Extended Autocorrelation Velocity Estimator Applied to Fluid Engineering

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Ultrasonic velocity profile generally uses autocorrelation method (ACM) to estimate the phase shift between emissions. The technique is preferred over the cross-correlation method (CCM) due to the high computational load, but it has problems with aliasing beyond Nyquist velocity. In this work an extended autocorrelation method (EAM) which combines both AM and CCM estimators is applied to fluid engineering. It can estimate velocities beyond the Nyquist limit and is more computationally efficient than CCM. The method is validated using the rotating cylinder experiment. For comparison all three estimators (EAM, ACM and CCM) are applied to velocities within and also beyond the Nyquist limit and all computational performance are compared.

Keywords: Ultrasonic velocity profile, autocorrelation, cross-correlation, rotating cylinder, signal processing.

1 INTRODUCTION

Ultrasonic Velocity Profile (UVP) is now a well-established tool for measuring instantaneous velocity fields in fluid dynamics and engineering applications [1]. The idea of UVP is to use the reflected echo from tracers inside the flow and use the time delay between each ultrasonic emission to estimate the velocity.

Two widely used velocity estimation methods are the autocorrelation (ACM) and the cross-correlation (CCM) [2]. The ACM uses the phase shift, also called Doppler shift, from successive ultrasonic pulses from the complex-demodulated signal. It was the first developed technique and is still used nowadays in commercial equipment due to its fast computational implementation. The phase shift is estimated by Equation (1):

$$\phi_{autocorr} = \arctan\left(\frac{\mathrm{Im}\{\widehat{R}(1)\}}{\mathrm{Re}\{\widehat{R}(1)\}}\right) \qquad (1)$$

where $\widehat{R}(1)$ represents the averaged autocorrelation function. *Im{ }* and *Re{ }* are the imaginary and real parts. The output of the inverse tangent is limited to the interval $[-\pi, \pi]$. Velocity is measured according to Equation (2)

$$v_{autocorr} = -\frac{c \cdot f_{prf}}{4\pi \cdot f_0 \cos\theta}\phi_{autocorr} \qquad (2)$$

Where c is the sound speed, f_0 is the transducer center frequency, f_{prf} is the pulse repetition frequency and θ is the angle between transducer and the flow.

To measure the phase shift a narrowband signal is desirable but it leads to a poor image resolution. The maximum velocity measurable is limited by the Nyquist limit considering f_{prf} the sampling rate. Equation 3 describes the maximum velocity:

$$v_{\max} = \frac{c \cdot f_{prf}}{4 f_0 \cos\theta} \qquad (3)$$

CCM velocity estimator uses the time shift of the received RF echoes. The original pattern from the first RF signal is correlated with the consecutive RF signal for a range of time shifts. The maximum of the cross-correlation function gives the best match and its related time shift t_s. Velocity is calculated from Equation (4)

$$v_{ccm} = \frac{c \cdot f_{prf}}{2\cos\theta}\widehat{t}_s \qquad (4)$$

where $\widehat{t}_s$ is the averaged time shift.

A wideband pulse is better suited to differ the ultrasonic pulses and improve the image resolution. The technique is not limited by the Nyquist sampling theorem but its computational cost is much higher than ACM because of the high sampling rate needed. The performance is compromised also due to the interpolation required to estimate the true location of the maximum of the cross-correlation function [2].

An extended autocorrelation method (EAM) based on the ACM and the CCM was developed by Lai, X. and Torp, H. [3] for estimation of blood velocity. It combines the advantages of measuring velocity beyond Nyquist limit and have a computational performance better than CCM.

In the present study the EAM is applied in the fluid engineering field. The classical experiment of the rotating cylinder is used to evaluate the ACM, CCM and EAM velocity estimation and also the computing performance.

2 PRINCIPLE

The idea of the EAM is to use ACM to have an initial phase estimation using Equation (5) Values beyond the interval of $[-\pi,\pi]$ may be off by an integer number n_p of 2π :

$$\phi_{true} = \phi_{autocorr} + n_p 2\pi \tag{5}$$

As CCM estimator can search over any range, a set of possible n_p values [...,-2,-1,0,1,2,...] are used instead to find the best match. The velocity is then calculated from Equation (6):

$$v_{eam} = -\frac{c \cdot f_{prf}}{4\pi \cdot f_0 \cos\theta}\phi_{true} \tag{6}$$

Compared to the traditional CCM the procedure greatly reduces the number of calculations as n_p << number of time shifts. The other advantage is the maximum velocity limit which is the same as the CCM and it is not limited to the Nyquist sampling theorem.

3 EXPERIMENTAL APPARATUS AND METHODOLOGY

3.1 Experimental Setup

The experimental setup was the classical experiment of the rotating cylinder to evaluate ultrasonic velocity profile [4]. Figure 3 illustrate the apparatus:

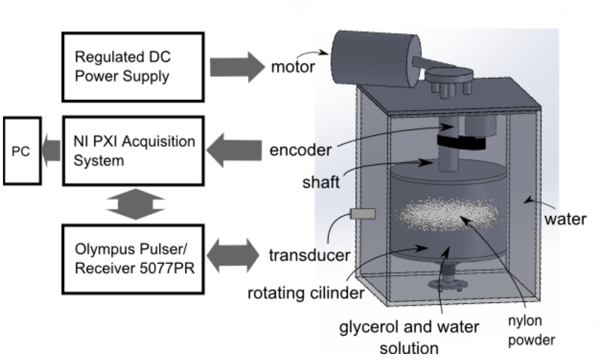

Figure 1: Block diagram of velocity measurement system build.

An acrylic rotating cylinder filled with a solution of 70% water and 30% glycerol was used to generate controlled velocities. The speed of sound of the solution was 1740 m/s. Tracer particles of 80 µm to 200 µm (EMS GRILTECH 1A P82), with 1.07 g/cm3 were added into the liquid to a concentration of 1g/L. An electric motor was used to rotate the apparatus and the rotational speed was monitored with an encoder.

Ultrasonic pulses were generated and received using an Olympus Pulser/Receiver model 5077R and a 4MHz transducer (Met-Flow). The pulse repetition frequency was set to 2000. The voltage pulse is configured to 130V at one cycle. The signal was digitized at a sample rate of 60MHz using the acquisition system NI-5105 from National Instruments. A LabVIEW program controls the system and stores the data. A computer with Intel®Core™ i7-3770 3,4GHz with 24Gb RAM, Windows 8 x64 and Matlab was used for signal processing. No parallel code was used.

The echo from the walls were removed using a stationary echo canceling filter method [2]. The spatiotemporal velocity maps was post-processed using a median filter with 3x3 matrix size.

3.2 Methodology

The rotating cylinder experiment is illustrated in Figure 2.

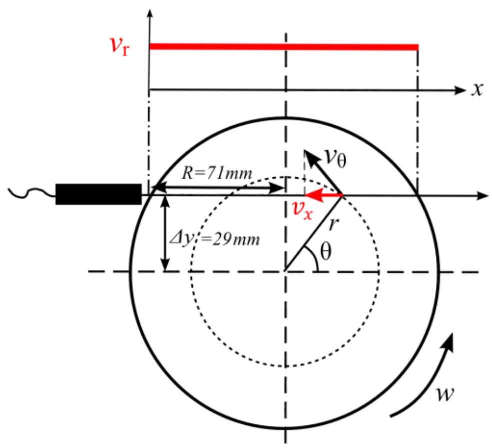

Figure 2: Velocity measured on the rotating cylinder experiment.

The velocity measured by the ultrasonic technique is in the transducer line, and is represented by v_x. Using trigonometric relations v_x is related to w by Equation (7).

$$v_x = w\Delta y \tag{7}$$

where w is the angular velocity and Δy is the distance between the transducer line of sight and the center of the cylinder, which in this work was 29 mm. For convention w is converted to revolutions per minute (RPM) using Equation (8)

$$w_{rpm} = w\frac{2\pi}{60} \tag{8}$$

Maximum velocity measured by the autocorrelation method was calculated as 71RPM using Equation (3). Based on this information four velocities were chosen: 55RPM, 65RPM, 75RPM and 85RPM.

4 RESULTS AND DISCUSSION

4.1 Velocity estimation

The mean velocity profile over the distance is described in Figure 3 to Figure 6. The mean value measured considered the interval of 20 mm and 120 mm. Before and after this interval the profile was affected by the echoes from the walls. A multiple reflection at position 75 mm had a minor influence due to the stationary echo filter applied.

The mean value velocity from the encoder is used as the reference. All three techniques showed good results for velocities below the 71 RPM as expected. Above the limit the ACM have problems with aliasing. The EAM technique successfully measures velocity beyond the Nyquist limit. Figure 7 shows the phase location in polar coordinates for both ACM and EAM at 75 RPM rotation. The values from both techniques are essentially at the same location. However, the averaged angle measured by EAM is considerably greater than the ACM due to Equation (5).

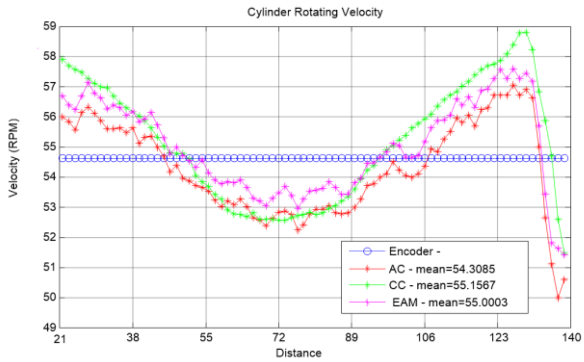

Figure 3: Velocity profile for 55RPM

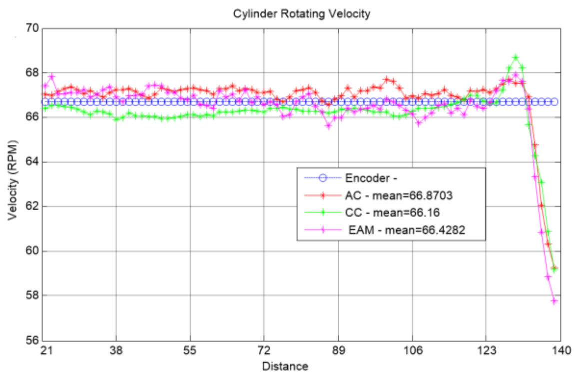

Figure 4: Velocity profile for 65RPM

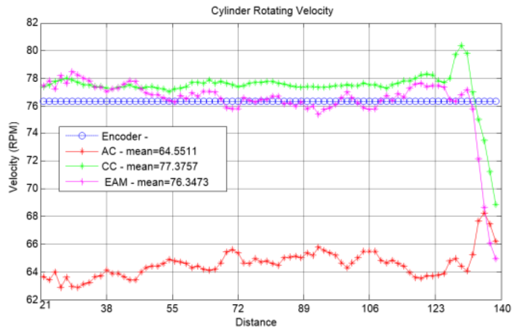

Figure 5: Velocity profile for 75RPM

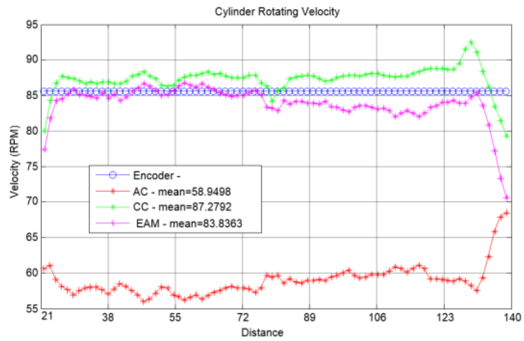

Figure 6: Velocity profile for 85RPM

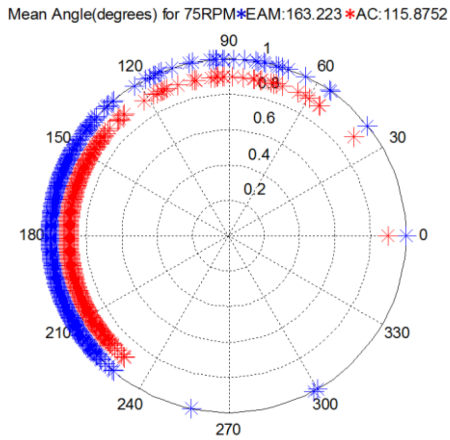

Figure 7: Phase Shift Comparison between ACM and EAM

Table 1 summarizes the mean velocity measured and Table 2 shows the relative error considering the encoder velocity as a reference.

Table 1: Summary of velocity results

Mean Cilinder Velocity(RPM)			
Encoder	AC	EAM	CC
54,63	54,31	55	55,16
66,68	66,87	66,43	66,16
77,38	64,55	76,35	77,37
85,54	58,95	87,28	83,84

Table 2: Velocity relative error

Encoder	AC error (%)	EAM error (%)	CC error (%)
54,63	0,59%	-0,68%	-0,97%
66,68	-0,28%	0,37%	0,78%
77,38	16,58%	1,33%	0,01%
85,54	31,08%	-2,03%	1,99%

4.2 Computational performance

Table 3 shows the computational performance of all three techniques in seconds. Autocorrelation method has the best results and is by far the fastest velocity estimator. The CCM estimator is the slowest technique due to the high number of operations required to calculate the cross-correlation. As EAM combines both ACM and CCM, the result is an intermediary performance, not fast as ACM and not slow as CCM.

Table 3: Velocity estimator performance

Processing Time (seconds)			
Velocity(rpm)	AC	EAM	CC
55	0,12	6,69	97
65	0,11	6,46	94,9
75	0,11	6,2	94,8
85	0,12	6,09	94

5 CONCLUSION

The Extended Autocorrelation Method for velocity estimation was succesfully applied for fluid engineering. The technique combines the ACM phase shift measurement and the CCM method for velocity beyond Nyquist limit. Results shows good agreement between the technique and the velocity measured by an encoder at the rotating cylinder experiment. Velocities beyond Nyquist were measured as the CCM does but with a lower computational cost.

6 ACKNOWLEDGMENT

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