Implementation of a Staggered Trigger Algorithm by Velocity Difference Dealiasing Rules: Experimental Results

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The staggered trigger technique consists of alternating between a long and a short Pulse Repetition Time (PRT) to mitigate the range-velocity ambiguity. Two different flow velocities are estimated due to the two PRT. The difference of these two velocities is used to estimate in which Nyquist interval is the real flow velocity. This method was originally proposed for Doppler weather radar where velocity folding factors are restricted to 2 times the conventional maximum velocity of the short PRT. In this work the staggered trigger method using the velocity difference for dealiasing purpose is applied to a rotating cylinder flow. Experimental results show that the method can be applied to fluid engineering. Results also shown that this method achieves a finer temporal resolution relatively to other methods proposed, which makes it suitable to be applied in flows with fast velocity transitions. The performance of the technique was also evaluated on two different reception gain settings.

Keywords: staggered trigger, dealiasing, velocity aliasing, ultrasound velocity profiling.

1. Introduction

Ultrasonic Doppler velocity profiler (UVP) is a technique that estimates the velocity along the measurement line by using periodic short bursts of ultrasound. However, this methodology has its limitations regarding the maximum range that could be measured. Increasing the period between emissions can overcome the measurement range but with a proportional reduction in the maximum velocity measured. If flow velocity is higher than the maximum measurable velocity, then velocity aliasing occurs [1]. Dealiasing techniques may be used to solve this issue. The use of two transducers with dissimilar frequencies can be used to measure velocity unambiguously. Such method, was proposed by [2-4]. This technique combines the information of the velocity from each transducer in such a way that the whole system can be viewed as one, which frequency is the difference between the two transducers frequencies. There are velocity estimation algorithms that can avoid aliasing. In the velocity-matched spectrum analysis, a velocity spectrum is obtained by analyzing the shift in each pulse emission through iso-velocity lines [5]. Still, to further extend the maximum velocity this technique uses much more computer power compared to the conventional phase-shift estimator (PSE). If a high SNR condition is guaranteed, time-shift estimators such as cross-correlation (CC) [6] can be used. However, CC algorithms are more time consuming than the conventional PSE. Extended autocorrelation technique [7] combines PSE with CC estimation. The combination can reduce significantly the amount of computation. However, the processing time of this approach is still very high (approximately 55 times slower) than the PSE [8,9]. Staggered trigger (ST) or staggered PRT (Pulse Repetition Time) is characterized by using a non-uniform pulse repetition time. ST alternates the pulse emission with a short-time and a long-time period. Compared to multi-frequency, ST only needs one transducer and the computation power is comparable with the PSE. It was first introduced for blood flow measurement by Nishiyama e Katakura [10]. Later, it was extended for weather radar field [11-12]. Recently, Murakawa et al [13] adapted it to fluid engineering, implementing a higher flowrate measurement system. They reported that the velocity error of the practical system was too high to measure velocity directly. Thus, they used the ST velocity only to discover aliasing factor. However, this strategy still was not enough to deliver an accurate flow rate. Therefore, they have used a moving average filter and relaxed the velocity time resolution. The measurement configuration used a high number of pulse (N_{pulse}=512) for every velocity estimate, and velocity profile was obtained through averaging 1,000 instantaneous velocity profiles. They reported an error of -0.8% (N_{cycle}=8 at flowrate of 500 m^3/h) and maximum measured velocity of 6 times larger than the conventional UVP method [13]. Torres and Dubel [14] proposed a new algorithm for ST that uses the velocity difference from the velocities estimated by the long and short PRT to decide the velocity dealiasing factor. Their work was focused in weather radar and they showed that their method could measure velocity up to 3 times greater than the maximum conventional velocity regarding the long PRT. In a previous work [15], we adapted the methodology of [14] for fluid engineering. It was showed, by simulation, that the method proposed can reach even higher velocities than described in [14]. Simulation results of [15] also show that the technique can perform well with a short time resolution (N_{pulse}=50). In this work, the technique developed in [15] is applied in real flow: a rotating cylinder flow. A measurement system was developed to implement the ST

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method. Results shows that the system can measure velocity up to 2 times higher than the conventional velocity regarding short PRT. Spatial velocity profiles estimated are obtained with a finer temporal resolution. Results are also tested under two different reception gain settings. The main purpose of this research is to develop a technique that: is computational comparable to the conventional PSE; can achieve temporal and spatial velocity resolution that is similar to the PSE; and can measure the same range of velocities of PSE but using a much longer PRT. A measurement system with similar performance of the conventional but using a longer PRT will imply in much less data to process resulting in a simpler acquisition hardware thus reducing the overall system cost. Another benefit is to achieve longer measurements range.

2. Staggered trigger by velocity difference method

2.1 Foundation of staggered trigger method

In ST, an ultrasonic pulsed wave is emitted in alternating time intervals, T_1 and T_2, with $T_2 > T_1$. Velocity estimation is evaluated by the lag one autocorrelation algorithm [7] using only adjacent pulses whose time interval is equal. The velocity relative to T_1, v_1, and the velocity relative to T_2, v_2, can be estimated using the following relations

$$v_1 = \frac{c}{4\pi f T_1} \arg\big(R(T_1)\big), \tag{1}$$

$$v_2 = \frac{c}{4\pi f T_2} \arg\big(R(T_2)\big), \tag{2}$$

respectively, where c denotes the sound velocity in the considered medium, f represents the transducer central frequency, arg is the principal argument restricted to the range (-π,π] and $R(\cdot)$ is the autocorrelation function. The maximum measured velocity is determined by the range of the principal argument as

$$v_{a1} = \frac{c}{4fT_1}, \tag{3}$$

$$v_{a2} = \frac{c}{4fT_2}. \tag{4}$$

Conventional ST method combines each lag one autocorrelation to result in a dealiased velocity estimated by

$$v_{st} = \frac{c}{4\pi f(T_2 - T_1)}\Big(\arg\big(R(T_1)\big) - \arg\big(R(T_2)\big)\Big). \tag{5}$$

And the staggered trigger maximum velocity will be

$$v_{max,st} = \frac{c}{4f(T_2 - T_1)}, \tag{6}$$

which will be higher than Eqs. (3) and (4) if $T_2 - T_1$ were small relatively to T_1 or T_2. However, velocity estimated using Eq. (5) will have a high uncertainty for some velocity intervals [15]. Therefore, to measure velocity above Nyquist limit, Eqs. (1) and (2) should be combined to discover the velocity aliasing factor.

2.2 Velocity difference by dealiasing rules

The $v_1 - v_2$ velocity difference can be used to determine the aliasing factor of v_1 or v_2 if the ratio $T_1/T_2 = m/n$, follow the condition that m and n should be relatively prime integers [14]. Applying this ratio, the maximum unambiguous velocity that can be measure are $v_{ua1} = mv_{a1}$ and $v_{ua2} = nv_{a2}$, for v_1 and v_2, respectively. The velocity difference rule can be demonstrated graphically. The velocity aliasing incurs that v_1 or v_2 cannot be higher than $\pm v_{a1}$ or $\pm v_{a2}$, respectively. By plotting the real velocity versus $v_1 - v_2$ the graph of Fig. 1 is obtained, for $m/n = 3/4$. Note in Fig.1, that, when v_1 is aliased, or $v_{a1} < v_1 < 3v_{a1}$, the velocity difference assumes two unique constant values ($-0.5v_{a1}$ and $+v_{a1}$). A similar behavior happens to negative aliasing in v_1, or the condition that $-3v_{a1} < v_1 < -v_{a1}$, in this case $v_1 - v_2$ assumes $+0.5v_{a1}$ and $-v_{a1}$. In the case of aliasing in v_2, one can notice (Fig.1) that for the first aliasing, i.e. when $v_{a2} < v_2 < 3v_{a2}$ (or $-3v_{a2} < v_2 < -v_{a2}$ for negative aliasing) the velocity difference assumes $2v_{a2}$ and $-0.5v_{a1}$ (or $-2v_{a2}$ and $+0.5v_{a1}$ for negative aliasing). When v_2 aliases for the second time, i.e. when $v_2 > 3v_{a2}$ (or $v_2 < -3v_{a2}$ for negative aliasing) then $v_1 - v_2$ equals to v_{a1} (or $-v_{a1}$ for negative aliasing). Therefore, $v_1 - v_2$ maps the aliasing factor in v_1 or v_2. In [14] it is shown that this function bijection occurs for any m/n, if m and n are relatively prime integers.

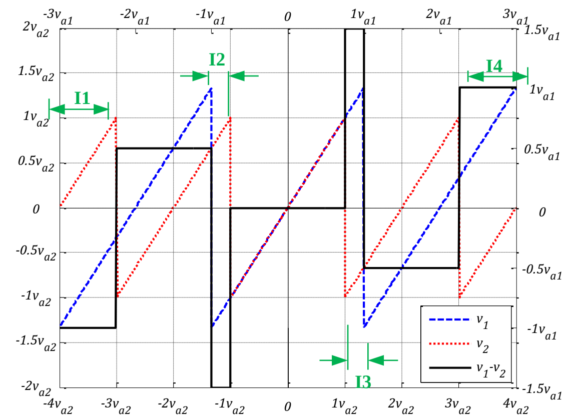

Figure 1: Velocity difference ($v_1 - v_2$) and aliased velocities v_1 and v_2 as a function of the real Doppler velocity. Time interval ratio used was $T_1/T_2 = m/n = 3/4$.

3. Experimental procedure

To evaluate the technique, a rotating cylinder flow experiment was set-up. A plexiglass cylinder was submerged in a water tank (Fig.2). The inner cylinder radius is 70 mm. Ultrasound transducer was positioned at *Δr=20 mm* from central axis (Fig.3). With this arrangement, Doppler velocity measured by the transducer will have a uniform velocity profile (Fig.3) [1].

Rotation is established through a motor/encoder from Maxon® EPOS2 24/5. Angular speed of the motor can be configured by a software, EPOS2® Studio (Maxon®), from a computer (PC). Ultrasound control and data acquisition is performed by a PXI system from National Instruments®, model NI5752R. The PXI system is programed using Labview® software running in a PC. An Olympus® pulser/receiver, model 5077PR, is used for excitation and reception of ultrasound pulses from a 4 MHz transducer (Met-flow).

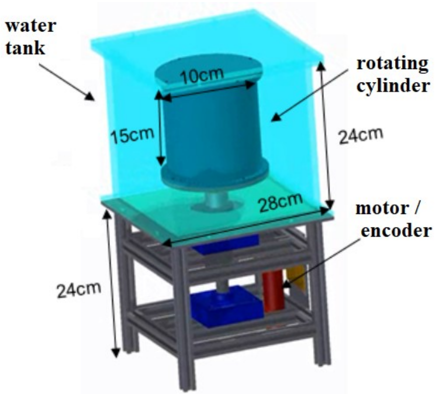

Figure 2: Rotating cylinder flow apparatus [16].

The pulser/receiver frequency was set to 1000 Hz (pulse repetition frequency). Pulse voltage used was 100 V. This pulser is limited to a 1-cycle pulse duration. Analog gain of 49 dB and 39 dB were used to amplify the echoes.

Sampling frequency of 50 MHz was set at the PXI system. A total of 2000 pulses or 2 seconds of data were recorded for each cylinder velocity tested. Cylinder rotations of 10 to 50 RPM in steps of 5 RPM were tested. A 0.5 g of nylon particles of 80 µm to 200 µm (EMS GRILTECH 1A P82), with 1.07 g/cm3 were added into the cylinder. Cylinder was filled with a density matching solution of water and glycerol. Sound velocity of the solution was characterized by having the value of 1680 m/s.

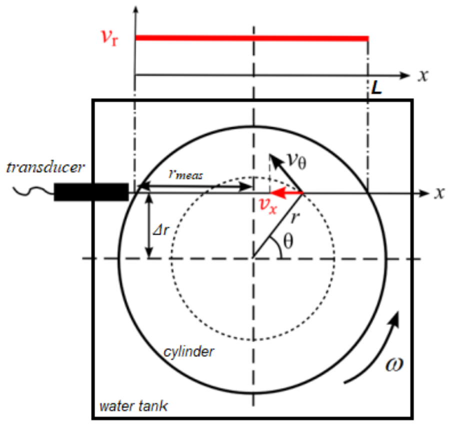

Figure 3: Top view of cylinder, transducer position and expected velocity profile. Adapted from [9].

3.1 Signal Processing

Each pulse was acquired with a fixed base frequency of 1 kHz resulting in a $T_{Base} = 1\ ms$ To achieve a PRT ratio of $T_1/T_2 = 2/3$, it was adopted the following method: $T_1 = 2T_{Base}$ and $T_2 = 3T_{Base}$. So, with all the 2000 RF pulses sampled (or 2 seconds of data), to transform this uniform sampled data to a non-uniform set, the system takes the first pulse, ignores the second pulse, takes the third pulse, ignores the fourth and fifth pulse and takes the sixth pulse repeating this procedure for all pulses.

Clutter filtering of a ST data cannot be done by a standard algorithm for uniform sampled data. Therefore, stationary echoes from cylinder boundaries were filtered using a polynomial regression filter technique described in [16]. The length of the polynomial regression filter used was $M_f = 30$. A second order polynomial was chosen.

Velocities data regarding each PRT (v_1 and v_2) were calculated every 50 emissions ($N_{pulse} = 50$). Dealiasing rules were applied to velocities estimated resulting in the dealiased velocities (v_{1d} and v_{2d}). By averaging each dealiased velocity the final flow dealiased velocity was obtained. The spatiotemporal velocity maps were post-processed using a median filter with 2x2 matrix size.

4. Results

To evaluate the performance of the ST, the mean value of the spatial velocity profile was calculated for PRT ratio $T_1/T_2 = 2/3$. In this case the maximum velocities are $v_{a1} = 52.5\ mm/s$ or 25.06 RPM and $v_{a2} = 35\ mm/s$ or 16.71 RPM. The mean value was computed for cylinder velocities from 10 RPM up to 50 RPM or from $0.3989v_{a1}$ up to $1.995v_{a1}$ (maximum velocity for 2/3 ratio is $2v_{a1}$ or $3v_{a2}$). Analog gain of the pulser was set to 49 dB and 39 dB. The technique provides a mean velocity value with error below ±5% for almost the entire range (Fig.5). Cylinder velocity of $1.995v_{a1}$ was the only value that the technique fails to measure. This behavior may be occurred because it is a velocity that is too close of the technique limit. Fig.5 also shows that the technique performance was similar considering the SNR reduction of 10 dB (39 dB).

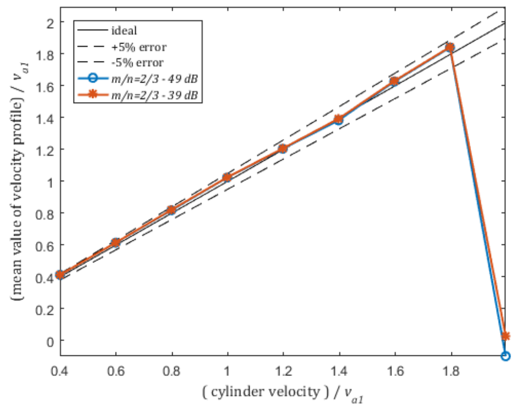

Figure 5: Accuracy assessment of ST for 2/3 ratio.

Accuracy performance of the ST was also assessed for the PRT ratio of $T_1/T_2 = 3/4$. In this condition the maximum velocities are $v_{a1} = 35\ mm/s$ or 16.71 RPM. The mean value was computed for cylinder velocities from 10 RPM up to 50 RPM or from $0.598v_{a1}$ up to $2.992v_{a1}$ (maximum velocity for 3/4 ratio is $3v_{a1}$ or $4v_{a2}$). Analog gain of the pulser was set to 49 dB and 39 dB. Results of Fig.6 indicate that, in this case, the technique fails before the theoretical maximum. At cylinder velocity of $2.693v_{a1}$ the error is far beyond the 5% error line. The condition is the same for 49 dB or 39 dB, possible showing that the limitation is not on SNR.

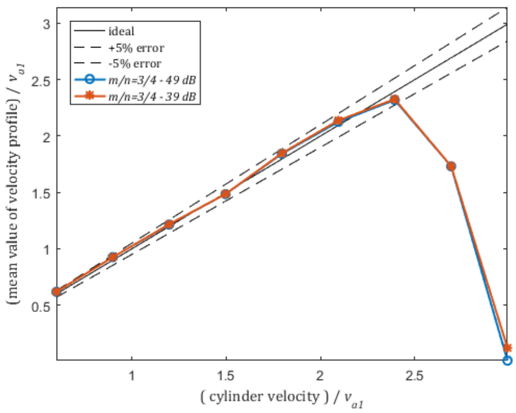

Figure 6: Accuracy assessment of ST for 3/4 ratio.

Spatial profile reproducibility is assessed in Fig. 7. It can be noticed that when velocity approaches 2 times Nyquist standard deviation (error bars) increases. Also, the polynomial regression filter fails to filter some stationary echoes from cylinder walls (x/L≈0.05 and x/L≈0.95).

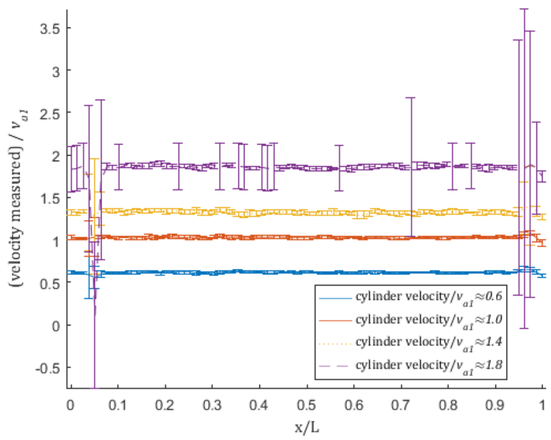

Figure 7: Spatial velocity profiles with errorbar (49 dB, 2/3 ratio).

A velocity temporal series for $x=0.08L$ was obtained to evaluate the time accuracy of the technique. The average error relative (AER) to cylinder velocity (CV) and standard deviation normalized by v_{a1} (STD) is shown in Tab. 1.

Table 1: Temporal series accuracy results (49 dB , N_{pulse}=50).

CV/v_{a1}	0.6	0.8	1.0	1.2	1.4	1.6	1.8
AER (%)	2.4	2.6	3.0	-0.9	-3.7	1.9	3.2
STD	0.08	0.09	0.06	0.03	0.06	0.14	0.06

5. Summary

A Doppler measurement system and signal processing algorithms for ST were developed and tested in a real flow situation. Results shows that the system can measure velocities beyond Nyquist limit with accuracy of less than 5% for $T_1/T_2 = 2/3$. Also, the system can measure velocity with a reduced value of pulses ($N_{pulse} = 50$) or with a finer temporal resolution, thus enabling the system to be used for fast transient flow analysis. Increasing the ST ratio to $T_1/T_2 = 3/4$ showed that the accuracy of the mean velocity value degrades as it surpasses two times the maximum conventional velocity. Therefore, for the experimental conditions tested, the ratio of 2/3 would be the best choice for application of the technique proposed because it will result in accurate velocity profiles. In the previous work of [15] higher PRT ratios were feasible to use with good accuracy. We think that it might be related to the size of the measurement volume. In [15], the ultrasound was excited by a 4-cycle pulse that is four times larger than the excitation used in this work. In a future work, we intend to test the system in pipe flows. Also, we intend to investigate if exists a tradeoff between the number of cycles emitted and the PRT ratio concerning the accuracy of velocity profiles.

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