Dual-Plane Ultrasonic Tomography Simulation using Cross-Correlation Technique for Velocity Measurement in Two-Phase Liquid/Gas Flow

N. M. Nor Ayob, M. H. Fazalul Rahiman, Z. Zakaria, S. Yaacob and R. Abdul Rahim

***Abstract*—Combining Ultrasonic Transmission Tomography ,UTT with the cross-correlation flow measurement technique can provide more information on the flow than usual. A simulated dual-plane UTT system for use on laboratory and plant-scale process equipment has been developed on the basis of this idea. This paper focuses on the correlator used to cross-correlate the tomogram images between the downstream and upstream plane of the simulated dual-plane ultrasonic transmission tomography system. This paper proposed the use of 2D correlation coefficient for the correlator and the result of its usage is discussed. The principle of measurement of the local gas velocity distribution in a bubbly gas/liquid pipe flow which is based on cross-correlation of two plane images is also described. Initial experimental results illustrate the feasibility of the method presented in this paper.**

***Index Terms*—Cross-correlation, correlation coefficient, dual-plane simulation, frozen pattern, ultrasonic transmission tomography.**

I. INTRODUCTION

NEW generation of process-parameter-measurement techniques, process tomography (PT), has been developed rapidly in recent years and now has come to the stage of industrial applications. PT techniques provide novel means of visualizing the internal behaviour of an industrial process, such as gas/liquid two-component flows in oil pipelines and processes of mixing or separation in plant vessels. Numerous valuable information for measurement, online monitoring and control of industrial processes can be administered using Process Tomography systems than can most traditional equipment [1–3]. Many suitable applications of Ultrasonic Transmission Tomography (UTT) have been found in monitoring of industrial processes and environmental areas, such as monitoring of the measurements of gas–liquid mixing in a stirred vessel [4–6], detection of leakages from buried pipes [7] and industrial monitoring of hydro cyclone operation [8]. UTT has been proven as one of the important tools that can be utilised to improvise the operation efficiency of such applications as this 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 also has helped in attracting great interest from researches and engineers in various fields [11].

This paper presents the use of 2D correlation coefficient for the correlator and the result of its usage is discussed. Initial experimental results illustrate the feasibility of the method presented.

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II. TYPICAL UTT SYSTEM

Like other PT systems, a typical UTT system is composed of four parts, as shown in Fig. 1: (1) the sensor, (2) the data acquisition system (DAS), (3) the image reconstruction and (4) the computer.

There has been an increasing 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 have enhanced these functions particularly in the fields of complex control and management information, has increased the requirement for the measurement of plant parameters.

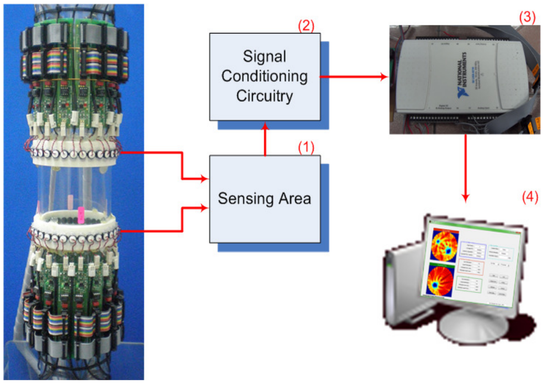

Fig. 1. Block diagram of a typical ultrasonic transmission tomography.

Flow measurement is a particularly important aspect of plant instrumentation. Cross correlation technique are ideally suited to the measurement of multi-phase flows while providing more information on the flow than traditional measurement instrumentation. It was proven that cross correlation technique is technically highly successful, although it was not adopted for process use because of prohibitively high cost of on-line electronic correlators at the time (the late 1950s) [12].

III. CROSS CORRELATION PRINCIPLE

Cross correlation is a measure of similarity of 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. The cross correlator for measuring the transit time of the disturbances is now a relatively inexpensive device because of the low cost of digital electronic systems.

Reference [12] stated that there are basically two pattern models of a cross correlation flowmeter, which is the frozen pattern model and the non-frozen pattern model.

This paper however will be focusing on using the frozen pattern model to be used in the simulation of the dual-plane ultrasonic transmission tomography. The frozen pattern model is used as it is conceptually very simple. The basic concept is that some patterns in the flow stream travels without distortion between downstream plane and upstream plane as shown in Fig. 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 as can be illustrated in Fig. 3.

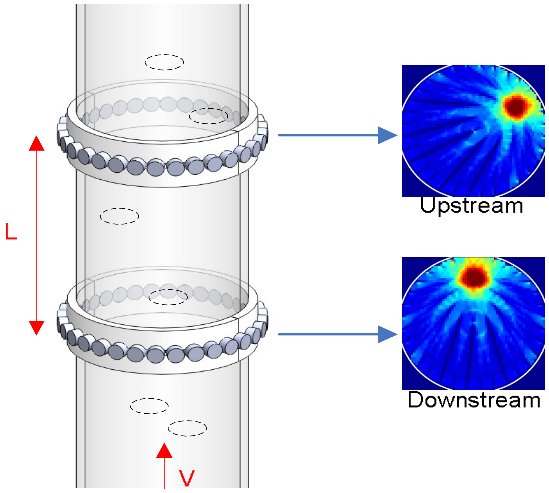

Fig. 2. The dual-plane UTT transducers array

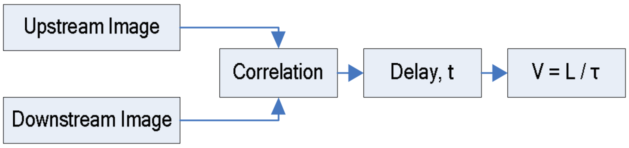

Fig. 3. The principle of velocity measurement using cross correlation technique

There has been a long history of application of the correlation function theory to measurements of physical parameters, especially measurement of velocity, ever since the early 1960s.

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 [13]. The sensors, which detect these signals in empathy 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:

$$V = L / \tau \qquad (1)$$

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 on 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 correlator using the frozen pattern method [14], allowing the transit time τ to be measured as illustrated in Fig. 2 and Fig. 3.

It should be made clear that the signal detected by each sensor should be 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 flowmeter 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 just caused by randomly distributed bubbles, so the correlation velocity denotes the average transit velocity of bubbles in the flow [14].

For stratified and annular flow, no random effect is registered by the sensor and the flowmeter does not work [15]. 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.

IV. VELOCITY MEASUREMENT USING CROSS CORRELATION

In this paper, the transit time for the frozen pattern method to rise upward from downstream to upstream sensor, was measured by means of 2-D correlation coefficient. The algorithm used to compute the correlation coefficient between both matrix of the reconstructed tomogram image of upstream and downstream plane is shown as below:

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

where,

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

The value of r is scalar and is scaled between 0 and 1. When r approaches 0 indicates 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. Perfect correlation between both planes is indicated by r = 1.0.

V. CROSS CORRELATION SIMULATION

A case study is designed to simulate the movement of a single gas holdup from downstream plane to upstream plane as shown below in Fig. 4.

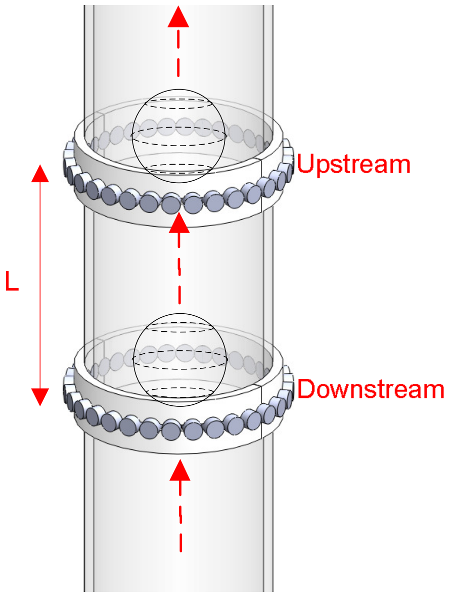

Fig. 4. Movement of the single gas holdup in the study case

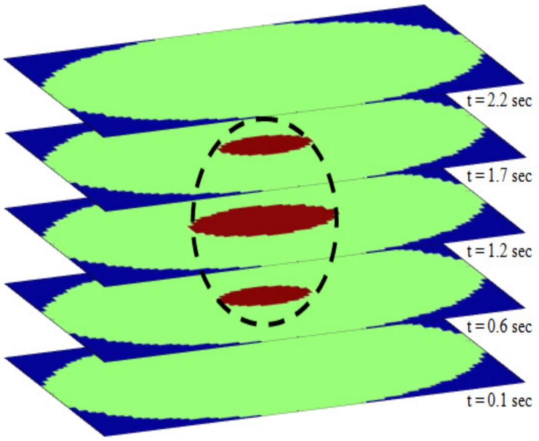

Fig. 5. Simulation model at downstream plane (frame by frame)

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 termed as L.

Simulation phantoms are then drawn (Fig. 5) where 3 frames are used to simulate the single gas holdup movement through the sensing area of each plane (downstream and upstream). Tomogram images for the simulation phantoms are then reconstructed using Linear Back Projection (LBP) algorithm as it is the simplest and the reconstructed image is well enough for interpretation.

The tomograms (Fig. 6) will then be used in simulating the whole movement of the single gas holdup starting from bottom, through the downstream plane, moving between the two sensing areas, continue through the upstream plane and finally past the upstream plane as graphically shown with the dashed red arrows in Fig. 4.

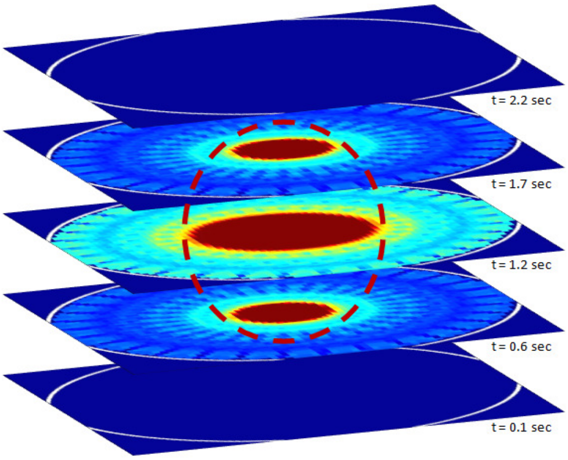

Fig. 6. Reconstructed simulation model images at downstream plane

VI. RESULTS

Pixels mean value for each frames of the reconstructed images of the flow is used to picture the flow measurement in 1D view. Fig. 7 shows the flow movement through downstream plane while Fig. 8 shows the activities through the upstream. However, it must be emphasized that these 1D signals were not used for the cross correlation between the two planes in Fig. 9.

The highest pixels mean value occurss 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.

The result for the 2D cross correlation between both planes is as shown in Fig. 9. The maximum value of the cross-correlation coefficient, r is detected at delay = 20.

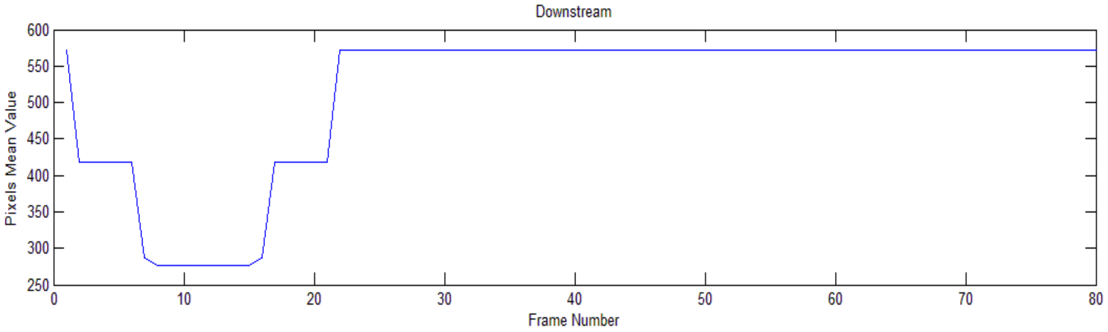

Fig. 7. Movement of the single gas bubble holdup in singular mean value of the reconstructed image through downstream

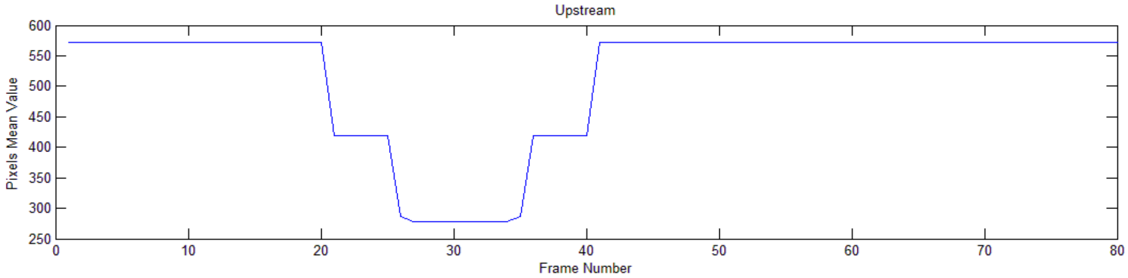

Fig. 8. Movement of the single gas bubble holdup in singular mean value of the reconstructed image through upstream

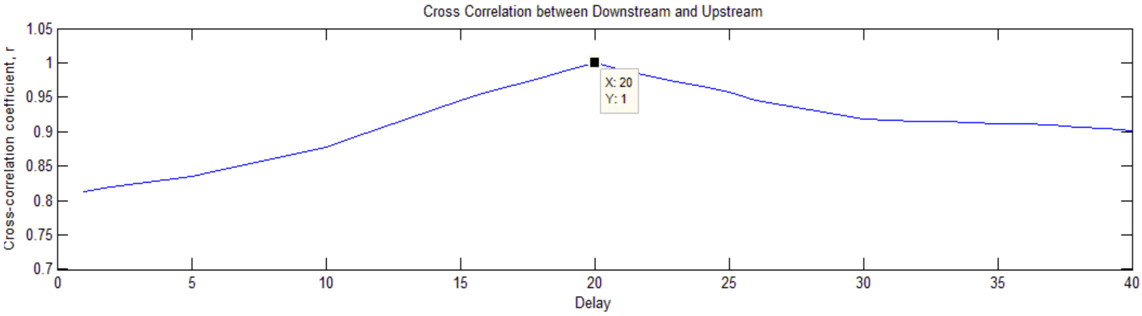

Fig. 9. 2D cross-correlation between downstream and upstream

VII. DISCUSSION

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

The complete flow movement of the single gas holdup from the bottom of the investigated pipe to the top is simulated in 80 frames each, where these frames are comprised of the reconstructed tomogram images of the corresponding activities that goes through the sensing area for downstream and upstream plane. If we assume that each sensing plane is able to acquire the ultrasonic projection data and reconstruct tomographic images at a rate of 10 frames per second (fps), thus each frame are produced every 0.1 second. As it has been shown in Fig. 9, the peak of the cross-correlation is recorded at a delayed frame of 20, by using this information and the fps rate, we can acquire the transit time of frozen method, τ which in this case is 2 second.

Estimation of velocity measurement of the flow in the investigated column can now be achieved as the transit time of the frozen method used as proposed in this paper have been acquired. As stated in the cross correlation principle, 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 we can estimate the velocity V using equation (1).

Thus if we take the distance, L that separates the two downstream and upstream plane as 5 cm, and use the acquired transit time of frozen method, τ which is 2 second, the estimated velocity is 2.5 cm/s.

In order to implement correlation of signals from the two corresponding sensing planes, the speed of image reconstruction and data processing, i.e. the real-time performance of the actual system, must be guaranteed [14]. In the interest of realizing the cross-correlation measurement, based on the equation by Deng et. al., the data acquisition speed, $Vdaq$ should be no less than:

$$Vdaq = \frac{1}{\left({}^{2L}/_{Vmax} \times {}^{\Delta V}/_{Vmax}\right)} \tag{3}$$

where,

$L =$ separation distance between sensing planes.

$Vmax =$ maximum expected velocity.

${}^{\Delta V}/_{Vmax} =$ velocity discrimination.

If data acquisition speed cannot be improved and is limited, equation (3) can be derived so that the system's performance can be compromised between the ability to estimate much slower flow velocity with the value chosen for the separation distance. This is because for estimating the velocity of much faster flow movement, the image reconstruction speed, i.e. the real-time performance of the dual-plane UTT must be improved.

It is also important to compromise the selection of the length of separation distance. Generally, a compromise between the similarity of the flow patterns over upstream and downstream planes and the resolution of measurement of the transit time should be made [14]. On the other hand, with slower data acquisition speed and increased image reconstruction processing time, requires a longer distance of L. So both the similarity of signals and the dynamic behaviour of the system must be simultaneously considered.

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