flotek.g 2017- "Innovative Solutions in Flow Measurement and Control - Oil, Water and Gas"
August 28-30, 2017, FCRI, Palakkad, Kerala, India

Acoustic Velocity Independent Ultrasonic Flow-Meter

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ABSTRACT

The work carried out under this project aims at improving the method of flow measurement using ultrasonic technique. Measurement on the basis of transit time difference is most universally applied flow measurement techniques. It is used to measure flow of cryogenic gases at -200°C and hot liquid, steam upto 500°C and above. The technology used in these meters requires knowledge of acoustic velocity of the fluid at operating temperature.

In this project it has been attempted to employ a technique of flow measurement using ultrasonic transducers in transmit-receive mode and the technique is independent of acoustic velocity.

The project also aims at finding the correct oscillation frequency of transducer to be used for a specific pipe size and find the correct angle of incidence for optimum results.

Key Words: Ultrasonic Flow meter, Acoustics, Doppler flow meter, transit time, crystal frequency, PRF (Pulse repetition frequency)

1. INTRODUCTION

1.1 Ultrasonic Flowmeters

Small magnitude pressure disturbances are propagated through a fluid at a definitive acoustic velocity relative to the fluid. Since the flow rate is related to the velocity, this effect may be used in several ways as the operating principle of an "Ultrasonic flow meter" [1].

Two major methods "transit time" and "Doppler" of implementing the above approach depend on the existence of transmitter and receiver of the acoustic energy. A common approach is to utilize piezoelectric crystal transducer for both the functions.

1.2 Doppler flowmeters

Doppler flowmeters operate similar to the radar speed traps used on the road. An emitter sends ultrasonic waves at frequency f at angle α into the flowing product. [2] The ultrasonic waves strike particles moving through the sound field at velocity v_P. Due to its rate of motion v_P, the particle moving away from the emitter 'sees' the wavelength λ_1 .

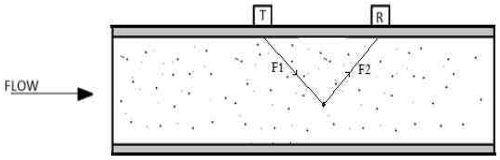

Figure 1: Doppler flow-meter

In turn, the receiver now 'sees' the reflected frequency λ_2 out of line because the reflecting particle is moving further away all the time,

This difference in frequency is a linear measure of the rate of motion of the particles.

$$f_1 - f_2 = \Delta f = \frac{2\, v_p\, f_1 \cos\alpha}{c} \quad \text{.............. (1)}$$

1.3 Time of Flight/Transit Time Flow Meters

Following technique used in TOF (time of flight/transit time) flow meters.

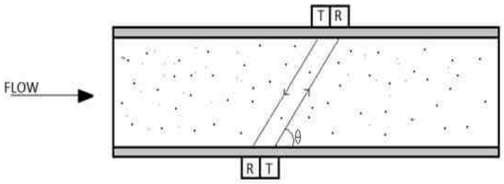

Figure 2: Transit time flowmeter

For diameter ‘D’ of pipe, the distance between a pair of transmitter receiver is ‘L’, where

Using vector algebra, time taken by ultrasonic pulse to reach receiver in forward propagation (in direction of flow of fluid) come out to be ‘t_1’ and in backward propagation (against the direction of flow of fluid) transit time comes out to be t_2.

Transit time flow meter calculates the time difference between backward propagation time and forward propagation time i.e. t_2-t_1. Mathematically,

$$\Delta \mathbf{t} = \frac{\mathbf{2Lv\ cos\theta}}{\mathbf{c^2 - v^2 Cos^2\theta}} \qquad \ldots\ldots\ldots\ldots (2)$$

Since $c^2 \gg v^2 \mathrm{Cos}^2\theta$, we can assume,

$$\mathbf{v} = \frac{\mathbf{\Delta t \ * c^2}}{\mathbf{2*L*\ cos\theta}} \qquad \ldots\ldots\ldots\ldots (3)$$

1.4 Limitations of Ultrasonic Time of Flight Flowmeters

- Dependence of velocity expression on acoustic velocity is a drawback as system loses repeatability when temperature fluctuates (Acoustic velocity is dependent on temperature). [3]

1.5 Major Limitations of the Ultrasonic Doppler Flowmeters

- The measuring method needs a sufficient number of reflecting particles in the medium on a continuous basis.
- The sound velocity of the medium is directly included in the measurement result. [2]

1.6 Proposed method

To overcome the drawbacks mentioned above, following technique will be adopted:

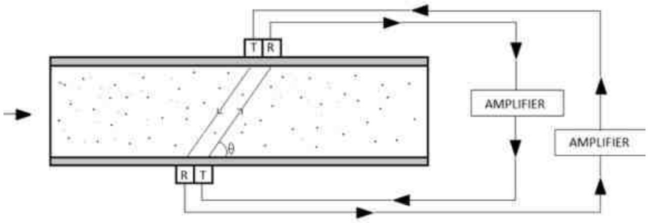

Figure 3: Self-excited oscillating circuit

In figure 3, two self-excited oscillating systems are created by using the received pulses to trigger the transmitted pulses in a feedback arrangement. The pulse repetition frequency in the forward propagating loop is $1/t_1$ while that in backward propagating loop is $1/t_2$,

$$f_1 = \frac{\mathbf{1}}{\mathbf{t1}} = \frac{\mathbf{c+v\ Cos\ \theta}}{\mathbf{L}} \qquad \ldots\ldots\ldots\ldots\ldots (4)$$

$$f_2 = \frac{\mathbf{1}}{\mathbf{t2}} = \frac{\mathbf{c-v\ Cos\ \theta}}{\mathbf{L}} \qquad \ldots\ldots\ldots\ldots\ldots (5)$$

$$\Delta \mathbf{f} = \frac{\mathbf{2v\ cos\ \theta}}{\mathbf{L}} \qquad \ldots\ldots\ldots\ldots\ldots (6)$$

Where,

f_1 = Pulse repetition frequency in forward propagation loop

f_2 = Pulse repetition frequency in backward propagation loop

v = Velocity of fluid

c = Acoustic velocity of fluid

L= Distance between transmitter and receiver

This is independent of acoustic velocity ‘c’ and thus not subject to errors due to temperature fluctuations. [3]

2. SIMULATIONS

Two set of simulations have been done in COMSOL to find out the correct transducer frequency to be used with respect to pipe size and to determine correct angle of incidence to be used. A pre-existing COMSOL model [4] has been used for both simulations with required modifications. Firstly, turbulent flow was simulated in the pipe line using CFD module and acoustic module was used later to study the choice of transducer frequency and angle of incidence.

The results and conclusion of the simulations have been discussed in further sections.

2.1 Simulation Set-1: To Find Correct Transducer to Be Used With Respect to Pipe Size

The aim is to find a transducer frequency/wavelength for which the ratio of reflected waveform to original waveform is the least.

To find out correct ultrasonic frequency for a given pipe size, three pipe sizes were chosen for interrogation with ultrasonic signals of six different frequencies/ wavelengths. The frequencies chosen were such that the wavelength of the signal varies from a quarter of pipe diameter to twice of the pipe diameter (λ1= D/4, λ2=D/2, λ3=3D/4, λ4=D, λ5=5D/4, λ6=2D).

This was done to study the effects of wave interference and reflection from the pipe boundary on the signal obtained at receiver.

D= pipe diameter,
λ = wave length,
v = frequency.

2.2 Results of first set of simulation

The eighteen graphs shown below show the acoustic pressure at the transmitter and the receiver end of the signal tube. The green coloured waveform shows the acoustic pressure at the transmitter, the first pulse is the ultrasonic pulse generated due to trigger signal to the transmitter but all the peaks/pulses that appear on transmitter after the pulse is sensed at the receiver(blue waveform) are result of reflections from side walls and receiver transducer.

Case 1.1: D = 2 inches, λ=2D

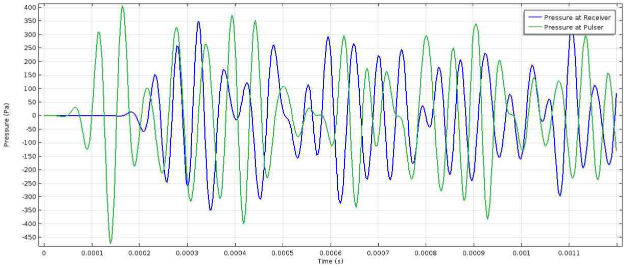

Figure 4: Acoustic pressure at transmitter and receiver for λ=2D

Case 1.2: D = 2 inches, λ=5D/4

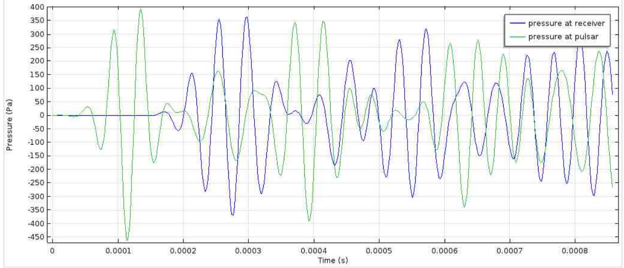

Figure 5: Acoustic pressure at transmitter and receiver for λ=5D/4

Case 1.3: D = 2 inches, λ=D

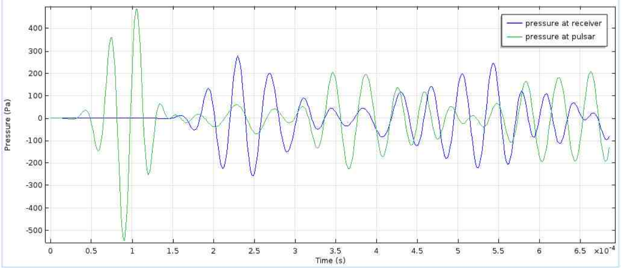

Figure 6: Acoustic pressure at transmitter and receiver for λ=D

Case 1.4: D = 2 inches, λ=3D/4

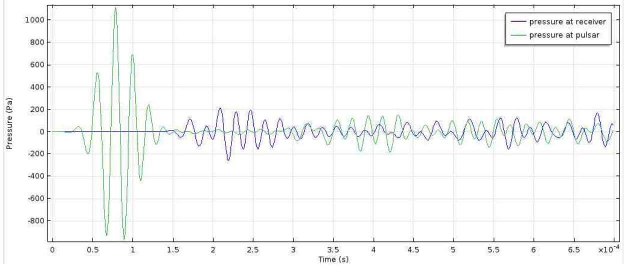

Figure 7: Acoustic pressure at transmitter and receiver for λ=3D/4

Case 1.5: D = 2 inches, λ=D/2

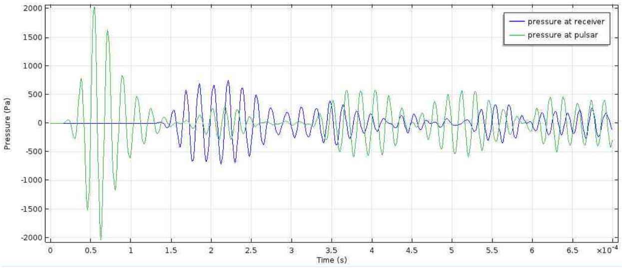

Figure 8: Acoustic pressure at transmitter and receiver for λ=D/2

Case 1.6: D = 2 inches, λ=D/4

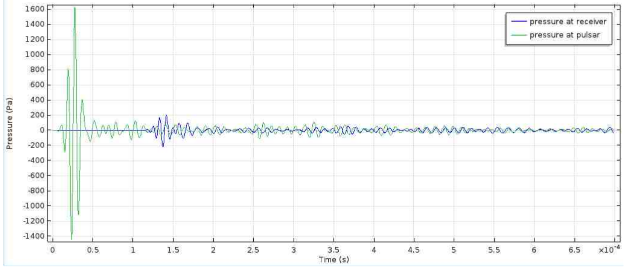

Figure 9: Acoustic pressure at transmitter and receiver for λ=D/4

Case 2.1 : D = 1.5 inches, λ=2D

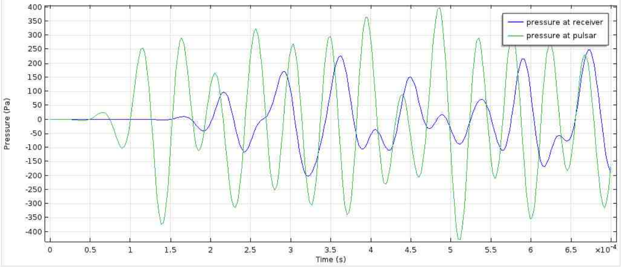

Figure 10: Acoustic pressure at transmitter and receiver for λ=2D

Case 2.2: D = 1.5 inches, λ=5D/4

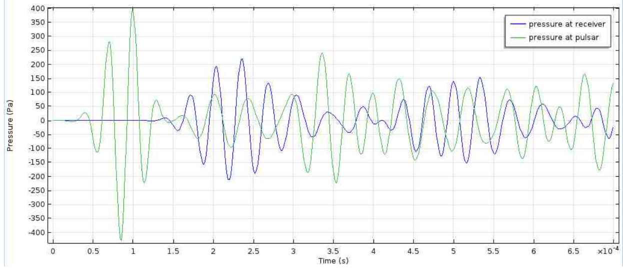

Figure 11: Acoustic pressure at transmitter and receiver for λ=5D/4

Case 2.3: D = 1.5 inches, λ=D

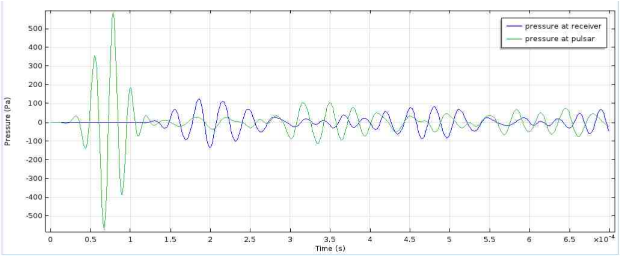

Figure 12: Acoustic pressure at transmitter and receiver for λ=D

*Case 2.4:*D = 1.5 inches, λ=3D/4

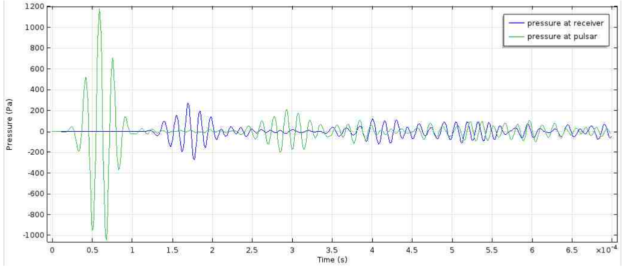

Figure 13: Acoustic pressure at transmitter and receiver for λ=3D/4

Case 2.5: D = 1.5 inches, λ=D/2

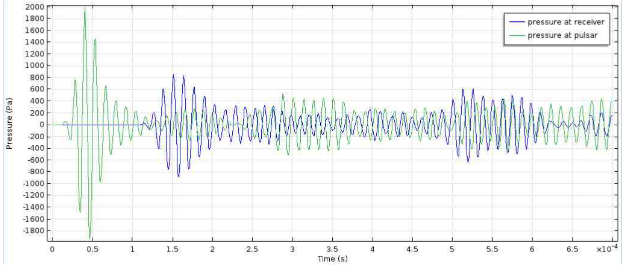

Figure 14: Acoustic pressure at transmitter and receiver for λ=D/2

<u>Case 2.6:</u> D = 1.5 inches, λ=D/4

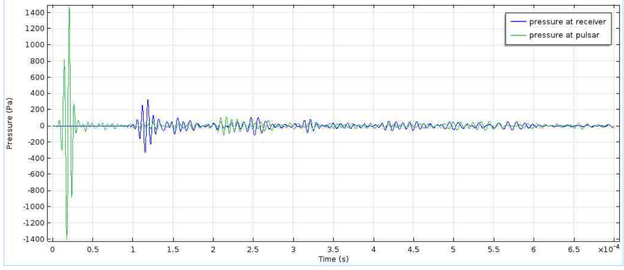

Figure 15: Acoustic pressure at transmitter and receiver for λ=D/4

<u>Case 3.1:</u> D = 1 inch, λ=2D

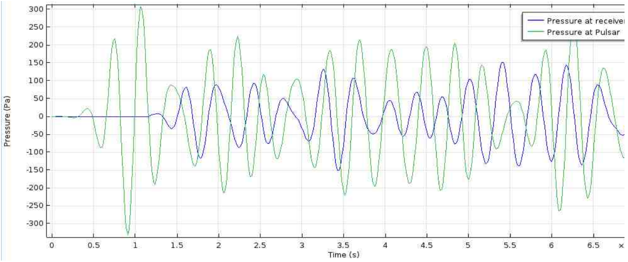

Figure 16: Acoustic pressure at transmitter and receiver for λ=2D

<u>Case 3.2: D</u> = 1 inch, λ=5D/4

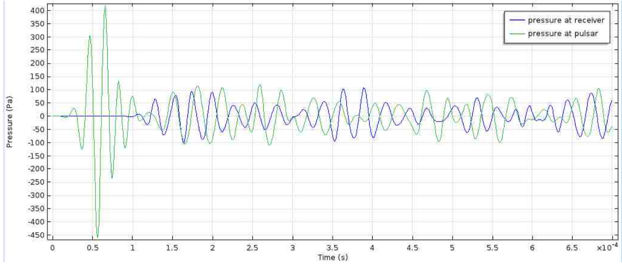

Figure 17: Acoustic pressure at transmitter and receiver for λ=5D/4

*<u>Case 3.3:</u>*D = 1 inch, λ=D

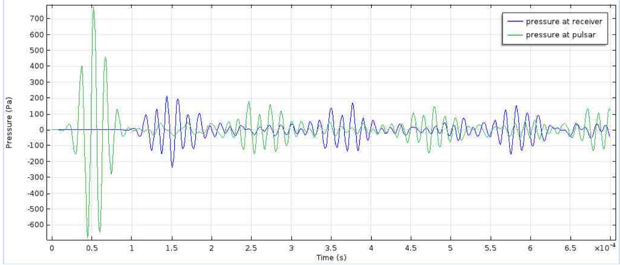

Figure 18: Acoustic pressure at transmitter and receiver for λ=D

*<u>Case 3.4:</u>*D = 1 inch, λ=3D/4

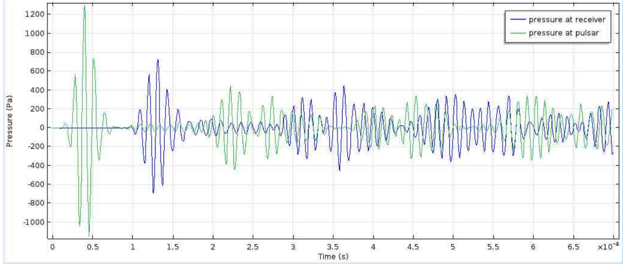

Figure 19: Acoustic pressure at transmitter and receiver for λ=3D/4

<u>Case 3.5:</u> D = 1 inch, λ=D/2, v = 116,614 Hz

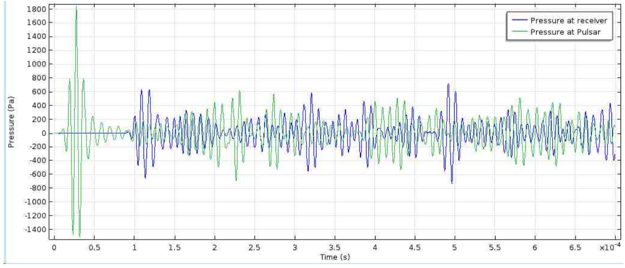

Figure 20: Acoustic pressure at transmitter and receiver for λ=D/2

<u>Case 3.6</u>: D = 1 inch, λ=D/4

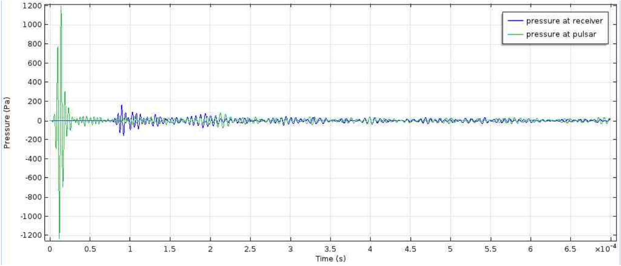

Figure 21: Acoustic pressure at transmitter and receiver for λ=D/4

Table 1: Ratio between reflected pulse and original pulse

	Case No.	Wavelength of ultrasonic crystal in multiples of pipe diameter 'D' (inch)	Maximum Amp. Of Source pulse (Pa)	Maximum Amp. Of Reflected pulse (Pa)	Ratio between Reflected pulse and Incident pulse
Pipe Diameter=2"	1.1	2D	475	400	0.842105
	1.2	5D/4	450	400	0.888889
	1.3	D	550	200	0.363636

	1.4	3D/4	1100	180	0.163636
	1.5	D/2	2000	500	0.25
	1.6	D/4	1600	200	0.125
Pipe Diameter=1.5”	2.1	2D	350	450	1.285714
	2.2	5D/4	450	250	0.555556
	2.3	D	600	100	0.166667
	2.4	3D/4	1200	200	0.166667
	2.5	D/2	2000	500	0.25
	2.6	D/4	1400	100	0.071429
Pipe Diameter =1”	3.1	2D	325	260	0.8
	3.2	5D/4	450	120	0.266667
	3.3	D	800	200	0.25
	3.4	3D/4	1300	400	0.307692
	3.5	D/2	1850	600	0.324324
	3.6	D/4	1200	100	0.083333

2.3 Conclusion for first set of simulations

It can be observed from all the three cases that amplitude of the wave received at transmitter after getting reflected from the receiver transducer and the pipe surface decreases as the wavelength of the transducer decreases.

Hence we conclude that to avoid the effects of reflected acoustic waves, the wavelength of the transducer should be lesser that at least quarter of the pipe diameter.

2.4 Simulation Set-2: To find out correct angle of incidence

The aim of second set of simulations was to determine the most appropriate angle of incidence for which error in measured flow is least.

To find out correct angle of incidence following steps were followed:

- Design geometric model for pipe size ‘D’ (D = Internal Diameter of pipe).
- Simulate turbulent flow using CFD with velocity ‘v’.
- Study the Acoustic Pressure signal at Receiver end of signal tube and note the value of time of flight (TOF) for angle of incidence ‘α’.
- For the same velocity ‘v’, change the angle of incidence ‘α’ and study the Acoustic Pressure signal.
  ($\alpha 1= 30^0$, $\alpha 2= 45^0$, $\alpha 3= 60^0$)
- Repeat above steps for different values of velocity ‘v’.
  (v= 0.25m/s, 0.75m/s, 1m/s, 1.5m/s, 3m/s, 5m/s, 10m/s)
- Calculate the measured velocity and compute error

2.5 Result of second set of simulations

The data in table-2 shows the relative error obtained in measured velocity for different pipe sizes and flow velocities. Same data has been plotted in graph (Figure-22) for better error analysis.

2.6 Conclusion for second set of simulations

It is observed from the above graph that error is limited to a band of 5% for 20^0,30^0 and 45^0 angle of incidences. There’s very high error of 11% for incidence angle of 60^0.

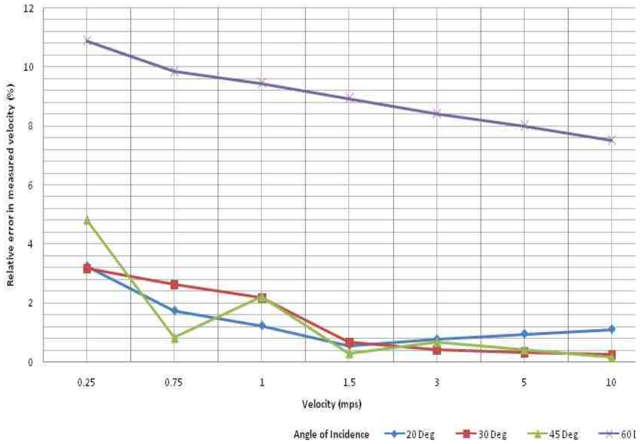

Figure 22: Relative error in calculated velocity versus angle of incidence

If we observe the flow profiles for above mentioned cases in figure-23, it can be concluded that for 60^0, a relatively higher amount of flow distortion is present; this error is purely an outcome of the geometry of the signal tube. Hence, for the prototype instrument we'll be using incidence angle of 45^0 as it offers Wide span in Δf, Error band 5% and Ease of fabrication.

Table 2: Relative error in measured velocity at various angles of incidence

S.No	Alpha α (Degree)	Velocity (mps)	Length of transducer duct (mm)	Δt Simulated (s)	Simulated velocity (mps)	Relative error in measured velocity (%)
1	20	10	55.88	1.73E-07	9.89	1.10
2	30	10	60.64	2.77E-07	10.02	0.24
3	45	10	74.28	4.80E-07	10.02	0.16
4	60	10	105.05	8.92E-07	10.75	7.52
5	20	5	55.88	8.65E-08	4.95	0.95
6	30	5	60.64	1.39E-07	5.02	0.32
7	45	5	74.28	2.41E-07	5.02	0.43
8	60	5	105.05	4.48E-07	5.40	8.01
9	20	3	55.88	5.20E-08	2.98	0.77
10	30	3	60.64	8.33E-08	3.01	0.39
11	45	3	74.28	1.45E-07	3.02	0.68
12	60	3	105.05	2.70E-07	3.25	8.41
13	20	1.5	55.88	2.63E-08	1.51	0.56
14	30	1.5	60.64	4.18E-08	1.51	0.65
15	45	1.5	74.28	7.17E-08	1.50	0.30
16	60	1.5	105.05	1.36E-07	1.63	8.94
17	20	1	55.88	1.77E-08	1.01	1.23
18	30	1	60.64	2.83E-08	1.02	2.17
19	45	1	74.28	4.90E-08	1.02	2.21
20	60	1	105.05	9.08E-08	1.09	9.45
21	20	0.75	55.88	1.33E-08	0.76	1.73
22	30	0.75	60.64	2.13E-08	0.77	2.63
23	45	0.75	74.28	3.62E-08	0.76	0.82
24	60	0.75	105.05	6.84E-08	0.82	9.85
25	20	0.25	55.88	4.51E-09	0.26	3.24
26	30	0.25	60.64	7.14E-09	0.26	3.16
27	45	0.25	74.28	1.26E-08	0.26	4.81
28	60	0.25	105.05	2.30E-08	0.28	10.88

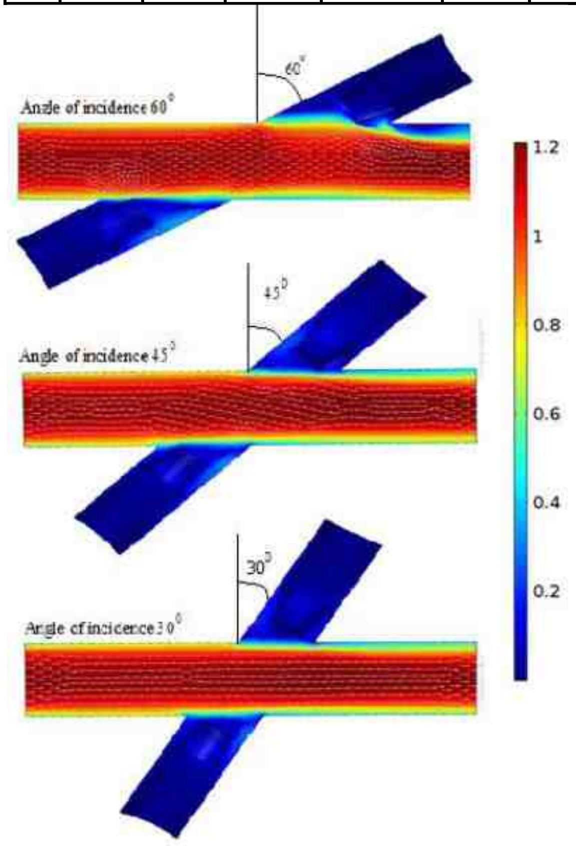

Figure 23: Flow pattern for different angle of incidence

3. CIRCUIT DESIGN AND ELECTRONIC SIMULATION

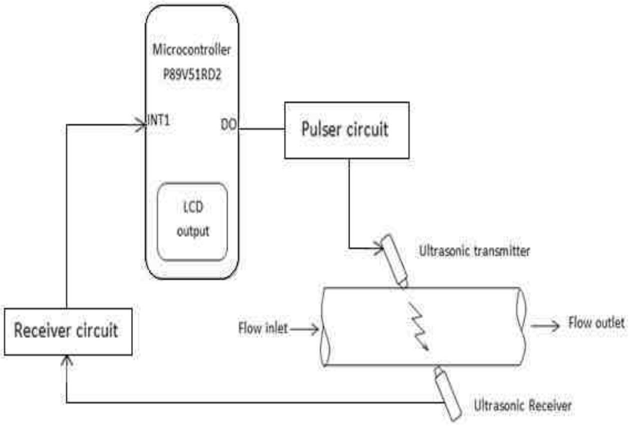

Figure 24: Block diagram of the setup

The circuit was first simulated in software. This was done in order to determine the correctness and efficiency of a design before the system is actually constructed and to understand the behaviors/interactions of all the components with each other within the system.

3.1 Ultrasonic pulser

Piezo-electric crystal requires a high voltage pulse for excitation, the pressure created by the crystal is directly proportional to the rate of change of excitation voltage. For this prototype spike type pulser has been utilized. [5]

A spike type pulser will take the input reference from the microcontroller and feed a negative spike to the ultrasonic crystal. Block diagram of pulser is shown in figure-25.

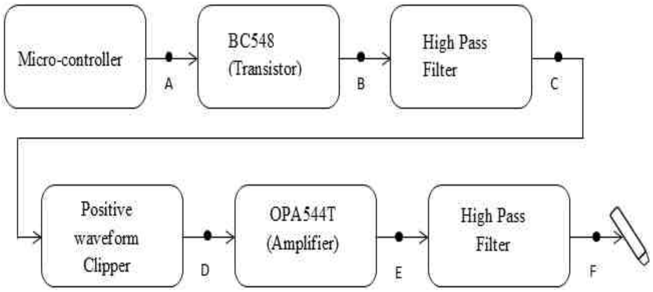

Figure 25: Pulser block diagram

3.2 Receiver

The ultrasonic pulse received at the other end of the signal tube is picked up by another ultrasonic transducer. This transducer gives an electrical output corresponding to the input pressure received.

This electrical signal is further conditioned using receiver circuit to get the desired results.

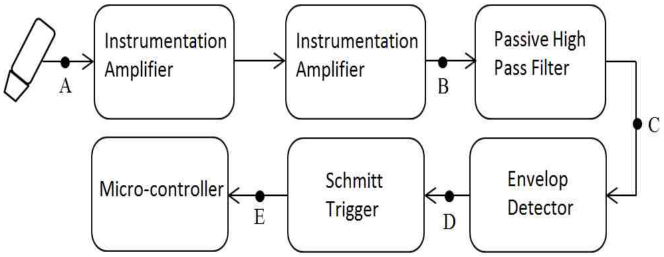

Figure 26: Receiver block diagram

Block diagram of the receiver circuit is as shown in figure-27.

4. FREQUENCY COUNTERS

We are using Philips microcontroller P89V51RD2 at clock frequency of 24 MHz to calculate frequency of forward and backward propagation loop.

Flow chart in figure: 30 show series of events to calculate the frequency of the loop. We are able to achieve accurate frequency with an error of +/-3Hz.

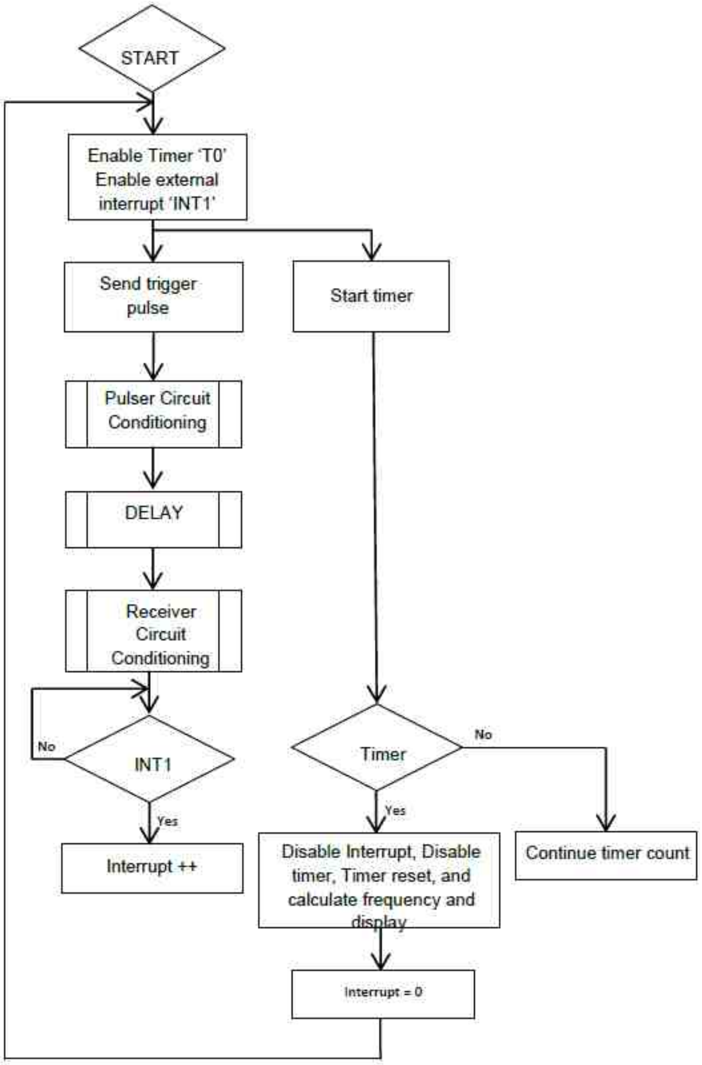

Figure 27: Flow chart of the operations for frequency calculations

5. EXPERIMENTATION RESULTS

The complete electronic circuit was setup as shown in figure 24. As explained earlier, in proposed method the measured velocity is directly proportional to difference between Pulse repetition frequency (PRF) of forward propagation loop and backward propagation loop.

Mathematically,

$$\Delta f = \frac{2v\cos\theta}{L}$$

Another set of COMSOL simulations were done with the actual pipe size (as installed in the setup) and the curve of frequency difference versus velocity has been plotted in figure-28.

The physical experiment was performed several times to check the repeatability of results by the prototype instrument. Few of the results have been plotted in figure number 29 to 32. It can be observed that experimental results tally with the simulated result within the limits of experimental error.

It is to be noted that these experiments were performed at random temperatures, still the repeatability in the results shows that the technique is independent of temperature.

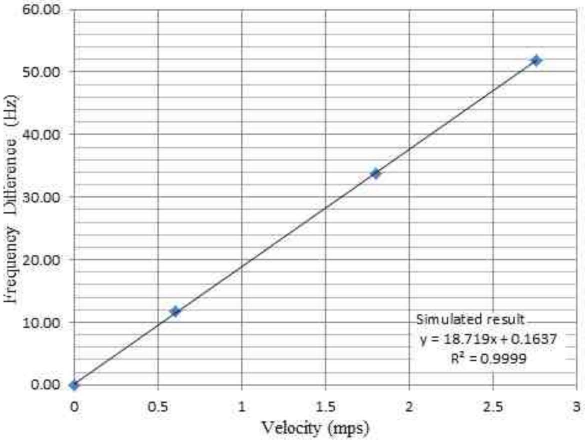

Figure 28: Simulated result of Δf versus flow velocity

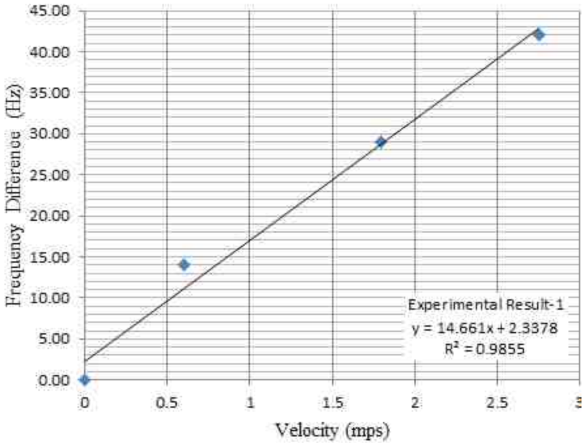

Figure 29: Experimental result-1 of Δf versus flow velocity

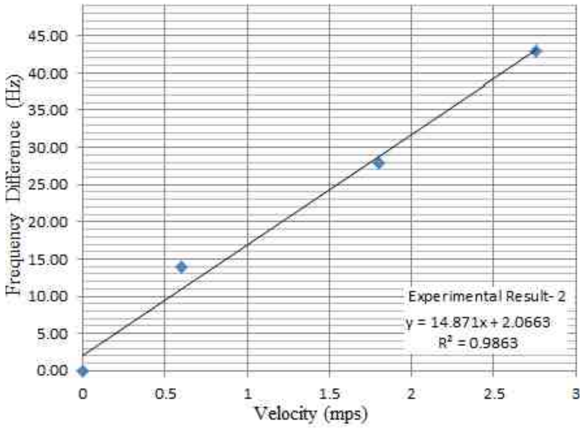

Figure 30: Experimental result-2 of Δf versus flow velocity

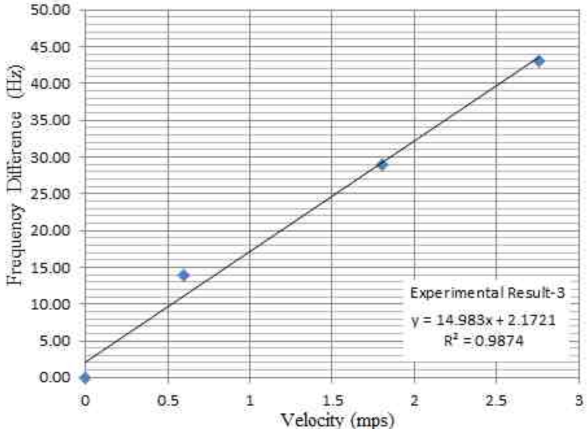

Figure 31: Experimental result-3 of Δf versus flow velocity

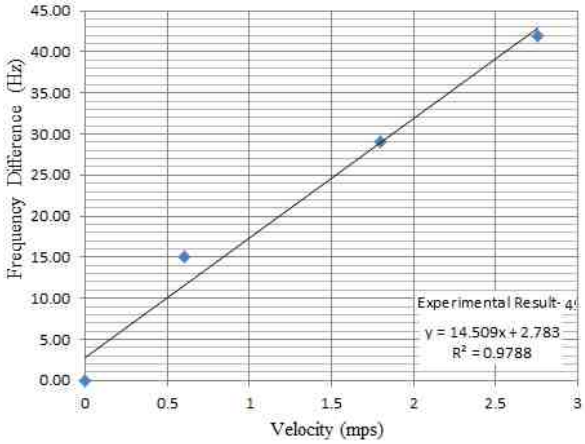

Figure 32: Experimental result-4 of Δf versus flow velocity

5.1 CONCLUSION

It can be observed that experimental results tally with the simulated result within the limits of experimental error. Hence, after proper calibration (according to the pipe size) this technique can be used to find out the correct flow even in transient temperature conditions.

REFERENCES

[1]. L.C. Lynnworth, Ultrasonic Flowmeters, Chapter 5 in: Physical Acoustics - Principles and Methods, W. P. Mason and R. N. Thurston (Editors), Vol. 14, pp. 407-525, Academic Press (1979).

[2]. Fundamentals of ultrasonic flow meter by Friedrich Hofmann, KROHNE 04/2001

[3]. Ernest O Deoblin, “Measurement systems”, Chapter 7 in McGraw Hill Education, Sixth Edition (2015).

[4]. COMSOL model (Application ID: 34991): Ultrasound flow meter with generic time of flight configuration.

[5]. Design and development of an ultrasonic pulser-receiver unit for non-destructive testing of materials by V. H. Patankar and V. M. Joshi ,Electronics Division, BARC (2002).

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JalTarang- Interactive fountain
It is MSP430 based fountain which gives jet stream patters according to the frequency band and amplitude of the sound.

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Number of Papers Published in Conferences: ONE