

Cross Correlation Velocity Measurement of Multiphase Flow

Muhammad Waqas Munir¹, Bushra Anam Khalil²

¹Teesside University, School of Science and Engineering, Middlesbrough, Tees Valley, TS1 3BA, UK

²University of Agriculture Faisalabad, Department of Physics, University Road, Faisalabad 38000, Pakistan

Abstract: *The cross correlation signal processing is not a new idea it has wide spread and has large numbers of applications in the engineering field. It became as a suitable tool for analysing time invariant systems and system identification dynamics. However, one of the eminent applications of cross correlation is velocity measurements in multiphase and difficult fluids such as; pneumatically conveyed solid materials, highly polluted liquids, mixture of extremely hot gases and liquids. This paper is divided into two segments practical execution and data acquisition analysis to ameliorate the accuracy of velocity evaluation. The cross correlation velocity evaluation is based on the measurement of transit time of the tagging signals of multiphase flow between two separated sensors. The number of techniques and multiphase flow sensors (MPFs) is used for velocity evaluation such as, ultrasonic sensors, capacitive sensors and electrostatic sensors etc. However, this comparative study was conducted on the coal test-rig of Teesside university while: ring shaped electrostatic sensor are used to determine the velocity of gas/solid two phase flow. The acquired data of the test-rig are executed on the LabVIEW (national instrument software).*

Keywords: Cross-Correlation, Velocity Measurement, Multiphase Flow, Electrostatic Sensors.

1. Introduction

The use of cross correlation for signal processing is not a new thing. Cross correlation measurement theory has been found since 1930's. However, until 1960's this theory is not used practically by the industries. Where, hardware called correlator has been invented [10]. Over the past few decades engineers, researchers and scientists have been using autocorrelation and cross correlation measurement technique as a powerful analysis tool especially, when the system is embedded with noise. The basic principles of cross correlation measurement technique are briefly explained, presenting how it can be used to recognize dynamic characteristic of multiple sensors that are extensively used for robust estimation, process systems, communication, target tracking, biological sensors and vascular diseases estimation [16].

1.1 Cross Correlation flow measurement

The study of gas/solid or gas/liquid two phase flow obtain vast attention in both scientific and engineering meadow because of its general appearance in several industrial processes such as nuclear industry, petroleum industry, metallurgical industry and chemical industry. Researchers from all over the world work on the challenges come across in two phase flow production, recognition, transmission and parameter measurement. For instance; in the petroleum industry process engineers frequently encounter multiphase flow such as, exploration and transportation.

Nearly it is always difficult to quantify this class of the flow. The precise measurement to the flow parameters of oil-water-gas multiphase flow is significant worth to industrial process. The conventional approach of multiphase flow measurement is to separate every phase of fluid by its physical characteristic and measured it with the conventional instruments. The most typical example of multiphase flow is

the oil production process where the oil-water-gas mixture is pumped out and then physically detached to measure the relative amount of oil and gas components with the help of turbines meters and orifice plates. At the outset, this method is extremely costly further that it take a extraordinarily long time. So the cross correlation, technique is introduced to escalate the efficiency in multiphase flow measurement [13].

Cross correlation measurement techniques has a very far along measurement echelon in ideal conditions and are becoming widely used to measure the rate of change of flow in the pipeline by deriving the transit time of a tagging signal (*turbulence, clumps of particles, etc*) in the fluid flowing through a pair of parallel mounted sensors on the target pipelines. In a pipeline, a two phase (solid or liquid) flow generate a random disturbance signals which can be identify by several kinds of transducers such as, capacitance and electrodynamics transducer [11]. The cross correlator also measured the transit time of the signal [2]. The resemblance of two waveforms is measured by cross correlation as an assignment of a time log applied to one of them. The essential principle of this method is simply to measure the time taken by a disturbance to pass between two points spaced along the direction of the flow [1].

2. Cross Correlation Flow Meters Layout

In early stage, the cross correlation flow meter was developed on the whole empirical basis for a specific range of applications. According to the Beck the comparatively easy-going and smartest way to build up a new technology is, develops and observed the experimental device for a range of functions. After the initial development, the slightly Prototyping in the experimental instrument according to the functions of application is the normal thing. Then take into account all experimental observations that help to stimulate the more theoretical approaches which are largely considered

to design the optimum efficient system in a cost-effective way [9].

In order to demonstrate the more fundamental aspects of cross correlation flow meter. The whole flow measurement model design will break down into subsystems as shown in figure (2.1).

3.1 Title and authors

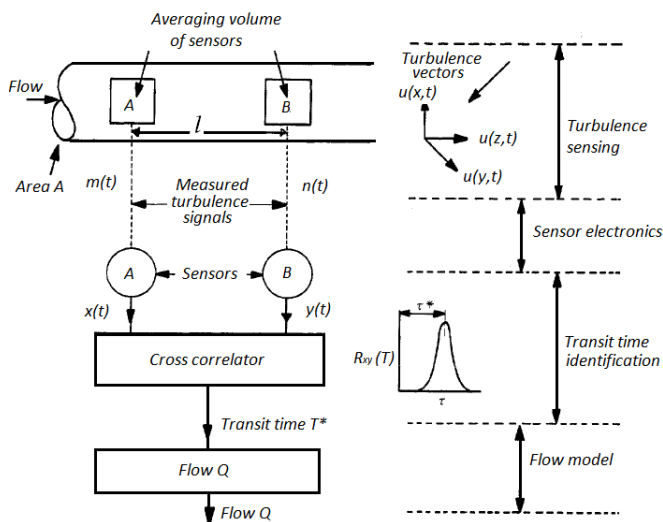


Figure 2.1: Schematic diagram of cross correlation measurement model

2.1 Tagging Signal Sensing Principles

Take into consideration figure (2.1) the tagging signals along the flow axis are detected by the sensors at point A and B. The sensing method is classified into three main categories: measuring electrical and thermal properties of the flowing fluid, radiation emission of the flowing fluid and radiation modulation by flowing fluid. There are numerous substitutes' techniques that might be used according to a particular situation for practical measuring problem. The reliability and cost of the sensing devices are the major factors of their choice in industrial use. In cross correlation measurement, time delay of the signals between the sensors is not dependent on the gain. So the sensor gain and stability is unimportant here. Some of these sensors are described below:

- 1) Electro conductive sensors
- 2) Thermal sensors to correlated injected heat pulses
- 3) Electrostatic sensors
- 4) Cross correlation measurement capacitance sensors

2.2 Electrostatic Sensors

Solid particles are accumulated by the extensive amount of electrostatic charge whenever they entrained in flowing gas stream. Sensors have the sensing plates to detect these electrostatic charges. However, simple AC amplifier is used to amplifying the voltages of the sensing plates and then flow velocity is given by cross correlating the output [8]. In multiphase flow measurement community, electrostatic sensors attain significant attention due to their simple electrostatic approach. However, it studied by a lot of

engineers and scientists. The filtering effect of ring shaped electrostatic electrodes are studied by [5] and in 1996 model established by Cheng that based on the electrostatic field theory to describe the relationship between the charge carried by the particle with respect to its location and induced charge electrodes (*insulated pipe section*), known as "spatial sensitivity" [3]. The further study carried out by Zhang through employing stochastic process theory on the same model. He relates the charge level on electrodes to solid mass flow rate and flow concentration [12]. Number literature [14], [15] are published for velocity measurement like exploitation of frequency method has also been based on the Cheng's model [13]. The product (*PfMaster*) has been developed and manufactured by ABB Ltd, which operates on dynamic electrostatic techniques. While, its extremely useful to monitor and control the Pulverised Fuel (*PF*) velocity in coal-fired power stations [15]. So in last decay a lot of work done on this approach by the researchers and scientists and these sensors are widely used in industrial process because they are inherently robust and less expensive. Even an external signal source is not required in most of these sensors.

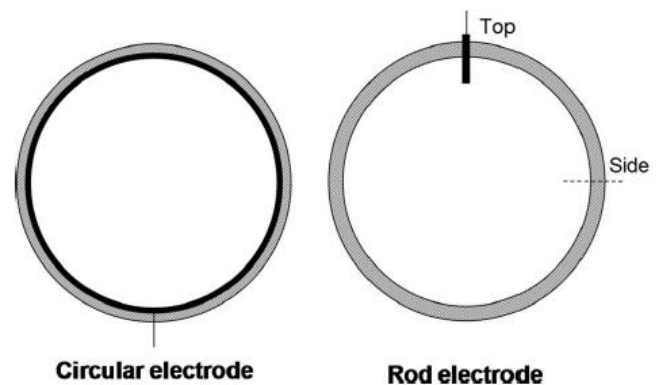


Figure 2.2: Electrodes used in electrostatic sensor [6]

Non-intrusive conducting rings are most researched and most common electrostatic sensor as shown in figure (2.2). It forms like a part of pipeline walls and that thin electrode electrically insulated from it. Though they are supremely efficient, but it suffers from some difficulties Such as they are difficult in installation, cost of installation and normally impractical for large pipelines in inconvenient environments. So the rod electrodes are an alternative to the circular electrodes as shown in figure (2.2). In this case, the rod protrudes into the pipeline at a right angle to the flow axis [6].

3. Methodology

Cross correlation became as a suitable tool for analysing time invariant systems and system identification dynamics. The close mathematical relationship between frequency response method and cross correlation technique such as power spectral function makes it easier.

However, one of the eminent applications of cross correlation is flow measurements in multiphase and difficult fluids such as; pneumatically conveyed solid materials, highly polluted liquids (*slurries and sewage*), extremely hot gases and liquids. Under such conditions non-contact and very robust

equipment are required. Definitely considerable amount of work done on cross correlation flow meters by researchers and engineers but still a significant research is required concerned with sensor design for abrasive conditions, understanding the sensing behaviour of sensors in difficult fluid and effecting factors in velocity measurement of multiphase fluid. So the study would be conducted to observe the factors affecting the velocity in multiphase flow measurements. The schematic diagram of the basic model is shown in figure (3.1). The project classified into two segments practical observation of multiphase flow and software based analysis of the data that we collect in practical observation.

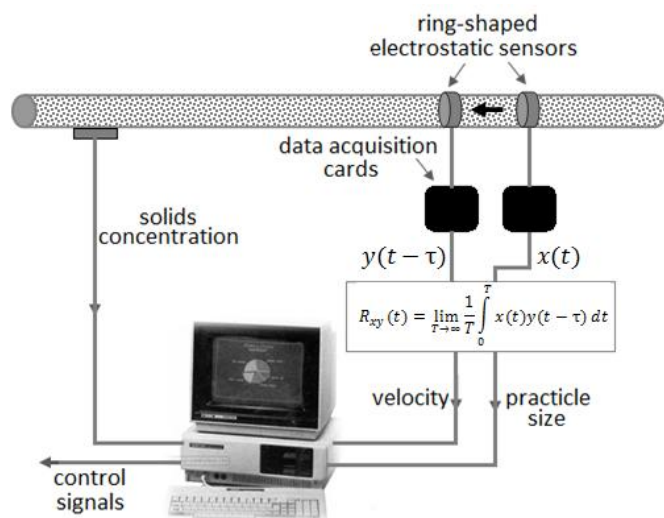


Figure 3.1: Schematic diagram of basic flow model

3.1 Practical executions on the test rig

Two phase flow test rig model (*pneumatic conveyor*) of Teesside University is shown in the figure (3.2).

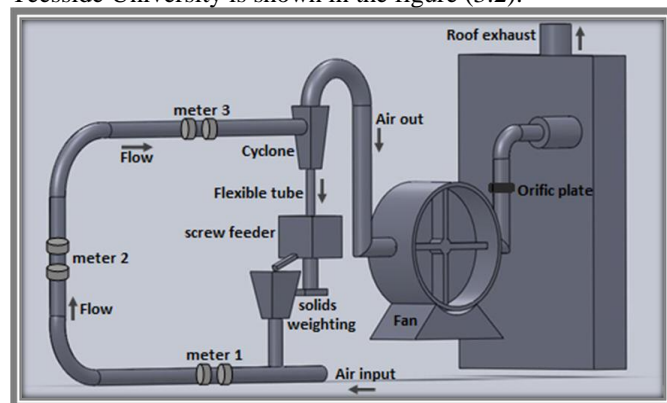


Figure 3.2: Coal test-rig model Teesside University

3.2 Pneumatic conveying

In two phase flow field, gas-solid flow is a most common transport form, conveying of solid particles by gas or air power are called pneumatic conveying. From many years, it has been successfully used in industrial process like, lime making, flour production, pulverized coal burning and plastic chips. In the transportation, of granular material using air power have many advantages such as, transmission efficiency, flexibility of layout reliability and safety of

production, environmental friendly and hygienic and foremost is ease of automation in process. In industrial or experimental process pipe transmission should be made in best conditions because the transmission rate needed to maintain at a certain level, not too low transfer rate that the whole system stop or not too fast that the energy waste in a process. So it is an important task to estimate and control the pneumatic flow velocity in industrial process. Gas-solid two phase flow velocity has been a study from several years and idiosyncratic computing devices mechanisms and measuring elucidation are developed. In pneumatically conveying, the accuracy of measuring date of the flow process may be affected by the solid-gas flow characteristics such as, irregular velocity pattern, variable particle size, an uneven distribution of solid in pipeline, humidity.

3.3 Pulverized coal or “fillite” flow process

The test rig shown in figure (3.2) is based on suction principle. To investigate the two phase gas-solid flow velocity “fillite” a commercial product of fly ash with an average particle size $100\mu m$ are transported by air power through 40mm diameter pipelines. It's the same mechanism as the coal pneumatically conveyed through the pipe from mill to furnace in coal fired power station. And this is normally known as lean phase conveying. The solid and air ratio usually less than 1:5:1 in term of mass conveying [4] and at $100^\circ C$ the equivalent volumetric concentration is less than 0.5%. Various sensors such as, capacitive, microwave, ultrasonic, modulation/attenuation or optical all used for two phase velocity measurement. But due to the low concentration the sensor like capacitance or microwave may not be sensitive enough for this type of applications and the system based on the modulation or attenuation or typically considered as expensive or challenging to install. Through the nonintrusive ring shaped electro statistic sensor has advantages in this aspect of measurement. However, the electro-statistic flow meters are executed on a test rig for velocity measurement in gas-solid two phase flow. That operates on dynamic electro-statistic technique established by [3], [13] and after that the product was manufactured and developed by ‘ABB Ltd’ with a trade name of ‘pfmaster’. As shown in figure (3.3), the screw feeder is used to discharge solid particles into the test rig. The solid mass flow rate was about 50kg/hr, and it determined by ‘rate of loss’ of weight and orifice plate indicated in a test rig is located at downstream of the cyclone to identify the air mass flow rate. To maintain the constant air to solid ratios (i.e., Mass flow rate of air/mass flow rate of solid) the air and solid mass flow rate were controlled. Because, they are proportional to each other when solid mass flow rate increases the air mass flow rate also increased.



Figure 3.3: Photographs of screw feeder and electrostatic sensors

4. Results and discussion

4.1 Two phase flow cross correlation velocity measurement

Virtual instrument are developed in LabVIEW to get cross

correlation peak position of two individual signals $x(t)$ and $y(t)$ of individual pipeline of gas/solid two phase flow. The velocity of gas/solid two phase flow measured at the set of time delay (10, 15, 20, 25, 30, 35, and 40). At time delay 10: Simplified representation of two signals from individual pipe are shown in figure (4.1)

Two signals from individual pipe

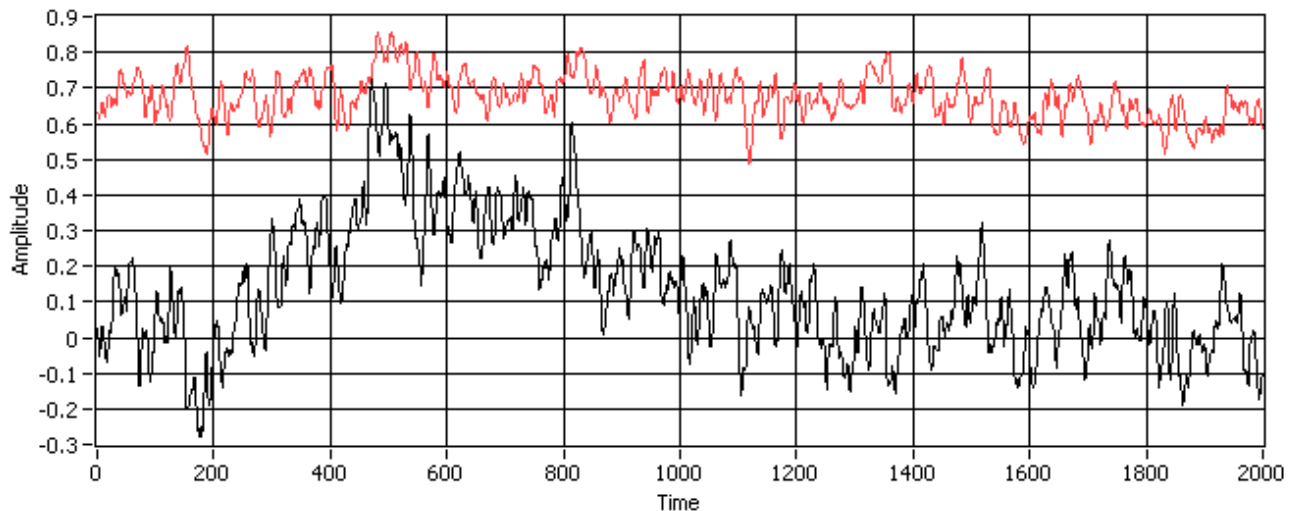


Figure 4.1: Simplified representation of two signals from individual pipe obtain by LabVIEW (VIs)

To acquire the velocity of gas/solid two phase flow cross correlation peak position of these two signals are accomplished by virtual instrument fundamental model of signal $x(t)$, $y(t-\tau)$ with a known time delay $\tau=10$. The cross correlation curve is shown in figure (4.2).

Cross correlation curve

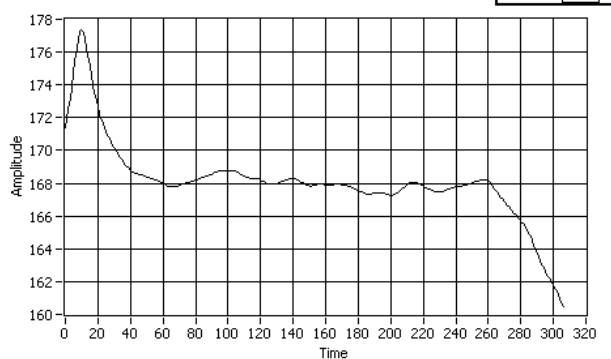


Figure 4.2: Cross correlation curve representation of these two signals at time delay '10'

The cross correlation of two signals are defined by the equation:

$$R_{xy}(t) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T x(t)y(t-\tau) dt \quad (1)$$

Where

$x(t)$ is upstream signal and $y(t-\tau)$ is the downstream signal with a time delay τ . The flow velocity of gas/solid two phase flow is given by:

$$V = \frac{L}{\tau^*} \quad (2)$$

Where

$L=5\text{cm}$ it is used to define the spacing between upstream and downstream transducers. Suppose the sampling frequency is 1 KHz . As we know

$$\tau^* = n \cdot \Delta t \quad (3)$$

n is used to defined the direct peak position.

$$n=10$$

$$\Delta t = \frac{1}{f} \rightarrow \Delta t = \frac{1}{1} \rightarrow \Delta t = 1$$

By putting the values of ' n ' and ' Δt ' in equation 3:

$$\tau^* = 10$$

$$L=5\text{cm} \rightarrow L=50\text{mm}$$

Now put the values of ' τ^* ' and ' L ' in equation 2: Then

$$V = 5\text{mm/ms} \rightarrow V = 5\text{m/s}$$

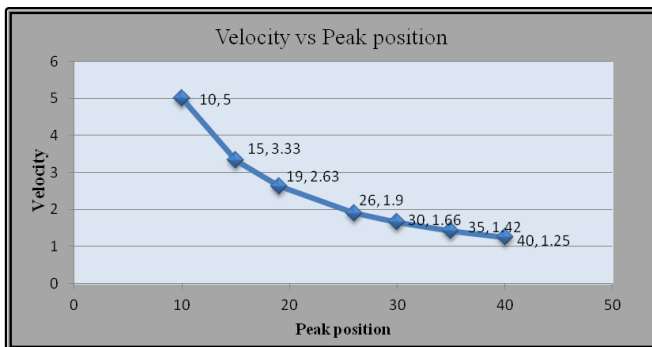
So, the velocity of two phase flow at time delay '10' is '5m/s'. However, by following the same pattern velocity can be calculated at each time delay (15, 20, 25, 30, 35, 40). The signal representation and its corresponding cross correlation peak position at each time delay are imported from LabVIEW.

The table (4.1) show the transit time ' τ^* ' and velocity at time delay (10, 15, 20, 25, 30, 35, 40).

Table 4.1: Cross correlation velocity measurement at each time delay when $f_s=1$

N0	True delay time	Peak position	Frequency KHz	Transit time (T*)	Velocity (m/s)
1	10	10	1	10	5
2	15	15	1	15	3.33
3	20	19	1	19	2.63
4	25	26	1	26	1.9
5	30	30	1	30	1.66
6	35	35	1	35	1.42
7	40	40	1	40	1.25

The values displayed in the above table show that as the delay time between two signal $x(t)$ and $y(t)$ increase the value of cross correlation peak position are also increase and by this increase the velocity of gas/solid two phase flow are decrease.



Graph 4.1: Cross correlation peak position and velocity at set of time delay

When the sampling frequency $f_s= 5 \text{ KHz}$.
 As we know

$$\Delta t = \frac{1}{f} \Rightarrow \Delta t = \frac{1}{5} \Rightarrow \Delta t = 0.2$$

At time delay 10:

$$n=10$$

Now again put the values in equation 3

$$\tau^* = n \cdot \Delta t \quad (3)$$

$$\tau^* = 0.2$$

Now again put the values in equation 2

$$V = \frac{L}{\tau^*} \quad (1)$$

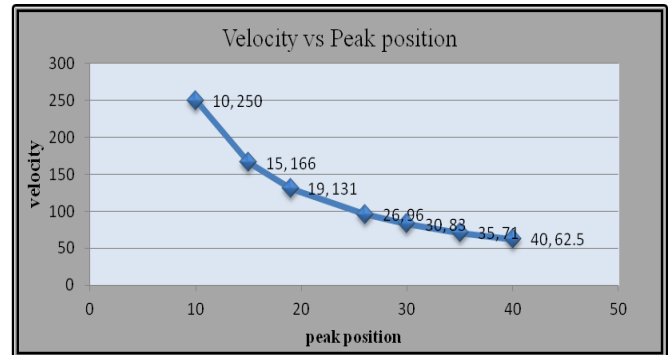
$$V = 250 \text{ mm/ms} \Rightarrow V = 250 \text{ m/s}$$

The table (4.2) show the transit time τ^* and velocity at set of time delay.

Table 4.2: Cross correlation velocity measurement at each time delay when $f_s=5$

N0	True delay time	Peak position	Frequency KHz	Transit time (T*)	Velocity (m/s)
1	10	10	50	0.2	250
2	15	15	50	0.3	166
3	20	19	50	0.38	131
4	25	26	50	0.52	96
5	30	30	50	0.6	83
6	35	35	50	0.7	71
7	40	40	50	0.8	62.5

The values in table (4.2) shows that if the sampling frequency increase the velocity also increase.



Graph 4.2: Cross correlation peak position and velocity at set of time delay

The graph (4.2) displayed the values of velocity at different time delay. The value of velocity is inversely proportional to the cross correlation peak position. By comparing the values of both tables (4. 1) and (4.2) it's clear that by increasing sampling frequency the velocity is also increase.

5. Conclusion and Recommendation

5.1 Conclusion

The results and outputs of cross correlation velocity measurement are presented in this paper. The process of gas /solid two phase flow is elucidated by practical execution on a test rig that how, why and what steps are adopted in this project. However, each process is described step by step such as, pneumatic conveying, two phase "fillite" flow process, electrostatic sensing mechanism and velocity measurement. Whereas, the data acquisition process from sensor to cross correlation velocity measurement are amelioration in accuracy is based on software based analysis. Data acquisition also elucidates the working of variant techniques that put into practice by virtual instruments of LabVIEW (national instrument software).

5.2 Recommendations

In data acquisition process the signals x and y are discrete because they are sampled in time. Thus, in discrete increment it's difficult to constrain the actual location of maximum correlation coefficient and has more chances to fall between set of discrete sampling points and that is the major factor of the inaccurate estimation. To improve the accuracy of time delay estimation the interpolation techniques are more widely used in signal processing.

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Author Profile



M. Waqas Munir was born in Faisalabad, Pakistan. He received M.S Degree in Control System and Electronics from The University of Teesside, United Kingdom. Also, B.Eng [Honor] in Electrical & Electronics Engineering from The University of Faisalabad, Faisalabad, Pakistan. He is a member of IEEE, PEC, PECP & IAENG. He is a research scholar and lecturer, work with Engineering Institute. His major research interest includes: Control System, Power Electronics & Signal Processing.

Bushra Anam Khalil was born in Faisalabad, Pakistan. She received M.S Degree in Physics from The University of Agriculture Faisalabad, Pakistan and B.Sc Physics from Punjab University Lahore, Pakistan. She is Gold medalist in M.Sc and B.Sc and acquires several scholarships & awards in her academic career. Her major research interest includes: Electrodynamics, Mechanics, Instrumentation and Control.