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SIMULATIVE STUDY ON LIQUID/GAS TWO-PHASE FLOW MEASUREMENT FOR DUAL-PLANE ULTRASONIC TRANSMISSION-MODE TOMOGRAPHY

NOR MUZAKKIR NOR AYOB[1*], MOHD HAFIZ FAZALUL RAHIMAN[2], ZULKARNAY ZAKARIA[3], SAZALI YAACOB[4], RUZAIRI ABDUL RAHIM[5] & MOHD RIZAL MANAN[6]

Abstract. Simulative studies are done on the use of cross-correlation technique based on a dual-plane ultrasonic transmission tomography for liquid and gas two-phase flow measurement. This technique is used to correlate the signals from each sensing area namely downstream plane and upstream plane. Separation distance between both sensing areas is fixed. The result from cross correlating the dual-plane signals, combined with the known separation distance and the system's acquisition rate is used to estimate the velocity of the flow inside the investigated process column. Combining Ultrasonic Transmission Tomography (UTT) with the cross-correlation flow measurement technique can provide more information on the flow than a single-plane UTT system. This paper focuses on the mean value of the images and the 2D correlation coefficient that is used to cross-correlate the tomogram images between the downstream and upstream plane of the simulated dual-plane ultrasonic transmission tomography system. The principle of measurement for local gas velocity distribution in a bubbly gas/liquid pipe flow based on cross-correlation of two plane images is also described. Initial experimental results illustrate the feasibility of the method presented here.

Keywords: Cross-correlation; frozen pattern; mean correlation; dual-plane simulation; ultrasonic transmission tomography

Abstrak. Kajian simulatif telah dijalankan mengenai penggunaan teknik korelasi-silang untuk ultrasonik transmisi tomografi satah berganda. Teknik ini digunakan untuk membandingkan isyarat dari setiap satah yg masing-masing dinamakan satah-bawah dan satah-atas. Pemisahan jarak antara kedua-dua satah adalah tetap. Hasil dari perbandingan isyarat satah berganda, digabungkan dengan jarak pemisahan yang telah diketahui termasuk kelajuan sistem memproses maklumat, boleh digunakan untuk menganggarkan kelajuan aliran di dalam paip pemprosesan yang hendak

[1,2,3,4&6] Tomography Imaging Research Group, School of Mechatronic Engineering, Universiti Malaysia Perlis, 02600 Jejawi, Arau, Perlis, Malaysia

[5] Process Tomography Research Group (PROTOM), Control and Instrumentation Engineering Department, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor Darul Ta'azim

* Corresponding author: normuzakkir@mail.com

diteliti. Penggabungan Ultrasonik Transmisi Tomografi (UTT) dengan teknik pengukuran korelasi-silang dapat memberikan maklumat yang lebih lanjut mengenai aliran jika dibandingkan dengan sistem UTT bersatah tunggal. Diskusi dalam artikel ini lebih memfokuskan kepada nilai min setiap gambar dan pekali korelasi 2D yang akan digunakan untuk mengkorelasikan gambar tomogram antara satah-bawah dan satah-atas. Prinsip pengukuran kelajuan pergerakan gas di dalam keadaan gas dan cecair yg bergelembung berdasarkan pada korelasi-silang antara kedua-dua satah juga dijelaskan. Keputusan awal eksperimen menggambarkan kesesuaian kaedah yang dibentangkan di sini.

Kata kunci: Korelasi-silang; corak beku; korelasi min; simulasi satah berganda; tomografi transmisi ultrasonik

1.0 INTRODUCTION

Process Tomography (PT) is a new generation of process-parameter measurement techniques which has been developing rapidly in recent years. This promising technology, which is more famously used for medical imaging, has now also come to be used in industrial applications. PT techniques provide novel means of visualizing the internal behaviour of an industrial process, such as gas/liquid two-component flow in oil pipelines and processes of mixing or separation in plant vessels. Valuable information for online measurement and control of industrial processes can be administered using Process Tomography systems [1, 2, 3].

Ultrasonic Transmission Tomography (UTT), being one of the many available tomographic imaging techniques supported in Process Tomography, promises to be suitable for many applications for monitoring of industrial processes and environmental areas, such as monitoring of gas–liquid mixing in a stirred vessel [4, 5, 6], detection of leakages from buried pipes [7], and industrial monitoring of hydro cyclone operation [8]. UTT has been proven to be an important tool that can be utilised to improvise the operation efficiency of such applications, as it results in accurate measurement and control of hydrodynamic parameters such as flow regime and flow rate [9, 10]. The non-invasive nature of the UTT sensing method has also helped in attracting great interest from researches and engineers in various fields [11].

There has been an increased use of instrumentation in the process and energy conversion industries for many purposes including safety, energy saving, product quality, operational efficiency and manpower saving. More recently, the advent of process computer systems, which has enhanced these functions particularly in the fields of complex control and management information, has increased the requirement for the measurement of plant parameters. Flow measurement is a particularly important aspect of plant instrumentation. Flow rate measurement of two-phase flow is an unsolved problem in the industrial field due to its complex fluid condition. In the research of two-phase flows, the flow velocity can be estimated using two groups of axially separated sensors with the cross-correlation technique [12]. Cross correlation techniques are ideally suited to the measurement of multi-phase flows while providing more information on the flow than the traditional measurement instrumentation.

Generally, a typical UTT system constitutes of four main parts separated by their different objectives in the system; (1) sensing area, (2) signal conditioning circuitry, (3) data acquisition and (4) display module.

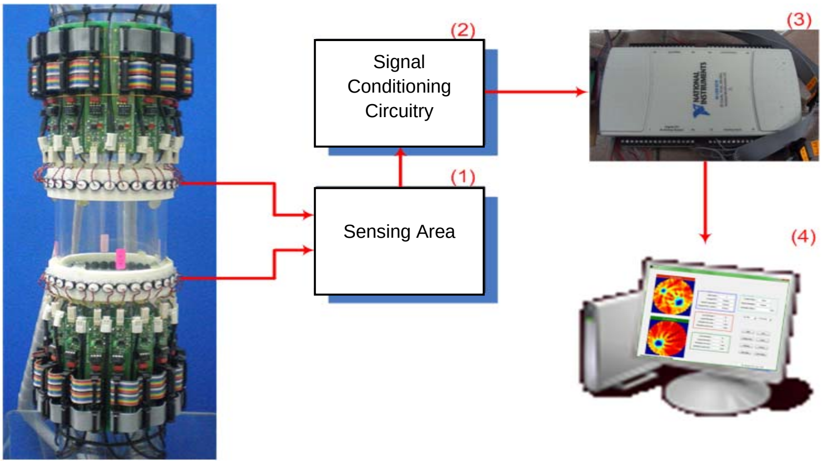

Figure 1 Block diagram of a typical ultrasonic transmission tomography

2.0 CROSS CORRELATION PRINCIPLE

Cross correlation is a measure of similarity between two waveforms as a function of a time-lag applied to one of them. The basic principle of cross correlation is simply to measure the time taken by a disturbance to pass between two points spaced along the direction of the flow. There are two pattern models of a cross correlation flow meter, which is the frozen pattern model and the non-frozen pattern model [13].

This paper however will be concentrating on the frozen pattern model. This particular model is conceptually very simple and thus was used in the simulative studies for a dual-plane ultrasonic transmission tomography system. The fundamental concept for the frozen pattern model is that the signals acquired from both sensing areas (downstream and upstream) indicating the flow activities inside the process vessel imitate each other with a time-lag applied to one of them (Figure 2). This assumption of no distortion in the pattern enables the basic principles of cross correlation flow measurement to be presented in an easily understandable theoretical framework (Figure 3).

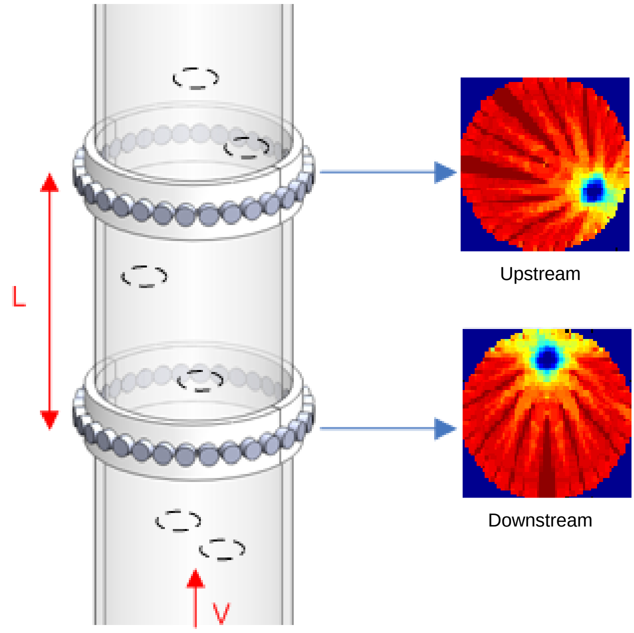

Figure 2 The dual-plane UTT transducers array

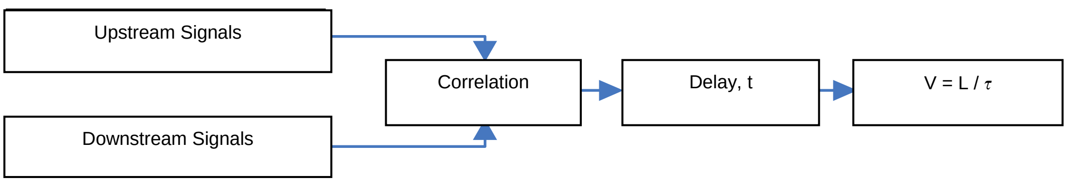

Figure 3 The principle of velocity measurement using cross correlation technique

The fundamental principle underpinning cross-correlation flow measurement is the 'tagging' of signals generated by turbulence of the fluid or suspended particles moving within the pipe [14]. The sensors, which detect these signals relative with the turbulence of the fluid or suspended particles, could be based on various techniques including the use of ultrasound. In an ideal case, if a signal detected by the downstream sensor reappears after a certain period of τ at the upstream sensor and the distance L between the two sensors is known, then the velocity V can be calculated:

$$V = \frac{L}{\tau} \tag{1}$$

where,

V = flow velocity.
L = distance between two plane sensors.
τ = transit time for frozen pattern.

In practice, the reconstructed images from the turbulence of the fluid or suspended particles will gradually change upon moving upstream; however, if the position of the upstream sensor is reasonably close to that of the downstream sensor, the patterns or signals would be sufficiently similar to be recognized by correlation using the frozen pattern method [15], allowing the transit time τ to be measured more accurately.

It should be made clear that the signal detected by each sensor should be a random series and reflect a random modulation effect of the fluid in the sensing volume of the sensor to the energetic field of the sensor. The correlation velocity denotes precisely the transmission velocity of such a random modulation effect. If such an effect is not random, however, the sensor will not work.

For instance, in a bubbly gas/liquid flow, bubbles are generally of various sizes and distributed randomly over a cross section of the pipe. If a correlation flow meter using ultrasonic sensors is used to measure the velocity of the flow, the randomly distributed bubbles will modulate the ultrasound beam of each transducer and signals detected from upstream and downstream transducers appear randomly in relation to such a modulation effect. In the present case the modulation effect is caused only by randomly distributed bubbles, so the correlation velocity denotes the average transit velocity of bubbles in the flow [15].

For stratified and annular flow, perhaps no random effect is registered by the sensor and the flow meter does not work [16]. Naturally, when the perturbation of the wavy interface is random and can be registered by other sensors, the transit velocity of the perturbing interface can still be obtained. Even for slug or plug flow, slugs or plugs that are too long may blur signals obtained from two planes, which are not sufficient to assess the flow rate through correlation analysis.

3.0 SIMULATION MODEL FOR THE LIQUID/GAS TWO-PHASE FLOW

A simulation model is developed as the case study to investigate the usability of the two proposed methodologies in this paper. The case study is designed to simulate the hold-up movement of a single gas bubble inside the vertical column as graphically shown in Figure 4.

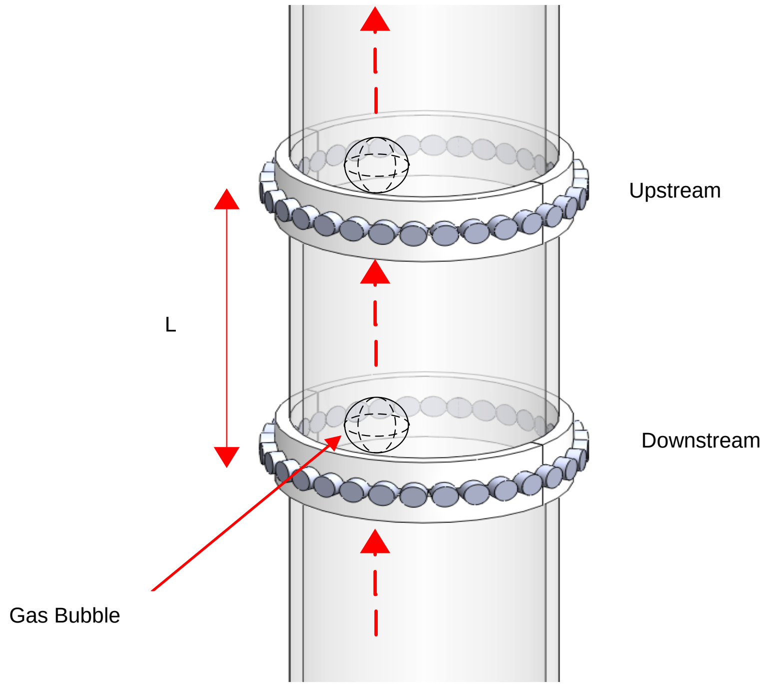

Figure 4 Simulation model for a single gas bubble hold-up movement

The simulation phantom model used for the single gas bubble is built using 20 frames. All the simulation frames have a 64 x 64 pixels dimension, where the simulated gas bubble have a dimension of 10 pixels and the centre of the gas bubble is Gas_{xy}(15,15). The simulation model for a single gas bubble is shown frame by frame in Figure 5 where 10 out of the 20 frames used are made visible.

The distance, *L* between the downstream and upstream plane are fixed. This is because the cross correlation method of flow measurement is based on the determination of the transit time of a measurable disturbance moving along the pipe over an exactly known distance which is *L*.

Tomogram images (Figure 6) for the whole simulation phantoms movement inside the vertical are constructed using 100 frames and each frame which shows the internal activities of the flow are reconstructed using Linear Back Projection (LBP) algorithm as it is the simplest and the reconstructed image is well enough for interpretation.

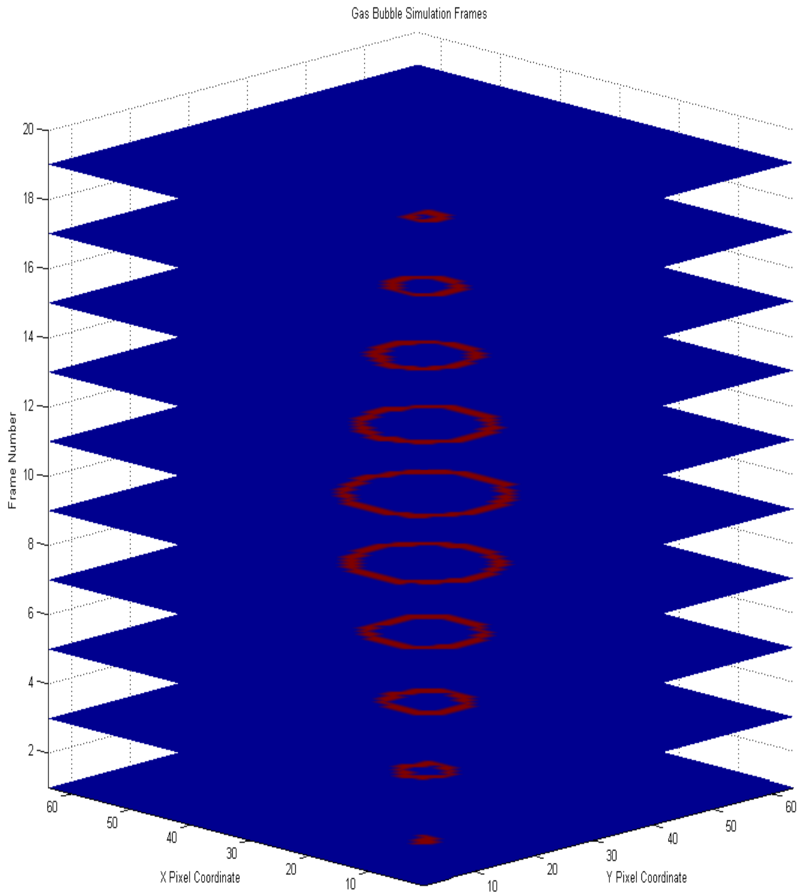

Figure 5 Simulation model for the single gas bubble

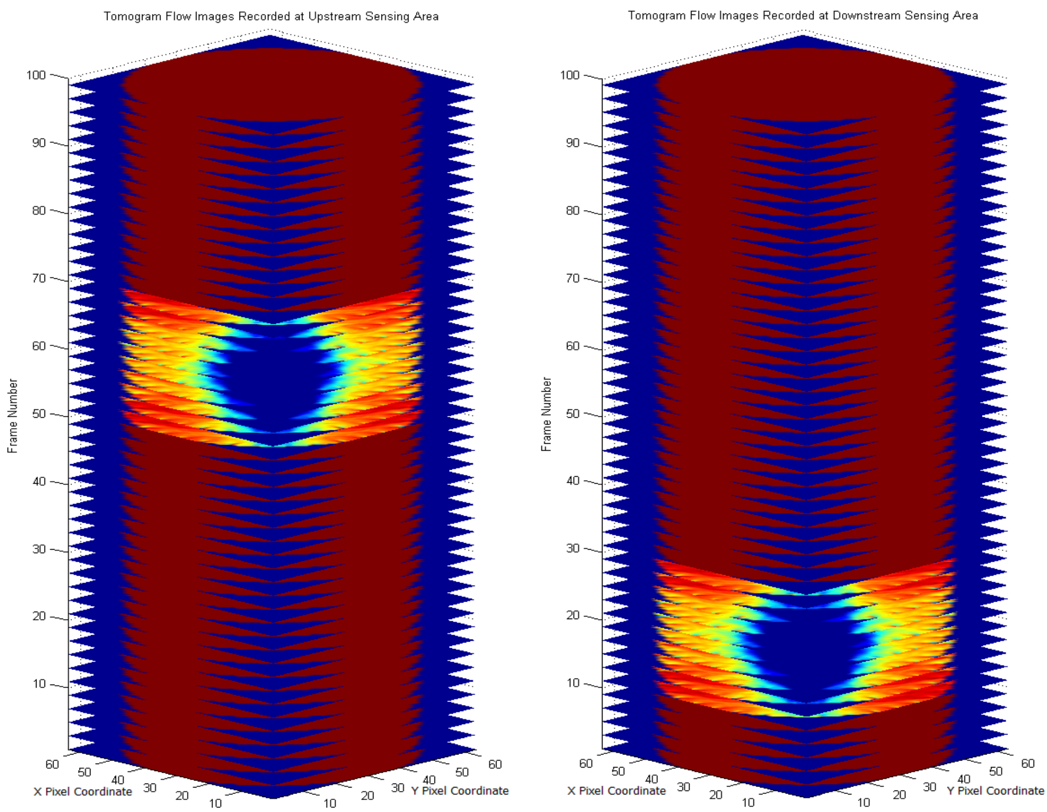

Figure 6 Reconstructed tomogram images of flow imaging recorded at Upstream and Downstream sensing area

4.0 VELOCITY MEASUREMENT USING CROSS CORRELATION

Two different methods to estimate the velocity of the flow inside the investigated column by measuring the transit time for the frozen pattern method to rise upward from downstream to upstream sensor are discussed in this paper. The two methods are namely the Mean Correlation method and 2-D Correlation Coefficient method.

4.1 Mean Correlation

The use of Mean Correlation is the simplest technique between the two methods that is discussed in this paper. As described earlier, each frame that shows the flow imaging has an image resolution of 64 x 64 pixels. The Mean Correlation method computes the overall mean of each frame's image by determining the mean of all the data in the matrix. The main objective in implementing this method is so that each frame determining the flow activities are given a single characteristic value (Figure 7).

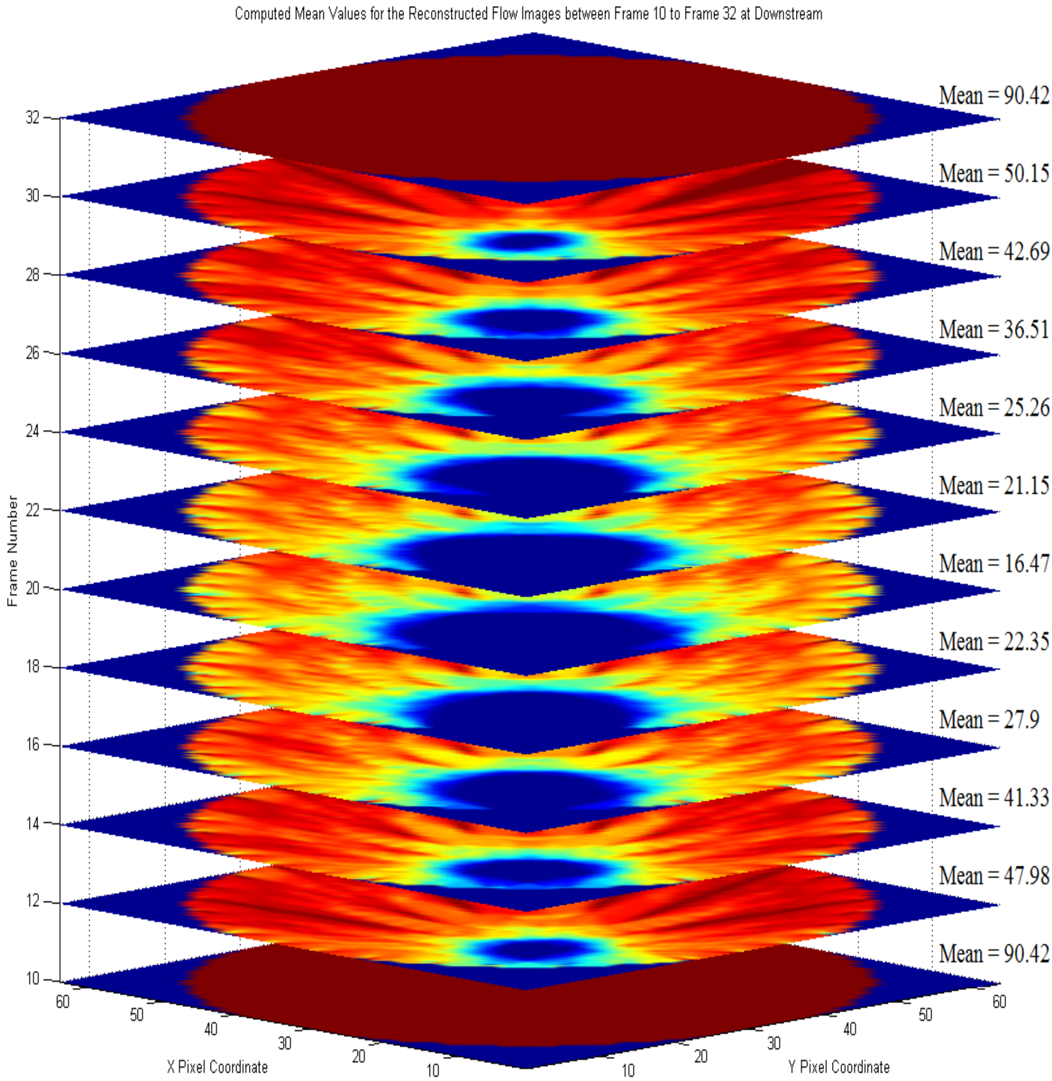

Figure 7 Mean values for reconstructed flow images between Frame 10 to Frame 32 at the Downstream sensing area

Mean Correlation technique agrees with the fundamental principle correspond to cross-correlation flow measurement by 'tagging' the signals generated at both the downstream and downstream sensors by the turbulence of the fluid flow moving inside the column.

All the mean values computed for upstream and downstream sensing areas are then plotted, and then used in this paper to graphically visualize the fluid flow movement in 1-dimensional view at different frame numbers. Figure 8 shows the flow movement through upstream plane while Figure 9 shows the activities through the downstream plane.

The highest pixels mean value is when the condition at any downstream or upstream plane is full with liquid. The pixels mean value decreases when the reconstructed image contains gas bubble. The lower the mean value, the bigger the size or quantity of gas bubble detected at each plane.

Mean values for upstream and downstream sensing areas are then cross-correlated with each other to produce a correlation graph. When the time delay equals the flow transient time, τ, the cross correlation graph produces the maximum value (Figure 10).

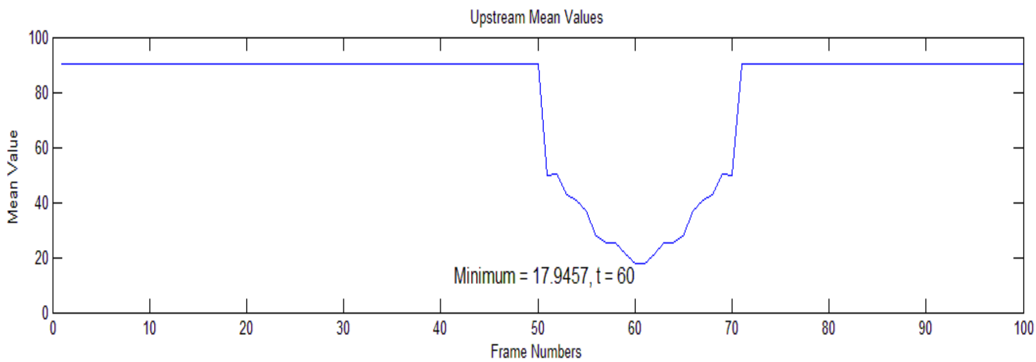

Figure 8 Mean values plotted for each frame recorded at Upstream sensing area

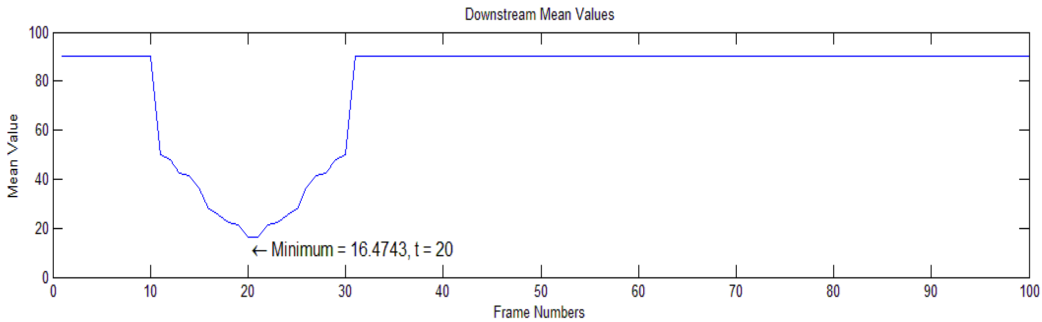

Figure 9 Mean values plotted for each frame recorded at Downstream sensing area

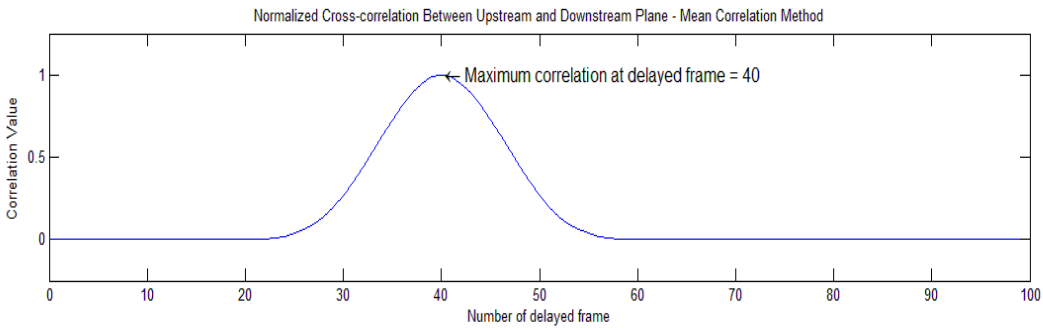

Figure 10 Cross-correlation signal between Upstream and Downstream

4.2 2-D Correlation Coefficient

In this method, 2-D Correlation Coefficient algorithm [17] is used to compute the correlation coefficient between two images. The algorithm used to compute the correlation coefficient between the matrix of the reconstructed tomogram image of upstream plane and the matrix of the downstream plane is shown as below:

$$r = \frac{\sum_m \sum_n (A_{mn} - \bar{A})(B_{mn} - \bar{B})}{\sqrt{(\sum_m \sum_n (A_{mn} - \bar{A})^2)(\sum_m \sum_n (B_{mn} - \bar{B})^2)}} \tag{2}$$

where,

$\bar{A}$ average or mean of A.
$\bar{B}$ average or mean of B.
r correlation coefficient.

The value r is scalar and is scaled between 0 and 1. The r value will approach 0, which indicates the absence of correlation between both downstream and upstream image. The r value will increase gradually as images between both planes become significantly similar to each other (Figure 11). Perfect correlation between both planes will results in r obtaining the value of 1.

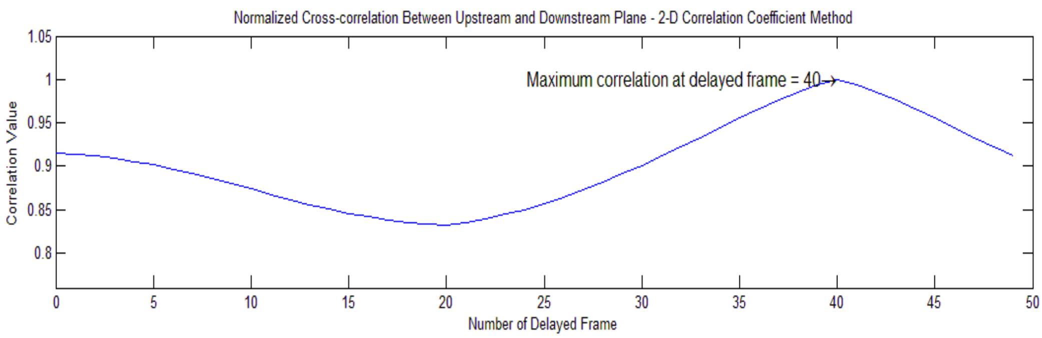

Figure 11 Signal cross-correlation between Upstream and Downstream using 2-D correlation coefficient

5.0 RESULTS

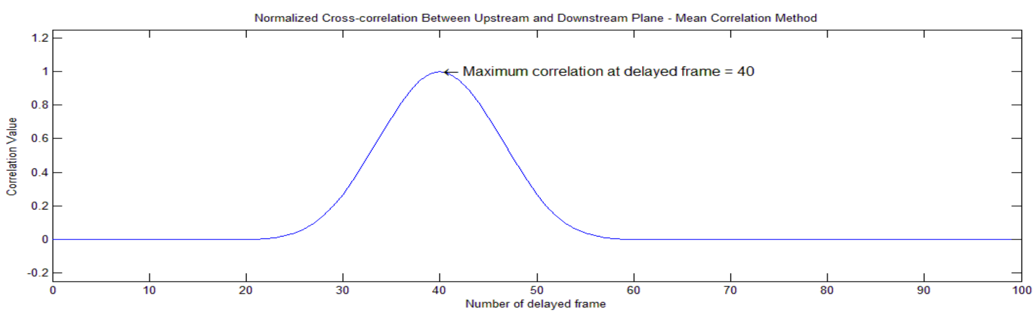

Figure 12 Mean correlation results for $Gas\_Up_{xy}(15,15)$ and $Gas\_Down_{xy}(15,15)$

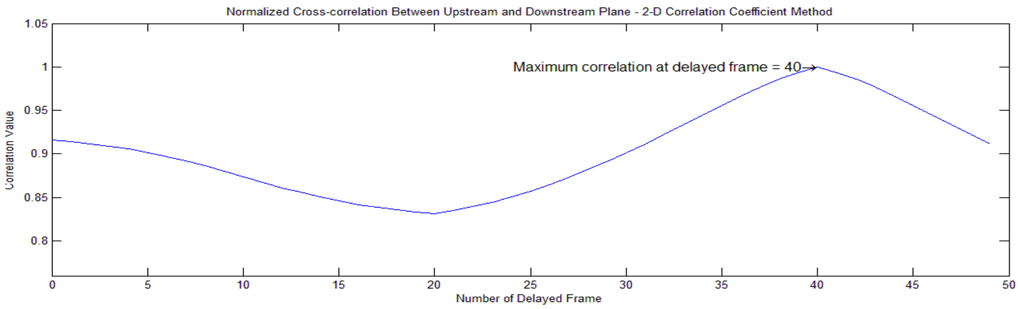

Figure 13 2-D Correlation Coefficient results for *Gas_Up*$_{xy}$(15,15) and *Gas_Down*$_{xy}$(15,15)

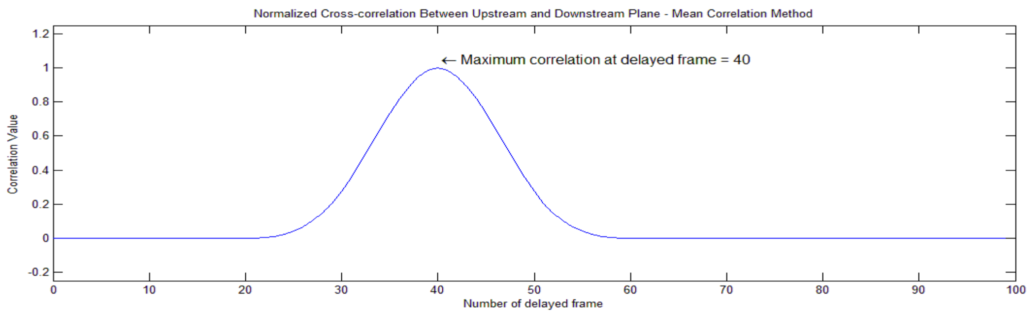

Figure 14 Mean Correlation results for *Gas_Up*$_{xy}$(45,45) and *Gas_Down*$_{xy}$(15,15)

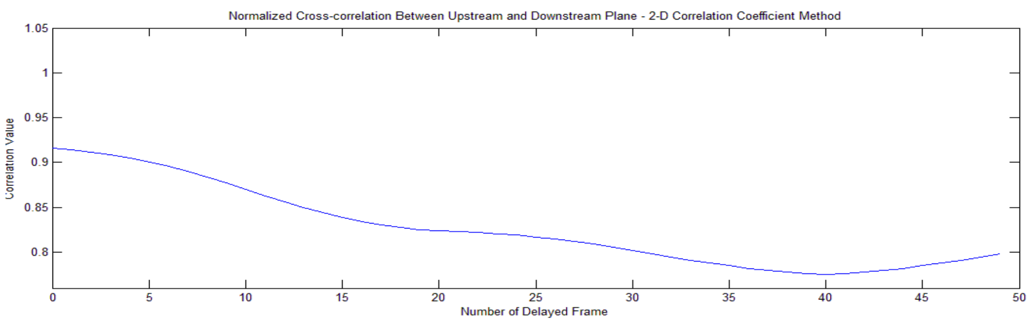

Figure 15 2-D Correlation Coefficient results for *Gas_Up*$_{xy}$(45,45) and *Gas_Down*$_{xy}$(15,15)

6.0 CONCLUSION

The results using the proposed methods in cross correlating signals between downstream and upstream plane from the simulated dual-plane ultrasonic transmission tomography has been presented.

Two different simulation profiles were constructed to test the flow measurement using the two proposed correlation methods. The first simulation profile (Sim_1) flow condition is that the single gas bubble with a diameter of 10 pixels, appear at both the upstream and downstream plane at different frame number but at the same coordinates, centered at $Gas\_Up_{xy}(15,15)$ and $Gas\_Down_{xy}(15,15)$. Flow condition for Sim_2 however is different where the appearance of the gas bubble on the upstream plane is centered at $Gas\_Up_{xy}(45,45)$ while at downstream plane stays $Gas\_Down_{xy}(15,15)$.

It can be noted that the correlation graph using Mean Correlation method detects maximum correlation at delayed frame number of 40 in Figure 12 and Figure 14. Incorrect data collection is detected during Sim_2 flow setup where the same result is registered even though the gas bubble that appears at upstream and downstream sensing area is centered at different coordinates. This is because similar mean values will always be calculated (for same gas dimension) even though the location of the gas bubble is different.

Results from using the 2-D Correlation Coefficient however neglected this inaccurate flow measurement. During Sim_2 flow setup, the correlation graph (Figure 15) did not register any maximum correlation at any delayed frame number. 2-D Correlation Coefficient algorithm assigned different values for different gas bubble locations even though they had the same gas dimension. This ensured that utilizing the 2-D Correlation Coefficient method to register the delayed frame number at the maximum correlation to acquire the transit time of frozen method is more accurate than using Mean Correlation method.

Accurate detection of maximum correlation is the most important objective in a dual-plane UTT system that implements cross correlation technique. As introduced earlier, cross correlation is a measure of similarity between two waveforms as a function of a time-lag applied to one of the signals. Maximum correlation will occur when similar stream of flow images has been cross correlated between both sensing areas. The number of delayed frames, N_{delay} of the maximum correlation will then be used to determine the transit time by multiplying N_{delay} with the time taken for each image frame to be generated.

Equation (1) can then be used to estimate the velocity of the flow. If we assume that the separation distance of the dual-plane UTT system, L is 5 cm and the system's acquisition rate, V_f is 15 fps, the equation can be solved as below:

$$V = \frac{L}{\tau} = \frac{5}{\frac{1}{15} \times 40} = 1.875\ cm/s$$

By solving equation (1) with the known parameters of the UTT system, cross correlation technique can be used to estimate the flow velocity inside a process vessel.

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