ULTRASONIC TRANSDUCERS FOR GAS AND LIQUID FLOW METERING

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ABSTRACT

Accurate fluid flow metering is essential for modern process control, and ultrasonic flow meters are well established in this area. However, the specific acoustic impedance mismatch for most piezoelectric ultrasonic transducers is different when operating liquids and gases, hence there are problems measuring two-phase flows when using a single type of piezoelectric transducer in a flow meter.

This work focuses on the development of a transit-time flow meter using a novel type of capacitive ultrasonic transducer, which can measure the flow in both gases and liquids. A rig for investigating gas and liquid flows has been constructed to enable a thorough study of fluid flow measurement in pipes ranging from 25mm to 100mm in diameter, enabling an analysis of flows from the laminar region through to the fully turbulent. The ultrasonic propagation times in fluid flow have been measured through the use of cross-correlation techniques implemented in MATLAB, which has proved to be a very robust method of measuring the differences between the upstream and downstream signals and thus it was possible to accurately determine the fluid flow rates in the pipe. Further signal processing was used to smooth the output of the flow meter. Different transit-time flow meter configurations were tested to examine the effects of positioning the transducer ports at different angles to the pipe and also, to examine the effects of multiple reflections of ultrasound in the pipe on the output data.

KEYWORDS: Ultrasonic flowmetering, capacitive ultrasonic transducers, signal processing, transit-time flowmeter.

1. INTRODUCTION

It is essential in all industries, involving the flow of a product, to be able to measure the exact amount that is flowing at any given time. There are several different types of flow meters available such as, Mechanical Flow meters (e.g. Piston Meter, Woltmann Meter or a Jet Meter, which all measure flow through some mechanical means), a Vortex Flow meter (vortices are generated by obstructing part of the fluid path, producing a voltage pulse, the frequency of which can be measured and hence flow can be determined), Magnetic Flow meters (potential difference of a conducting fluid, as a result of an applied magnetic field, is measured and flow can be determined), Turbine flow meters, etc. This research involves ultrasonic flow meters [1], a few of the variations of which will be discussed in the next section.

The main aim of this research is to design and construct an ultrasonic flow meter that can be used to measure the flow in both liquids and gases. Currently, piezoelectric transducers are generally only effective in liquids as there is a specific acoustic impedance mismatch between most piezoelectric materials and gases, rendering them ineffective in gases. Ones that are effective in gases, usually have high acoustic impedance and a narrow bandwidth [2]. Therefore, capacitive ultrasonic transducers (CUTs) will be used to measure the flow in gases in this project.

This paper will focus on experiments conducted in water, in a pipe of 32mm diameter (27mm inside diameter), using 2.25MHz commercial piezoelectric transducers, with different transducer configurations composing the contra propagating flow meter, such as the 'V' path for a single reflection off the pipe, where two pairs of transducers will be placed at 45° to the flow and one pair will be used to measure the time taken for the ultrasound to travel downstream and the other pair will be used to measure the time taken for the ultrasound to travel upstream. Each flow meter configuration will be calibrated with no flow to determine optimum transducer position and then tested in the circulation system.

A software program developed in MATLAB to measure the fluid flow will be discussed. The fundamentals of this program involve windowing the waveforms to remove any dc offset and cross-correlating the waveforms to determine the time difference between the upstream and downstream signals being received. Thus, this can be used, in conjunction with mathematics, to determine the flow of the fluid in the pipe. The following section will give a brief overview of the theory involved in this research.

2. BACKGROUND THEORY

Ultrasonic flow meters can measure the mean velocity or flow of a fluid. They measure the flowrate by analysing the interaction of the acoustic waves with the moving fluid. The popularity of using ultrasonic flow meters is rapidly increasing and they are currently manufactured to be highly accurate for many applications including ones involving high-pressure gas transmission systems [3-4], for natural/domestic gas [5], for producing an image of the flow in the pipe [6], for very low velocity flows [7], and very high velocity flows [8].

There are numerous ultrasonic techniques, which can be employed to measure the flow of a fluid. Three of the most common types of ultrasonic flow meters are the Doppler (reflection) flow meter [9], the transit time (time-of-flight) flow meter and the cross-correlation flow meter [10]. However, in this research, the transit time flow meter will be used to determine the flowrate of fluids and it is discussed in section 2.1 below.

2.1. Transit Time Flow meter

The average fluid velocity may be determined by calculating the differences between the transit times of the signals, since the flow velocity component either adds to or subtracts from the fluid's apparent velocity of sound in the downstream and the upstream directions respectively [11]. An illustration of the ultrasonic transit time flow meter is given below in Figure 1, where t_u and t_d are the upstream and downstream propagation times respectively, d is the diameter of the pipe, L is the ultrasonic beam path length between the transducers, v is the flow velocity, θ is the angle of flow to the ultrasonic beam and c is the speed of sound:

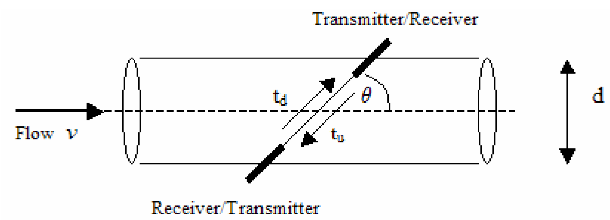

Figure 1: Transit time flow meter.

Thus, t_u and t_d may be calculated using the relation of $L=d/sin\theta$ as follows:

$$t_u = \frac{d}{\sin\theta(c - v\cos\theta)} \quad (1)$$

$$t_d = \frac{d}{\sin\theta(c + v\cos\theta)} \quad (2)$$

The transit time difference between the received signals, Δt is:

$$\Delta t = \frac{2 \times d \times v \times \sin\theta \times \cos\theta}{c^2} \quad (3)$$

since usually v<<c^2.

However, the speed of sound can be difficult to measure. To eliminate it from the expression in equation (3) is preferable, as it means that the measurement of the fluid velocity is independent of properties such as pressure, temperature and gas composition (when measuring gases).

Hence, manipulating equations (1) to (3), the flow velocity, v, is:

$$v = \frac{d}{2\sin\theta\cos\theta} \times \frac{\Delta t}{t_u t_d} \quad (4)$$

A flow profile correction factor must be applied to the flow velocity to calculate the mean fluid velocity, shown in equation (5).

$$K = {}^{v}/_{v_m} \quad (5)$$

Hence, the volumetric flowrate, Q, may be calculated by multiplying the mean fluid flow velocity by the cross-sectional area of the pipe as shown in equation (6).

$$Q = Av_m \quad (6)$$

2.2. Ultrasonic Transducers

In a flow metering or a flow imaging system, one of the most important parts of it is the front end, i.e. the transducer or transducer array required to acquire the necessary data to determine the fluid flow or to produce a meaningful image [12]. A transducer is used to produce and detect an ultrasonic wave in a material, by converting electrical energy into ultrasonic energy and vice-versa. Usually, for a clamp-on transducer, a couplant-layer is used for transducers to overcome the impedance mismatch between air and any solid material [13]. However, in this research, wetted transducers are used where the transducers are situated in the pipe fluid flow, in the flowmeter section. Therefore, there is no need for a couplant layer. Two types of transducers will be investigated such as commercial piezoelectric transducers and experimental capacitive ultrasonic transducers.

2.2.1. Piezoelectric Transducers

Four piezoelectric transducers (Krautkramer, Alpha Series, 0.5 inch, 2.25 MHz, non-focussed immersion probes) are used in this work to measure the flow of liquids, as shown in Figure 2. Two of these are to measure the upstream propagation of the ultrasonic wave and two are to measure the downstream, which can then be used to calculate the flow of the liquid under examination.

Generally, ultrasound is produced when an AC signal is applied to the transducer. When the transducer is used in transmitting mode, the AC voltage causes the piezoelectric material to radiate a sound wave in the front face of the transducer and conversely, in receiving mode, the sound waves hitting the front face of the transducer induce a strain on the piezoelectric material that leads to an electric field, which is then sent to the electronic apparatus (oscilloscope etc.).

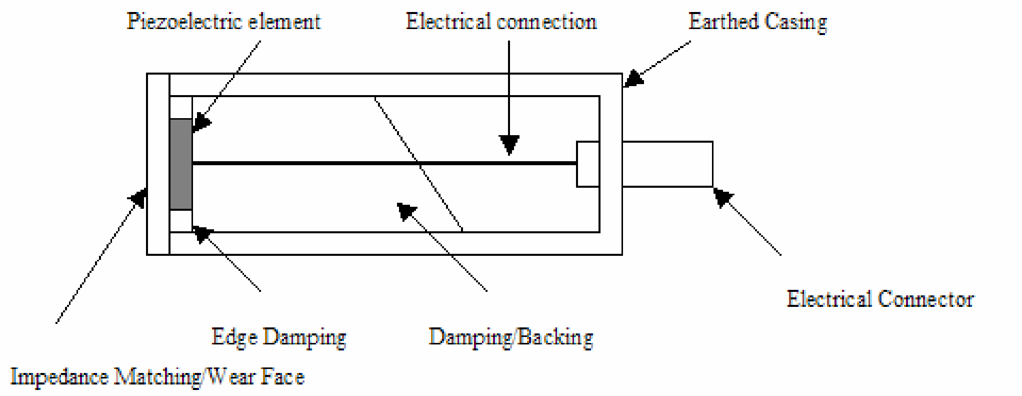

Figure 2.2: Schematic of a typical piezoelectric transducer.

2.2.2. Capacitive Ultrasonic Transducers (CUTs)

Air-coupled ultrasonic transducers are rapidly becoming a growing area of research [14-15]. This study will use experimental capacitive (electrostatic) ultrasonic transducers (CUTs) when measuring the flow of gas through the flow meter. These CUTs theoretically operate in air at frequencies up to and over 1 MHz. In general, they consist of a rigid conducting backplate and a thin metallized dielectric membrane that form the two electrodes of a capacitor, as shown in Figure 3.

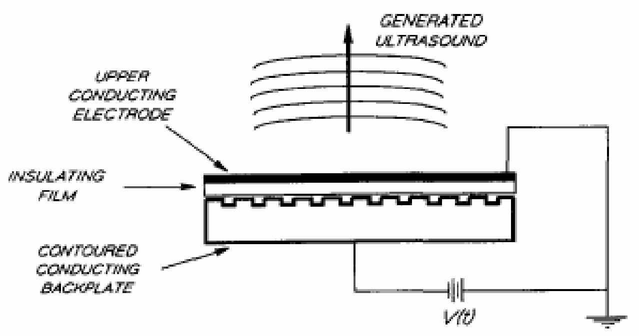

Figure 3: Illustration of CUT [15]

3. EXPERIMENTAL PROCEDURES

The experimental apparatus consisted of the following; a pump, with a maximum flowrate of 115 litres/minute, was placed a the water tank used to circulate the flow through the flow meter section. The flow meter section was placed 20 diameters (i.e. 20x1.25”) from the first 90°

bend and 20 diameters to the second 90° bend to ensure that the flow profile was fully developed in the flow meter section. A second tank was used to ensure continuous operation of the process. Thus, the water was returned via a sloped recirculation pipe to the first tank, by means of gravity. A schematic diagram of the experimental apparatus is given in Figure 3.

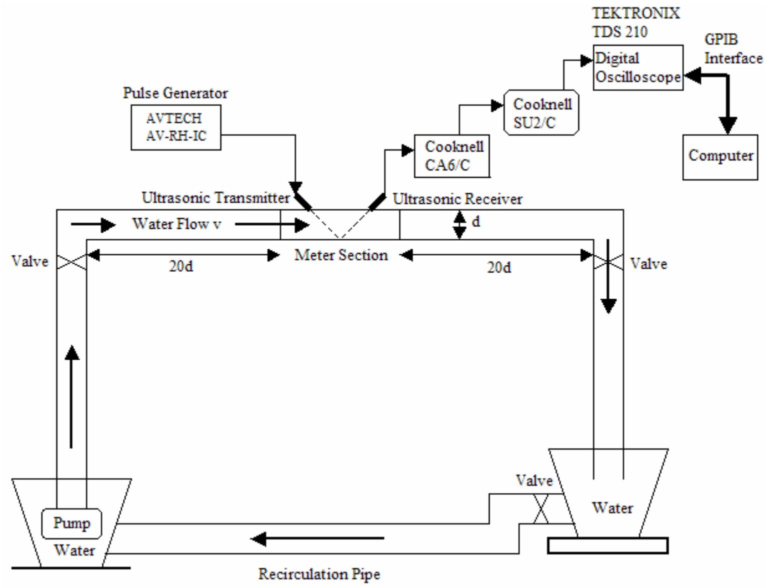

Figure 3: Experimental apparatus to measure the flowrate of water.

As the length of the ultrasonic path between the transmitting and receiving transducers increases, the accuracy in determining the transit time difference between the upstream and downstream times increases. Thus, flow meter sections with one or more reflections off the pipe wall generally produce increasingly more accurate results. The 'V' flow meter section is shown in Figure 3 and the experimental results for the 'V' flow meter are discussed in the next section.

4. RESULTS AND DISCUSSION

The fluid flowrate in the 'V' configuration flow meter using the piezoelectric transducers is determined through MATLAB as follows:

- Acquire the data from the oscilloscope using MATLAB.
- Apply a moving average filter to the data.
- Use cross-correlation on the reference data at zero flow and export data to desired location.
- Determine transit time of experimental signals (when there is a flow) by comparison with reference signals (at zero flow).
- Determine ultrasonic flowrate and compare with the measured flowrate.

When there is a flow in the pipe, the waveforms at that flow are recorded, averaged and windowed. Thus, when there is a theoretical flow of 28 litres/min, after averaging and windowing functions have been applied, the upstream and downstream ultrasonic signals are as shown in Figure 4.

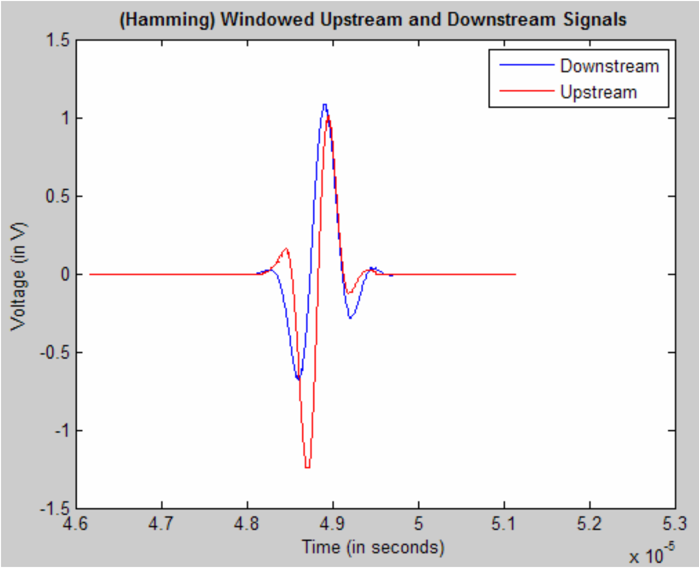

Figure 4: Windowed Waveforms at Theoretical Flowrate of 28 litres/min

The flowrate is calculated for the waveforms in Figure 4 by cross-correlating the upstream signal with the reference upstream signal (when there is no flow) to determine the upstream time difference, t_u, and similarly for the downstream direction. Equations (4) to (6) may then be used to calculate the ultrasonic flowrate of the fluid. This procedure was repeated for other theoretical flowrates and the theoretical flowrates were plotted against the ultrasonic flowrates, shown in Figure 5. An R^2 line was fitted to the plot, which showed a correlation of 0.998 between the data sets. Thus, the meter correction factor, K, may be calculated using the slope of the R^2 line. In this case, the meter correction factor is 0.98, which shows that there is good correlation between the measured and ultrasonic flowrates.

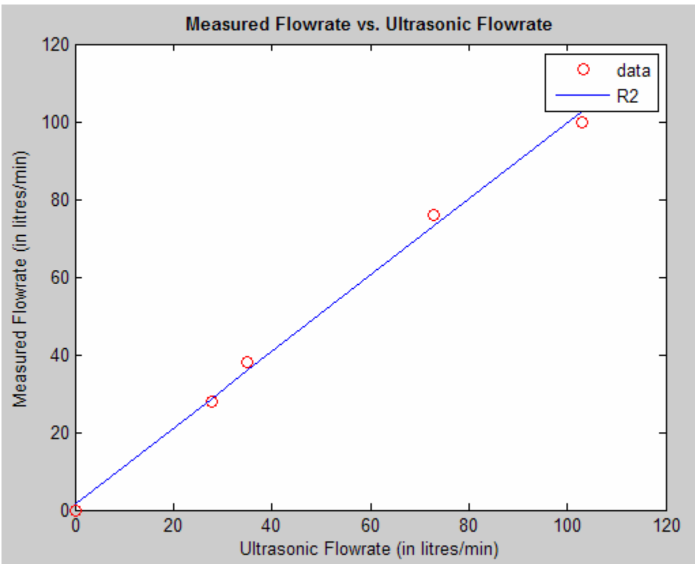

Figure 5: Summary of flowrate results for 'V' flow meter

Gas flowrates may be determined using the same signal processing techniques as described previously. However, CUT transducers are used to measure gaseous fluid flow. Figure 7 shows the pulse transmitted by a CUT and received by another CUT, when there is no flow in the pipe. The pulse in Figure 7 has been averaged and windowed to isolate the useful information. A second set of CUTs may be used to measure the upstream and downstream airflow, when compressed air is flowing through the pipe, utilising various transducer configurations as mentioned previously. It is expected that the shape of the pulses will change slightly and they will also be out of phase when there is a flow in the pipe. The phase shift will indicate the flowrate.

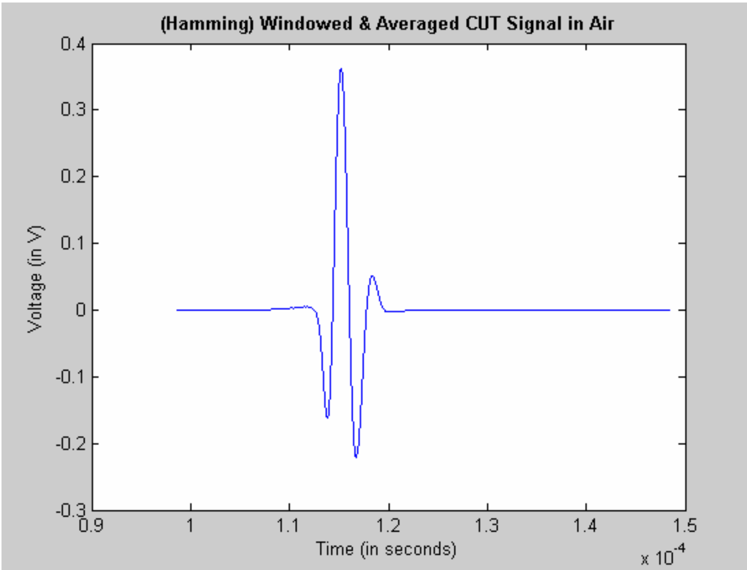

Figure 7: CUT waveforms in Air (zero flow)

5. CONCLUSIONS AND FUTURE WORK

In this research, a system (comprised of hardware and software) was set up to accurately measure fluid flow. A contra propagating (transit-time) flow meter was used. Piezoelectric transducers (placed at 45˚ to the flow) were used in the flow meter section and the 'V' flow meter configuration was used, as mentioned previously in the report.

Software was successfully developed in MATLAB to accurately measure the flowrate in the system (i.e. flow of fluid passing through the flow meter). Firstly, it was required to import the data from the oscilloscope correctly to MATLAB, i.e. the data points (time of peak, etc.) on the oscilloscope exactly matched the data reproduced in MATLAB. An averaging function was then applied to the data, to smooth it slightly. A hamming windowing was applied to the data to isolate the ultrasonic pulses. Cross-correlation was then used to accurately determine the transit times of the signals and hence the flowrate was calculated. A GUI was set up to implement the aforementioned functions.

The ultrasonic flowrate was calculated using a 'V' flow meter configuration with the developed software and compared with the theoretical flowrate, for water. The data was fitted with an R^2 line of 0.998, showing that there is very good correlation between the ultrasonic and measured results and giving a meter correction factor of 0.98. Thus, the ultrasonic measurement of flow is a very accurate method of measuring the flowrate of water.

Future work for this research project includes testing the CUTs in different flow meter configurations at different flowrates of compressed air; to waterproof the CUTs and to test them in water; to compare the CUT results in water with the results produced by the piezoelectric transducers; to test the CUTs and piezoelectric transducers in oil and oil and water mixtures.

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