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Ultrasonic fluid flow measurement using PZT crystals

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***Abstract*—Ultrasonic fluid flow measurement using PZT crystals presents and discusses an embedded system for determining fluid flow velocity in thin pipes of size less than 10mm by using piezoelectric transducers for transmission and reception of ultrasonic signals. The fluid flow velocity is found by the transit time measurement.The paper discusses twodesign approaches, one using inbuilt signal processing elements and other using application specific IC- TDC GP22 that are employed to develop a prototype ultrasonic flow meterwhich provides high accuracy, low power, and most importantly largely scaled down body. Out of the two approaches, TDCGP22 provides higherrangeof operation and better accuracywhile the inbuilt signal processing approach reduces the cost exponentially in its limited range of operation.**

***Keywords*—Transit time method; ultrasonic signal; fluid flow measurement; piezoelectricity**

I. Introduction

Presently there is a dearth of devices which measure the blood flow velocity in an individual blood vessel during various neural, cardiac and other critical incisional treatments, which play a critical role for monitoring and controlling the blood flow rate. The flow meters in the market operate with internal tube diameters significantly higher than that of the Aorta (the main artery of the human body), thereby making them unserviceable for surgical purposes. To build a device competent enough, use of expensive ASICs could increase the cost, making it a distant high end technology. A prototype is designed in which the flow rate of the liquid in the pipe is calculated from the acquired transit-times by a time to digital converter (TDC) GP22 circuit and in parallel with the designed signal conditioning and microcontroller based circuitry. The microcontroller based approach reduces the cost by a great extent compared to the ASIC GP22 setup. The main advantages of the systems are the fluid flow measurement with high accuracy, low power consumption and a largely scaled down body compared to the commercially available flow meters.

A. Selecting the transducer

Ultrasonic flow measurement refers to the measurement of velocity of fluids flowing in a closed medium[1]. This is made possible with the use of PZT (Lead-Zirconium-Titanate ceramic) crystals which exhibit piezoelectricity, the conversion of electric energy to mechanical energy or sound energy and vice versa. The PZT crystals transmit and receive mechanical waveswhich unlike the electromagnetic waves require a mediumfor their propagation. The mechanical waves with frequency higher than the upper audible limit (20,000Hz) of human hearing are ultrasonic waves.These waves undergo attenuation due to viscosity of the medium, heatconduction and molecular absorption. The ultrasonic propagation distance is inversely proportional to the square of frequency**.** Thus a higher resonant frequency crystal is chosen, as our application involves low dimensions. Further it is advisable to have several wavelengths of travelof the ultrasonic wave in the fluid flow path; this is best accommodated when the wavelength is small or the frequency is higher. The resonant frequency is the frequency of electrical signal which excites the piezoelectric material to maximum energy vibrations. The resonant frequency is found experimentally using laser Doppler vibrometer (LVD), which is a scientific instrument that is used to make non-contact vibration measurements on a surface. The laser beam from the LVD is directed at the surface of interest, and the vibration amplitude and frequency are extracted from the Doppler shift of the reflected laser beam frequency due to the motion of the surface. The LVD frequency measurement graph is shown in fig. 1. The resonant frequency is found at 535 kHz. The piezoelectric element used has piezoelectric coupling co-efficient, k_{33} of 0.70 and piezoelectric charge constant, d_{33} as $400x10^{-12}$ CN^{-1}. The crystal has a Curie temperature of 360° Centigrade.

B. Principle of fluid flow measurement

The average flow velocity of the fluid can be found using transit time method and Doppler frequency shift method.In transit time method, ultrasonic flow meters measurethe difference between time of ultrasonic pulses propagating upstream (t_{up})and downstream (t_{down}) flow direction. The time difference (Δt) is the measure of the average velocity of the fluid along the path of the ultrasonic beam.

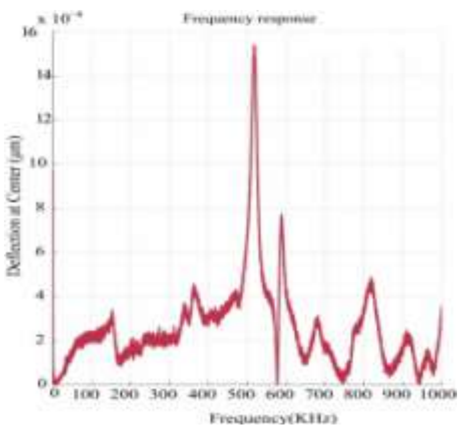

Fig. 1. Plot of applied frequency (kHz) at the PZT crystal plates versus the displacement measured (μm).

Using thetime instances pair t_{up} and t_{down}, the transit time Δt, which is proportional to the flow velocitycan be calculated as follows.

$$\Delta t = t_{up} - t_{down} \quad (1)$$

Another method in ultrasonic flow metering is the use of the Doppler shift that results from the reflection of ultrasonic beam from sonically reflective materials, such as solid particles, entrained air bubbles in a flowing fluid, or the turbulence of the fluid itself. Doppler flow meters are used for slurries, liquids with bubbles or gases with sound-reflecting particles [2]. Since, we are considering a homogeneous fluid, without any particles to satisfy the requirements of Doppler shift method, the technique of transit time flow measurement is used.

C. Selecting the embedded interface

The measurement of transit time is done in two approaches. The first approach reduces the cost of the system exponentially by the use of in-house developed signal conditioning elements supported by a low-power 16 bit microcontroller, MSP430G2553 for the calculation of transit time. The second approach uses the application specific IC-TDC GP22, which provides end-to-end electronic solution for fluid flow measurement providing Pico second resolution in time of flight applications.

II. Working Principle

The transit-time ultrasonic flow meter utilizes two pairs of piezoelectric transducers, which are placed at specified distances from each other [3] [4]. In principle, when transmitters A and C of Fig. 2 are biased with their resonant frequencies, they vibrate with maximum amplitudeemitting ultrasonic signals. Ultrasonic signals travelling in the direction of the flow is depicted with the subscript "up"and is propagated at a faster rate compared to ultrasonic signals travelling against the flow,denoted by the subscript "down". The received signals from receivers B and D are fed to time difference calculator circuitry. The difference in transit times is directly proportional to the mean flow velocity of the fluid. The calculated difference is fed to a microcontroller which is programmed to calculate the velocity of the fluid in real-time. The volumetric flow rate per unit is the product of the mean flow velocity and the cross sectional area of the pipe. The fluid flow velocity is calculated as follows,

$$\Delta t = \frac{2dv\cos\alpha}{c^2 \sin 2\alpha} \quad (2)$$

Where, 'Δt'is the transit time calculated from (1). 'd'is the distance between the receiving and transmitting transducers.

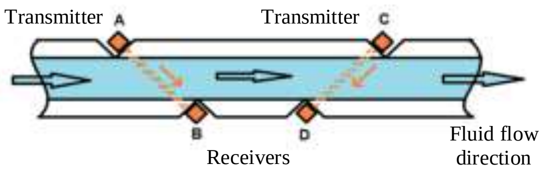

Fig. 2. Principle of ultrasonic flow meters

'α' is the angle of inclination of the transducers with respect to the normal at the pipe-fluid interface. The volumetric flow [5] of the fluid in the pipe can be found by,

$$Q = \frac{\pi}{4D^2 v} \quad (3)$$

D is the diameter of the pipe in meter; Q is the volumetric flow rate in m^3/s.

A. Design

The configuration in fig-2 did not seem suitable for our design withthin pipes. Due to low acoustic impedance provided by solids, mechanical waves travel faster in metal compared to fluid. Assuming the pipe to be made up of stainless steel and the flowing fluid to be water, the velocity of sound in stainless steel is 5800m/s compared to its velocity in water at 1480m/s and in air at 330m/s. The acoustic impedance provided by stainless steel is negligible compared to that provided by water or air. As described by Snell's law the acoustic wave undergoes reflection and refraction while passing from one medium to another. The amount of reflected and refracted (and hence further propagated) intensities can be found by[6].

$$R = \frac{m\cos\alpha - n\sqrt{1 - \frac{\sin^2\alpha}{n^2}}}{m\cos\alpha + n\sqrt{1 - \frac{\sin^2\alpha}{n^2}}} \quad (4)$$

$$T = 1 - R = \frac{2m\cos\alpha}{m\cos\alpha + n\sqrt{1 - \frac{\sin^2\alpha}{n^2}}} \quad (5)$$

$$\theta_{Critical} = \arcsin\frac{v_{water}}{v_{stainless\ steel}} \quad (6)$$

Where R is the reflection coefficient and T is the transmission coefficient. 'm' is the ratio of medium densities and n the ratio of sound velocities in the medium, also known as refractive index of the medium with respect to sound, '$\theta_{Critical}$' is the critical angle for water-stainless steel interface, 'v_{water}' and '$v_{stainless\ steel}$' are the velocity of sound in water and stainless steel respectively. It can be shown that around 50% of the sound energy is propagated from the transmitter to the receiver. Furthermore, the large difference of acoustic impedances between fluid and solid mediacauses the critical angle, given by (6) for total internal reflectionto be 14° with respect to the normal, inferring any angle above 14° to be completely reflected back into the water media. From Snell's law the angle of incidence can be calculated for incident wave to be at 3° with respect to the normal.

Due to low critical angle, the maximum path distance of the ultrasonic wavecannot approximately exceed the cosine of total reflection angle times the diameter of the pipe. To overcome these limitations we choose the design shown in Fig-4, which provides highest transit time possible for the given configuration[7][8].

B. Transit time determination

The feasibility of having discrete digital and analog components was explored. The overall signal conditioning block diagram is shown below.

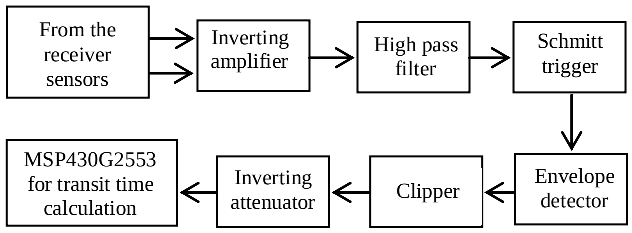

Fig. 3. The overall signal conditioning block diagram

The firstprocess is the amplification of weak signals received from the sensors. An op-amp inverting amplifier is used for this purpose as it provides high input impedance and electrical stability. The gain of an inverting amplifier is given by,

$$G = -\frac{R_f}{R_{in}} \qquad (7)$$

Where G is the closed loop gain, R_f is the feedback resistance and R_{in} is the input resistance. The gain is appropriately calculated to increase the signal strength from an initial 75-150mV to 2-4V. The low output impedance makes the signal compatible for further conditioning. A measurable quantity of low frequency noise is present in the amplified signal. This was reduced using an active second order high-pass (Sallen Key) filter. The cutoff frequency of the filter is fixed near the signal frequency.

In the real world, most data is characterized by analog signals. In order to manipulate the data using a microcontroller or a microprocessor, analog signals must be converted to digital signals. The process of converting analog continuous time signal into digital values is digitization.We choose not to use an ADC as the minimum sampling rate of the ADCs must be at least twice greater than the maximum frequency component of the input signal, as defined by the Nyquist-Shannon sampling theorem. To get a better quality of digital/discrete time samples, the signal must be oversampled, i.e. much beyond the Nyquist rate (twice the maximum frequency).

Fig. 4. The implemented design

As the operating frequency of the sensors is close to 1MHz, the sampling rate comfortably enters a few Megahertz, to which finding a compatible microcontroller would be difficult. Thus we chose a simpler method by converting the entire burst of signals into a single envelope, triggered by the first signal in the burst.Schmitt trigger devices are typically used in signal conditioning applications to remove noise from signals used in digital circuits. It is an active circuit configurable to convert an analog input signal to a digital like output signal. The circuit is named a "trigger" because the output retains its value until the input changes sufficiently to trigger the change in the output.The inverting Schmitt trigger circuit was designed for a reference voltage, V_{ref} of 0.20V.

The next section uses an envelope detector, which takes a high-frequency signal as input and provides an output which is the envelope of the original signal. Most practical envelope detectors use either half-wave or full-wave rectification of the signal to convert the analog input into a pulsed DC signals. Filtering is then used to smooth the signal by removing high frequency spikes. Unwanted voltage components can be clipped and an inverting amplifier is used to keep a constant 3V level, along with impedance matching and phase change compensation caused at the first stage amplification.

The microcontroller is used to calculate the transit time between the first wave of the receivedupstream and downstream flow direction [9]. Most modern day microcontrollers do not run at a clock rate greater than a hundred megahertz. Even though we assume to use an ultrahigh speed microcontroller near 100MHz, each machine cycle takes 10 nanoseconds for completion. Programming the controller using a high level language like embedded C program increases the latency as each high level instruction is a set of multiple machine level codes, requiring multiple machine cycles for its execution. Posing a limit on the least time that can be measured by a given microcontroller. Thankfully there are ASICs- Time to digital converters which can be used to measure transit times as low as 50 picoseconds.

A TDC GP22 It is an integrated circuit for high precision time interval measurements. It uses the propagation delays of simple logical gates (i.e. inverters) for fine quantization of time intervals. Due to the enormous achievements in signal speed, especially in the CMOS sector, it has become possible to implement such TDCs in standard CMOS technology with a resolution in the picosecond range.The TDC GP22 produces a 1 MHz sine burst of 20 pulses which is provided alternatively to the two transmitters.The two receiver sensors are given as the input to the ASIC. The transit time 't_{up}' and't_{down}' are sent to the microcontroller ATMEGA 328P through serial peripheral interface (SPI) protocol. SPI is a synchronous serial communication interface used for short distance communication, primarily in embedded systems. SPI devices communicate in full duplex mode using a single master and slave architecture.The microcontroller ATMEGA 328P receives the transit times and is programmed to calculate the fluid flow velocity. The fluid flow velocity is displayed on the serial monitor.

The other approach to determine fluid flow rate employs the use of microcontroller MSP430G2253 along with the signal conditioning elements to calculate the fluid flow velocity. The microcontroller is used to find the time duration between the first waves of the receiver signals for upstream and downstream direction. The ultralow power microcontroller which consumes typically 230uA during active operation and 0.5uA during standby mode can be calibrated to run at 18.5MHz(theoretical maximum clockfrequencyis to26MHz), amounting to 54ns for each machine cycle. The digitized pair of signals from the PZT sensors is provided into the microcontroller as port interrupts configured for rising edge detection. The 16 bit timer is started the moment the first pulse triggers an interrupt on one of the ports. The timer counts upto'0xFFFFh', after which it triggers an overflow-interrupt before resetting the counter value. The timer is stopped when the second pulse triggers an interrupt at the port. The value of duration is stored and converted to seconds by multiplying the total count with the machine cycle duration. This is further used in (2) to determine the fluid flow velocity. Instantaneous values can be observed on the serial monitor.

III. Results

This section details the results obtained during the execution of the project. It describes the results obtained for the setup using signal conditioning and MSP430G2553. Fig 5 shows the input signal (yellow) given to the transmitter, which is a sinusoidal burst of 585 KHz consisting of 20 cycles. The received signal is also a sinusoidal burst consisting of far larger number of cycles, occurring due to direct oscillation of receiver due to transmitted wave undergoing multiple internal reflections and echo from receiver and transmitter signal.However the first wave of the receiver is initiated by the transmitted wave, hence eliminating other wave components can be possible. The right hand image is the output from the signal conditioning side, which is given as the input to the port pins of MSP430G2553. The time difference between the transmitted and received signal for a single transmitter-receiver pair is transit time for that particular direction of fluid flow. Similarly, transit time is calculated for the other transmitter-receiver pair. The difference of duration in machine cycles and the corresponding fluid flow velocity along with error of measurement is shown in Table.1.On the other hand the results provided show TDC GP22 has a higher range of operation due to its capacity to measure lower time durations. We choose not to discuss the results provided by TDC GP22 as there is ample material which discusses the same in great detail [5]. A comparison of the results obtained for prototypes using TDC GP22 and the above mentioned method shows that TDC GP22 provides higher accuracy and better range of performance. However the proposed method drastically reduces the cost of manufacturing a flow meter. By incorporating more sophisticated designs and hardware, the proposed method can be made highly accurate and operational in a wider range of fluid flow velocities.

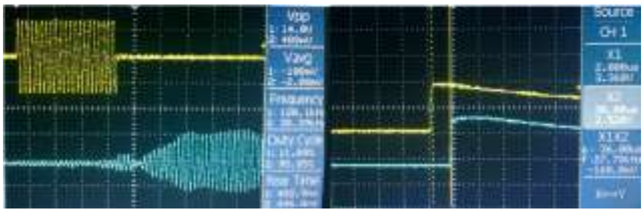

Fig. 5. Left- Input signal provided to the transmitter sensor (top). Output signal received from the receiver sensor (bottom). Right- The signals provided to the microcontroller to determine the transit times.

In TABLE I, the machine cycles corresponding to the transit time is shown. The measured velocity and the actual velocity along with the error of measurement are shown.

TABLE I. MEASURED RESULTS

Sl.no	Machine cycles	Velocity	Actual velocity	Error %
1	30	1.340	1.40	4.28
2	32	1.4304	1.45	3.35
3	34	1.5198	1.50	-1.32
4	35	1.5645	1.55	-0.90
5	38	1.6986	1.70	0.08
6	40	1.774	1.75	-1.37
7	43	1.924	1.90	1.26
8	46	2.085	2.0	-4.25

IV. Conclusion

The ultrasonic fluid flow measurement using PZT crystal provides a prototype for determining fluid flow velocity in thin pipes of size less than one centimeter. The approach involves two different methods, one done ingeniously and other using application specific IC. There exists a tradeoff between the two approaches in terms of the lack of range of operation and the cost involved, respectively. The implementation can be further improvised by using more sophisticated devices and exploring other viable options to measure time differences of a few nano-seconds accurately.

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