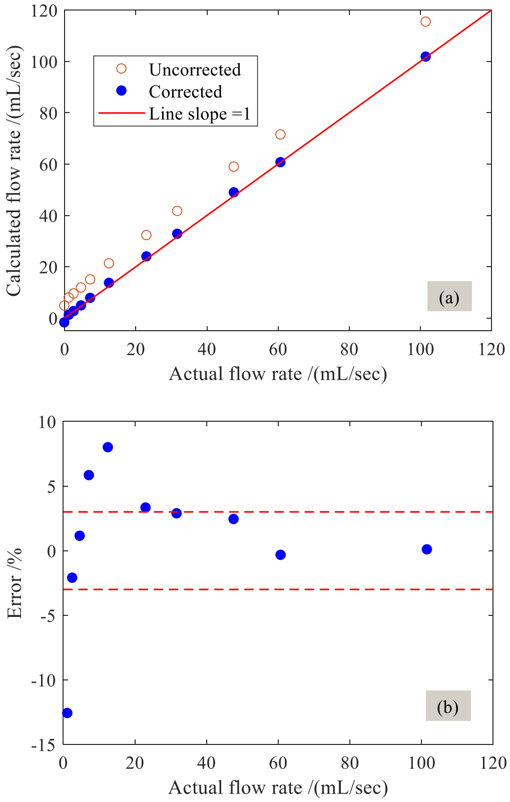

Fig. 6. (a) Flowrate measurement using average fluid velocity from ultrasonic measurement and the corrected flowrate is obtained using zero flow offset calibration and flow profile correction and (b) relative percentage error of the corrected flowrate.

Measuring the upstream/downstream ultrasonic transit time difference of the wave that has travelled 2 V-paths in the copper pipe at a data acquisition rate of 31.25 MHz yields the data shown in Fig. 6. Using the raw time difference data with zero flow calibration, one can calculate the flowrate based on the ultrasound velocity obtained from PT2, but this needs correcting to account for flow profile [12]. In this case an empirically determined correction factor of 0.94 was applied to all the data from laminar to turbulent flow, which is surprising and will be the subject of further research.

Fig. 6(a) shows a good agreement between the calculated and actual flowrates after correction in the copper pipe when flowrate varies between 1 mL/sec and 100 mL/sec, yielding a measurement accuracy within a 3% error range (red dotted line in Fig. 6(b)) when the flowrate is larger than 25mL/sec. The largest percentage error is found at low flowrates as the time difference measurements become very small, on a scale where the oscilloscope time trigger jitter becomes more significant [5].

C. Test on a 70 mm stainless steel pipe

The new ultrasonic transducers were also tested on a larger stainless steel pipe (outer diameter 70mm, wall thickness 5mm, roughness 0.003mm) with a single V-path configuration and the results are shown in Fig. 7.

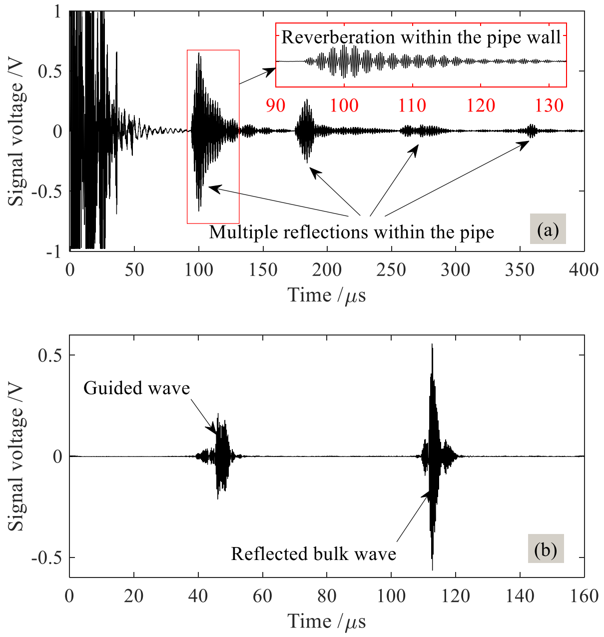

Fig. 7. Waveforms received from (a) normal path and (b) V-path on a 70mm stainless pipe filled with water.

Fig. 7(a) shows the A-scan waveform using the normal incidence ultrasonic path, where multiple reflection signals within the pipe cavity and wall can be used to calculate the liquid ultrasonic velocity as described before and the pipe wall thickness. The averaged frequency spacing in the FFT of this waveform is 12.36 kHz, and the calculated ultrasonic velocity in water is 1483 m/s. The inset of Fig. 7 (red box) shows reverberation within the pipe wall that can be used to calculate ultrasonic velocity in stainless steel. The averaged frequency spacing is 572.43 kHz and the calculated ultrasonic velocity is 5724.3 m/s. Fig. 7(b) shows a clear distinction between the guided waves and the reflected bulk waves with a good signal-to-noise ratio. The bulk wave signal can be used for flowrate measurement when there is flow in the stainless pipe.

IV. CONCLUSION

A new miniature clamp-on ultrasonic transducer for accurate flow measurement has been designed. It is much smaller than existing clamp-on ultrasonic transducers and has a much narrower PEEK wedge. The small size and simplified geometry of the transducer means that it can be injection moulded, which reduces the material and manufacturing costs, and speeds up manufacturing time. There is an extra piezoelectric element in the new transducer to generate and receive ultrasound that propagates vertically into the pipe and through the liquid. The ultrasonic velocity of the liquid can be accurately measured instead of being assumed or obtained from a “look-up” table, which is necessary for accurate flowrate calculation. The new transducers have been tested on different pipes and they produce excellent ultrasonic performance in small diameter pipes. In a 15 mm copper pipe, the new transducers can measure small flowrate down to a few millilitres per second, with high accuracy. The frequency of the transducers can also be easily varied by attaching a different piezoelectric element into the device.

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