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VELOCITY MEASUREMENT SIMULATIVE STUDY OF TWIN PLANE ECT USING ADVANCED CROSS CORRELATION TECHNIQUE

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ABSTRACT

Flow velocity is a critical information to have in order to ensure an optimum flow condition in a process plant. The combination of Electrical Capacitance Tomography and cross correlation technique has been successfully used to measure the velocity of multiphase flows. The peak of the cross correlated signals corresponds to the time taken by particles to move along the flow, thus its velocity can be derived. This paper investigates the capability of implementing an improved method of determining flow velocity by using a combined function of the cross correlation (CCF) and average squared differential (ASDF) functions in order to improve the accuracy of the velocity measurement. A velocity measurement simulation of a liquid/gas flow using MATLAB is employed and a comparison between the use of CCF and the combination of CCF/ASDF is made. The correlogram of the combined CCF/ASDF method has a sharper peak compared to the correlogram of the conventional CCF method, indicating that the peak of the function can be determined more accurately as the sharper peak can decrease the measurement uncertainty.

Keywords: electrical capacitance tomography, advance cross correlation, average squared differential function.

INTRODUCTION

Multiphase flow is a common occurrence in industrial environment where they are usually carried along process pipes or vessels. It is advantageous to know basic flow information such as its local velocity as it can help in providing an optimum process system as well as in controlling it. However, having the correct multiphase flow measurement is still a challenge due to the independent properties and behaviour of each phase of the flow (Brennen, 2005). Yang (Yang, 2010) has stated that the combination of electrical tomography and cross correlation is able to provide a reliable means of measuring the velocity profile of multiphase flow.

Electrical Capacitance Tomography (ECT) is one of electrical tomography techniques where the material distribution of the flow is determined by measuring the capacitance of the flowing material. Electrode sensors are placed around a cross section of the pipe and the inter electrode capacitances in reaction to electrodes' excitation are calculated. The cross sectional images of the pipe are then reconstructed. As the capacitance measurement will vary in accordance to the permittivity of the dielectric, it gives ECT the ability to differentiate materials that has different permittivity hence making it a reliable mean to measure multiphase flows.

To measure the flow velocity, two sets of ECT sensors are placed around the pipe at a known distance. The received signals or the reconstructed images from both sensor planes are cross correlated. Cross correlation is one of time delay estimation techniques in signal processing. The function will generate a sequence of the correlation between two signals which attained by shifting one sequence with respect to the other, taking the element by element product, and summing the result. The time delay is determined by identifying the time when the cross correlation function is maximum. The velocity can thus be calculated by dividing the time delay with the sensor distance.

It is crucial that the accuracy of the measurement is as high as possible. Although cross correlation method is robust against external interferences, there are some errors and uncertainties caused by a measuring system in itself. To ensure that the time delay is determined exactly and the mean flow velocity is then calculated correctly, these uncertainties must be reduced. A sharper peak of the correlation function is desired in order to have a more precise time delay reading (Gajewski, 2013).

Recently, other time delay estimation techniques such as differential (Chen *et al.* 2006), (Jacovitti and Scarano, 1993), average signal conditioning (Hanus *et al.* 2012), (Kowalczyk *et al.* 2011) and cross correlation with Hilbert transform use (Cabot, 1981), (Hanus, 2012), have appeared (Hanus *et al.* 2014). However, their capability in measuring flow velocity using ECT has not yet been determined. Hanus (Hanus *et al.* 2014), who has proposed the use of the combination of cross correlation function (CCF) and average squared difference function (ASDF), has implemented the method to measure two-phase flow using gamma ray attenuation technique. The proposed technique has been proved to provide smaller standard uncertainty and simultaneously improved the accuracy of the measurement as compared to conventional CCF method.

This paper will investigate the capability of the proposed method which is combining CCF and ASDF functions in order to measure liquid/gas flow using simulation. A developed velocity measurement program using MATLAB by PROTOM-i Group of Universiti Teknologi Malaysia is used and modified to implement the new method. The velocity measurement of a gas (air) hold up in a water filled pipe is simulated and the results are presented. A comparison is then made to analyse the performance of the combined correlation technique in reference of the conventional CCF technique.

TIME DELAY ESTIMATION TECHNIQUES

Conventional cross correlation (CCF)

Velocity measurement using cross correlation method is a standard signal processing technique that is frequently used in multiphase flow measurement. This method calculates the time delay of two signals observed at two spaced points with a known distance. The time delay can be identified as the maximum or the peak of the cross correlation function of the two signals.

In an ECT system, two pairs of electrode sensors are positioned at a known distance D on the periphery of the pipe (Figure-1). The transducer pairs are placed in the same plane in order to maximise the potential for correlating signals. The first set of sensors on the first plane is called upstream sensor and the second plane is called downstream sensor.

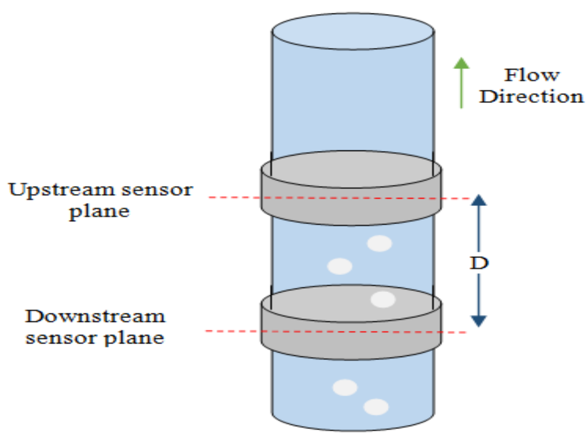

Figure-1. Upstream and downstream sensor planes.

Both sensors will measure temporal variation on the measured cross-sectional area of the pipe and will produce two output signals *x(i)* and *y(i)* respectively. Both signals will then be cross-correlated using the function (1) where N is the number of samples in the summation, M is the number of samples in the cross correlation calculation and j is the number of the delayed sample (Hanus *et al.* 2014):

$$R_{CCF}(j) = \frac{1}{N}\sum_{i=0}^{N-1} x.(i).y(i+j) \quad j = 1,2,..,M \qquad (1)$$

The transit time of the flow between the two sensors is found by observing the time lag at which the cross-correlation function is at a maximum, τ_0 (Figure 2). The dimension of the correlation function is $2N-1$. The velocity, V of the two signals can be found from:

$$V = D/\tau_0 \qquad (2)$$

An assumption in using the cross correlation method is that the signal at the second sensor plane is the time delayed replica of the signals that passes through the first sensor plane and that all particles is moving along the flow direction. Although in practical, this assumption is not true because the shift of particles arrangement and other movement effect such as collision with the wall, gravity etc. It is thus crucial to choose the right sensor distance, *D,* in order to provide a close case to the assumption as when *D* is too large, the particles arrangement in both sensor might have shifted greatly. *D* should not be too small as well because we have to take consideration of the computation and acquisition time of both sensors.

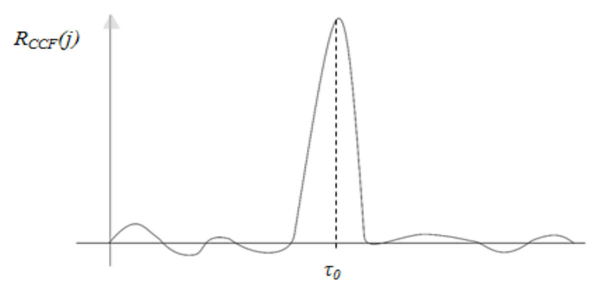

Figure-2. Cross correlation function representation (Hanus *et al.* 2014).

Average squared differential function (ASDF)

Instead of measuring the maximum similarity between two signals to identify the time delay, the ASDF method is based on finding the position of the minimum error square between the two signals (Figure-3). The ASDF function is described as below (Jacovitti and Scarano, 1993), (Zhang and Abdulla, 2005):

$$R_{ASDF}(j) = \sum_{i=0}^{N-1}[x(i) - y(i+j)]^2 \qquad (3)$$

ASDF is computationally faster than CCF as there is no multiplication used. In addition, the dimension of the ASDF function is N as this method does not require the knowledge of the input spectra (Zhang and Abdulla, 2005). Jacovitti, (Jacovitti and Scarano, 1993) has stated that one favourable advantage of this method over CCF method is it is able to give a perfect estimation in the absence of noise which is not true for CCF. However, the

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magnitude of the principle minimum of the ASDF is essentially influenced by the intensity variation and the background noise of the observation signal (Chen *et al.* 2005).

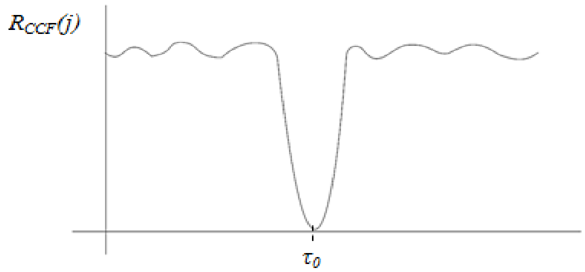

Figure-3. ASDF function representation (Hanus *et al.* 2014).

Combined method of CCF and ASDF

In order to compromise both accuracy of ASDF and robustness of CCF, a heuristic method by weighting the CCF is presented. The weighted cross correlation was first introduced by Chen, (Chen *et al.* 2005) that has combined the Average Magnitude Difference Function (AMDF) in acoustic application. Hanus, (Hanus *et al.* 2014) has then proposed the method of combining the CCF and ASDF functions resulting the equation below:

$$R_{CCF/ASDF}(j) = \frac{R_{CCF}(j)}{R_{ASDF}(j) + \varepsilon} \quad (4)$$

where ε is a small positive value that has been introduced to avoid division by zero where it is a possible value at τ0 when the case is ideal with zero noise.

The proposed combined method has yield a better accuracy in estimating the time delay between the two signals as reported by both Chen and Hanus. The weighted correlation function has a sharper peak at τ0 as compared to conventional CCF thus the determination of τ0 is more accurate.

METHODOLOGY

A simulative study to analyse the feasibility and capability of implementing the use of RCCF/ASDF in an ECT system was employed. The performance of the new method will then be analysed by comparing it to the conventional correlation method.

The study will simulate an ECT system in order to measure the velocity of a gas bubble hold up in a vertical, water-filled pipeline. The downstream and upstream plane distance is fixed as D = 120 mm, in order to calculate the velocity using (2). Both simulated sensors data will be used first to reconstruct an image of the phantom then the correlation function RCCF/ASDF (j) and RCCF (j) will be applied to the reconstructed image matrix. The image matrix is 64 x 64 pixels in dimension.

The phantom used in this study is a gas bubble with a radius of 8 pixel and located at position x = 20 pixel and y = 20 pixel. A study time of 76 frames were done where the bubble will slowly past through each sensor in 15 frames (Figure-4) and we consider an ideal case where in other frames there is only water detected at the sensors. The images detected at the upstream sensor are simply the replica of the ones that went through the downstream sensor but delayed in time. The correlogram of both correlation function will be normalised and then plotted in order to determine the time delay of the signals.

The simulation was done using a developed MATLAB program that were done to measure the velocity of liquid/gas flow using ECT technique. The reconstructed images are obtained by using the Linear Back Projection (LBP) algorithm where the simulated capacitance matrix reading as well as the sensors response matrix are needed (Mohamad *et al.* 2012), (Rahiman *et al.* 2013).

To gain more in term of computational time, both function were calculated in the frequency domain using the Fourier Transform. This method which was proposed by A. Rahim, (Abdul Rahim *et al.* 2012), were employed in order to use the less computation source of convolution as compared to multiplication calculation. As the function expected a complex value, the imaginary part of the signals was zero padded.

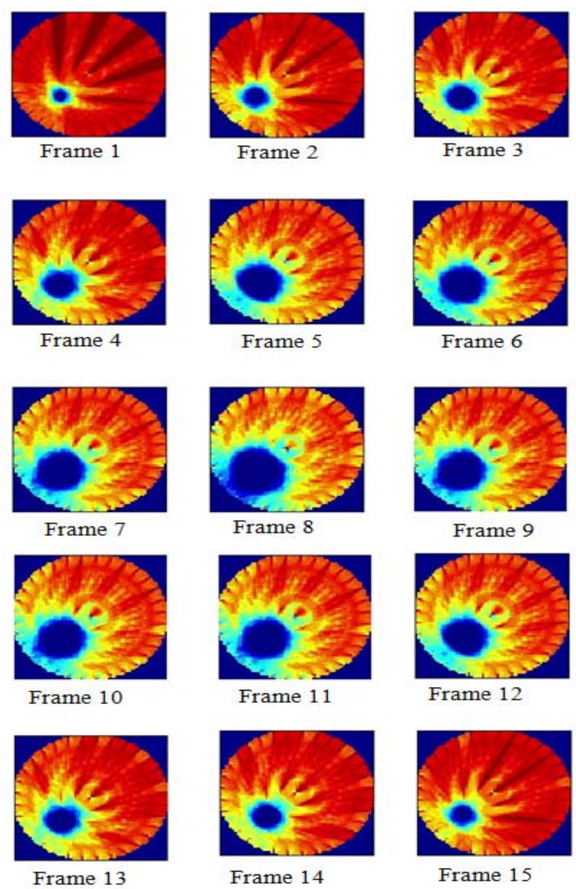

Figure-4. Reconstructed image of gas bubble phantom passing through the downstream sensor in 15 frames.

RESULTS & ANALYSIS

The simulation results of velocity measurement by identifying the time delay between signals from both sensors are presented. Figure-5 shows the conventional CCF sequence and Figure-6 shows the ASDF sequence. We can see that the maximum of the CCF and the minimum of ASDF is at τ0 = 40 thus the time delay is 4 s (the sampling time is 0.1 s). We can then derive the velocity, V, of the bubble by using (2) where V = 0.12 m / 4 s = 0.03 ms-1.

The computation time to obtain CCF sequence is averaged at 0.000457 s and for ASDF is at 0.000116 s after 5 simulations; indicating that the CCF function is computationally 4 times more expensive than the ASDF function.. The CPU used is an intel CORE i7 with a frequency of 2.6 GHz.

A Gaussian noise with a mean of 0 and variance of 0.01 was added to the image matrix in order to test the performance of each function in presence of noise. Figure-7 and Figure-8 shows the correlogram of both function after a noise function was added to the matrix. We can see that the CCF is robust to noise as the maximum peak is still distinguishable at identified at τ0 = 40 while for the ASDF function, the time delay estimation is no longer correct as the minimum peak is at τ = 0. It is proven that ASDF is more susceptible to background noise.

Figure-9 shows a comparison of the RCCF correlogram with the one from the combined method, RCCF/ASDF of the two signals from upstream and downstream sensors in the absence of noise. The green line indicate the RCCF while the blue line indicate the RCCF/ASDF function. We can see that the blue line has a sharper peak than the blue line. This corresponds well to the theoretical observation by (Chen *et al.* 2005) and (Hanus *et al.* 2014).

It is then proved that the combined method has less uncertainties because of the sharper peak of the function that can point a finer time delay thus giving a more accurate estimation. A wider peak of the conventional CCF function will give a bigger standard uncertainty.

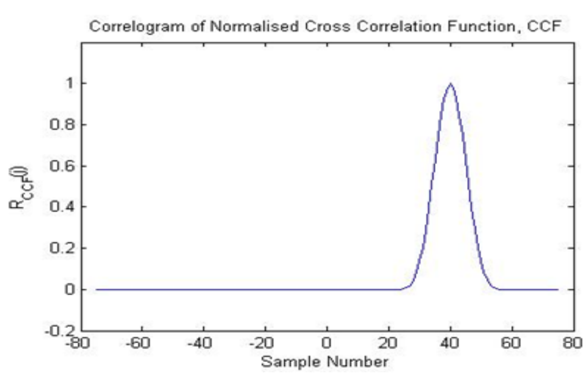

Figure-5. Representation of the normalised cross correlation function, CCF of the two sensors signals where τ_0 = 40.

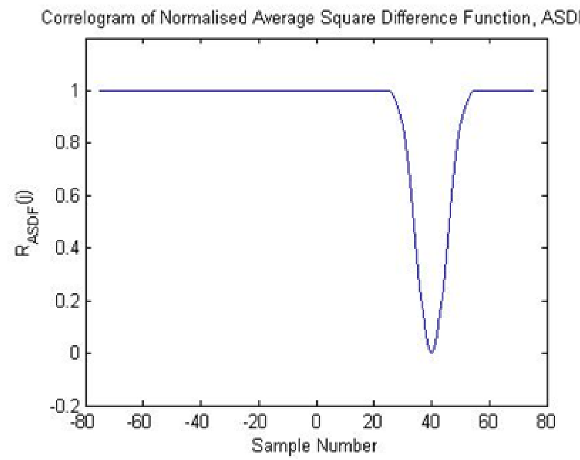

Figure-6. Representation of the normalised average square difference function, ASDF of the two sensors signals where τ_0 = 40.

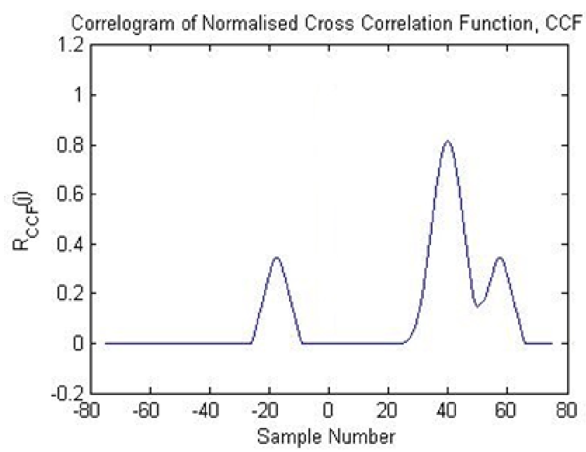

Figure-7. Representation of the normalised cross correlation function, CCF of the two sensors signals after a Gaussian noise is added.

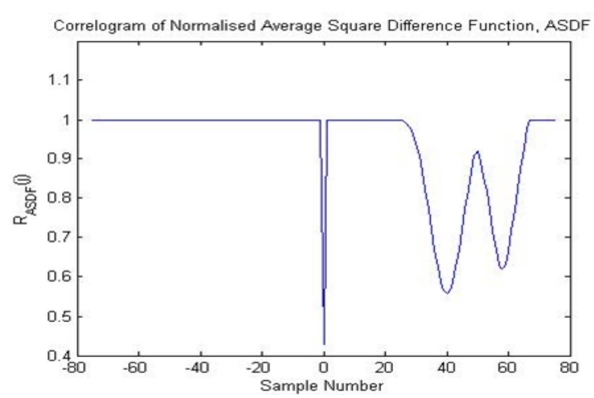

Figure-8. Representation of the normalised average square difference function, ASDF of the two sensors signals after a Gaussian noise is added.

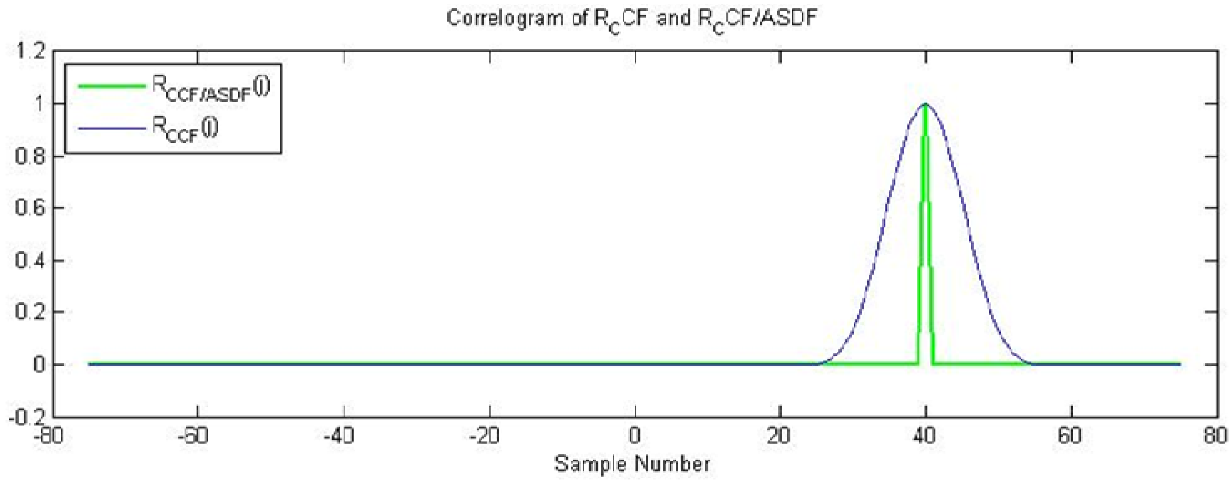

Figure-9. The correlogram of $R_{CCF}\,(j)$ (blue line) function and the combined method $R_{CCF/ASDF}\,(j)$ (green line). The combined method, $R_{CCF/ASDF}\,(j)$ has a sharper peak than $R_{CCF}\,(j)$.

CONCLUSIONS

This paper investigate the capability of using the combined correlation method CCF/ASDF as proposed by Hanus, (Hanus *et al.* 2014) in order to measure the velocity of a liquid/gas flow using an ECT system. A simulative study was done using MATLAB for the said investigation purpose. By observing the simulation result, it is proven that the combined method has a higher accuracy measurement compared to the convention CCF method as it has a sharper peak of the correlogram. The proposed time delay estimator is able to point a more precise measurement as standard uncertainties is lesser for a smaller peak interpolation fitting.

The simulative study shows that it is possible to apply the combined method in a real ECT system in order to improve the accuracy of the time delay identification. This technique is a promising method as it still conserve advantageous property of the conventional CCF which is its robustness to the noise.

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