Laser Pulse Separation Measurements for Spectral Flow Analysis using Particle Image Velocimetry

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A feedback methodology is developed for the correction of timing errors in double pulse laser systems operating at high repetition frequencies. With continuing developments in non-intrusive measurement techniques, such as particle image velocimetry, there is an ever-increasing demand for simultaneous high spatial and temporal resolution, which can make them well suited to the spectral characterization of fluid flows. This application places significant importance on the accuracy and repeatability of the timing between successive laser pulses of high-speed, double-pulsed laser systems, as any timing errors propagate directly into the computed velocity vectors and indirectly into all other derived quantities, including the spectral analysis of the flow. The present work proposes a feedback methodology to measure and correct for such errors in a time-resolved manner. Lastly, the proposed methodology is demonstrated on a test case of a cylinder wake, and the results are compared to corresponding hot-wire measurements.

Keywords: *timing error, particle image velocimetry (PIV), double-pulsed laser, power spectra, hot wire anemometry.*

1. INTRODUCTION

Traditionally, spectral characterization of fluid flows has been limited to experiments with high temporal and low spatial resolution, usually conducted by hot-wire (HWA) or laser-doppler (LDV) anemometry. Emerging from the 1990s, nowadays prevailing particle image velocimetry (PIV) techniques have traditionally enabled comparatively high spatial but limited temporal resolution measurements. In parallel with continuous advancement in both laser and imaging technologies, however, PIV has advanced during the last two decades to sufficiently resolve both spatial and temporal scales.

Most of the early forays into PIV spectral measurements relied on their direct comparisons with equivalent measurements by traditional 'point' spectral techniques. Foucaut et al. [1] studied turbulent flows using the temporal and spatial resolutions allowed with high-speed PIV. They examined the spectral content of a planar based PIV interrogation domain to characterize the spectral capabilities and understand the noise floor of motionless particles. They were able to demonstrate that careful adjustments to remove noise in the PIV analysis can result in good agreement with HWA measurements. Tanahashi, et al. [2] were able to further extend the study of turbulence to dual-plane stereoscopic PIV. These measurements were able to capture similar velocity fluctuations in both stereoscopic interrogation planes, as well as showing good agreement to HWA measurements in the center of these domains. Their laser and optics system allowed for resolution up to 26.7 kHz, which allowed the PIV to capture the coherent and fine scale eddies within the turbulent flow. Koschatzky, et. al. [3] demonstrated the ability to reconstruct pressure fields and extract acoustic frequency information for flow over a cavity using high-speed PIV. They were able to capture similar spectral information using a PIV acquisition rate of 3 kHz and a microphone array sampled at 100 kHz, and further concluded that PIV could be used successfully to capture acoustic information from their flow fields, while still allowing the ability to examine the flow structures responsible for such tonal information.

Along with improvements in the PIV acquisition and processing routines, numerous sources of possible errors due to inherent complexity of both the acquisition and processing schemes, are recognized, such as the calibration, optics, timing, and other sources of random error to name a few [4]. Therefore, there are a number of studies that address such errors by proposing modifications and variants of the PIV algorithms and suggestions on how to improve accuracy of the extracted flow fields [4,5,6].

A critical component of any high-speed PIV system is a Q-switched, high-speed, double-pulsed laser, where the two laser pulses can be individually generated within two separate laser cavities or in a single cavity. It is known that the complex nature of Q-switched lasers can lead to errors in the timing and uncertainty as factors such as the power, frequency, and triggering rates can affect them [7]. Bardet, Philippe, and Andre [7] further stated that lasers used in double pulse operation can have timing errors of up to 0.5 μs for dual cavity lasers and up to 1 μs for single cavity lasers operating in a dual-pulsed mode. Commercial PIV software relies on the correct pairing of the hardware

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and electronics but there is typically no feedback that ensures the assigned timing between the laser pulses is indeed executed as assigned. Knowing that high-speed flows often require a pulse separation of just several microseconds, an error of 0.5 – 1 μs can potentially lead to tens of percent error in the measured flow velocities. Atop of the static offset between the assigned and executed pulse separation, it is possible that some level of 'jitter' is present during high repetition rates of the pulse pairs that would deviate further from the constant offset; instead, the pulse separation would vary with time, introducing an unknown error in each instantaneous velocity field. Therefore, not only the velocity component magnitudes, but also their spectral energy distributions would be affected. This is especially evident for single cavity lasers operating in double-pulse modes, as a single Q-switch controls both laser pulses in a short time frame. The objective of the present work is to provide a feedback methodology and correction for the actual executed double-pulse separation in temporal measurements of the flow velocity fields with high pulse repetition rates.

2. EXPERIMENTAL SETUP AND PROCEDURES

In order to test the proposed feedback methodology (in both velocity magnitude and spectral content) a canonical case of a shedding cylinder wake is selected, and the PIV measurements are compared to traditional hot-wire measurements, having particular emphasis on the spectral content of the measured in-plane velocity magnitude fluctuations.

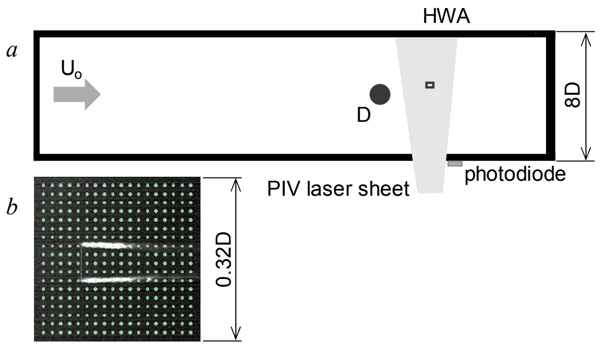

Figure 1. Experimental setup (a) and the zoomed-in PIV measurement plane with overlaid hot wire sensor (b).

Experiments are conducted in a small, open-return, subsonic blow down wind tunnel, where the temperature of the return air is controlled via a low pressure drop heat exchanger. The wind tunnel, and test section, terminate in a free jet discharge. The test geometry consists of a rectangular section of WxH = 2HxH cross section where H = 76.2 mm, and length of 8.43H (Figure 1). A cylinder (D = 0.125H) is placed in the center of the test section and spans the entire width (2H). The flow region of interest is selected to include the wake shear layer approximately four diameters downstream from the cylinder. The PIV field of view is marked by a small rectangle (0.32D on both sides) in Figure 1a. In a companion set of measurements, a miniature hotwire probe is placed in the wake of the cylinder such that the hot wire sensor is placed in the centre of the PIV field of view, which is shown with the hot wire prongs in the view, in Figure 1b. It should be noted that this PIV field of view results in a vector field of approximately 20 x 20 grid locations after the PIV processing, which is equivalent to about five PIV grid points across the HW sensor length.

2.1 Laser Timing

An Nd:YLF single cavity laser is used for the illumination of the particle-seeded flow. The laser pulses are detected by a Thorlabs DET10A-Si Detector photodiode, which is positioned at the edge of the laser sheet, outside of the tunnel (cf. Figure 1a). The photodiode allows for characterization of the laser pulses and outputs a voltage signal relative to the power of the emitted laser light. As the single cavity laser operates at high repetition rates, there can be a non-uniform separation of the double pulses (i.e. the measured Δt between laser pulses).

A sample of such a distribution of laser pulse separations is shown in Figure 2. These measured pulse separations are shown for an assigned $(\Delta t)_a$ = 1.6 μs and a laser repetition frequency of 5 kHz. Clearly, not only are the pulses offset from the assigned value, but they vary throughout the acquisition sequence. However, within this sample, the timings seem to based around a nominal mean, and offset, value that is higher than the assigned pulse separation. This collected time sequence does not demonstrate any significant drifting or hysteresis of the measured pulse separation timing, although this behavior could theoretically be present in other acquisition sequences or possibly over longer durations.

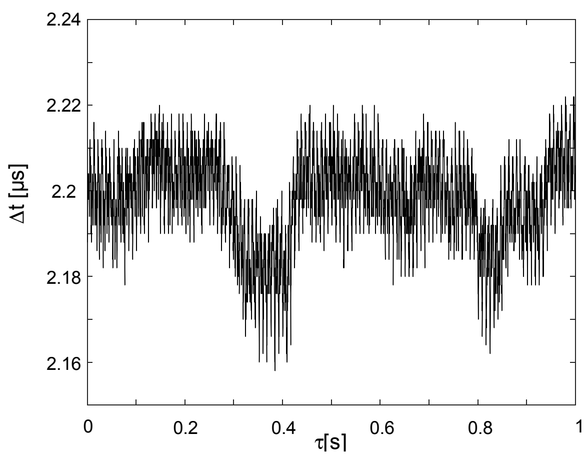

Figure 2. Time sequence of the realized laser pulse separation Δt for an assigned $(\Delta t)_a$ = 1.6 μs.

After verification of errors in the executed vs. assigned pulse separation times, these errors are quantified. Figure 3 shows the mean measured/executed Δt for varying assigned timing values $(\Delta t)_a$ and their associated error. There is a nearly linear increase in the measured timing between pulses when increasing the assigned values. However, there is not always a constant offset between the two. This can be seen in the error distribution, which decreases in a non-linear fashion with increased values of $(\Delta t)_a$. Clearly the highest error values occur at the shortest $(\Delta t)_a$ and decreases as $(\Delta t)_a$ is increased, although the overall error value does not seem to be approaching zero, but rather approximately 5%. This is most likely caused by the laser's inability to charge and discharge accurately and consistently at high repetition rates, especially when the single cavity laser must also use the same laser charge to form the two individual pulses. These findings clearly identify a need to independently verify the pulse separations, in particular when a small Δt is needed to accurately capture the seed-particle motion in PIV measurements. To increase the accuracy of temporally resolved PIV measurements, the instantaneous vector fields should be corrected for their actual particle travel time (i.e. the true Δt between laser pulses) rather than what is automatically incorporated into the data processing routines - the assigned $(\Delta t)_a$.

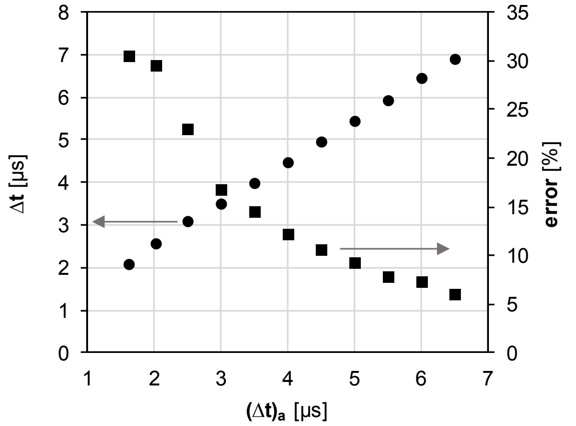

Figure 3. Mean realized laser pulse separation Δt (●) with the assigned $(\Delta t)_a$ and the corresponding error (■).

2.2 Laser Timing Circuit

Due to the above-stated errors, individual PIV laser pulses need to be measured and recorded with consideration of the timing scales in order to correct the instantaneous vector field results. One major challenge with correcting the timing is the scale of the pulse separation ($O[\mu s]$) and the scale of the pulse widths that need to be measured ($O[ns]$). These need to be measured with high enough resolution to resolve any deviation of the pulse separation, as well as correctly identifying the defining features of the pulses for the timing. Furthermore, when recording timing on this scale and resolution, the significant downtime between the double pulse repetition rate would render analog recording of the pulses excessive and contain predominantly irrelevant data over a full PIV acquisition sequence.

A custom timing circuit is developed to fulfil these data acquisition requirements without overloading the process with unnecessary data. A methodology is developed that includes converting the analog photodiode signal into digital pulses that coincide with the defining features (i.e. peaks) of the pulses which can then be sampled with a much higher repetition rate than an analog signal. This feedback methodology consists of three components. A photodiode is placed at the edge of the laser sheet to sample the train of laser pulses. These pulses are processed in real time by a custom circuit, which outputs a digital TTL signal that is used to measure the individual Δ*t* for each image pair. The digital output is necessary to prevent the computer RAM from filling and ensuing output file size from becoming unreasonably large while recording the individual pulses in high resolution and having significant down time between the pulse repetitions during a recording sequence. The TTL output is passed to a Saleae Logic Pro 8 high sample rate datalogger with resolution to capture extremely fine (*~2 ns)* timing intervals. The datalogger captures the timing of the rise and fall of the TTL pulses from an individual recording sequence. The ensuing digital timing sequence can be processed to result in a measured Δ*t* for each individual image pair in the PIV recording sequence. This Δ*t* sequence can then be used to correct each corresponding vector field result within the recorded image set.

The timing circuit consists of four main stages: the circuit isolator, amplifier, multivibrator, and delay stages. The circuit isolator stage is used to prevent the pulse creation circuit from propagating into the upstream electronic components (i.e. the sensitive photodiode) and contaminating the original signal. The amplifier stage after the isolator increases the gain of the raw signal to make sure the amplitude can trigger the multivibrator stage. This is essential in this experiment due to the lower power of the second pulse of the single cavity laser during dual pulse operation. After the amplifier, the signal reaches the multivibrator. This stage creates short TTL pulses based on the slope change at the peak of the raw laser pulses (i.e. when the pulse peaks have zero slope or an inflection point). The last stage is a delay for the location of the second TTL pulse. The second pulse peak in a single cavity laser can have a less prominent peak as compared to the first pulse, and as such can falsely trigger the location of the second TTL pulse in the multivibrator stage. Therefore, the delay stage allows for tuning of the location of the second TTL pulse (i.e. triggering location) to coincide properly with the pulse peak.

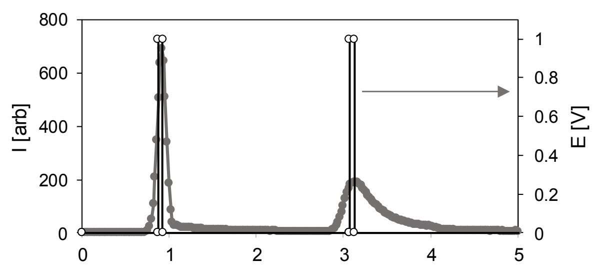

Figure 4. Light intensity of the laser double-pulse captured by the photodiode and the corresponding output of the circuitry described in section 2.2.

The operation of the laser timing circuit results in the ability to use digital sampling logic from TTL pulses to time the separation of the analog pulse shape. An example of such a measurement is shown in Figure 4. The analog measurement from the photodiode and the datalogger of a single double pulse from the laser is overlaid with the ensuing converted TTL signal of the laser pulse peak locations. The two TTL pulses clearly coincide with the peaks of the two individual laser pulses. This figure also shows the importance of being able to adjust the triggering of the second pulse detector. Since the second pulse may be lengthened due to the nature of the laser operation, the peak can be weakly defined. As such, the multivibrator stage may have an early (or late) detection of the slope change and may require some slight adjustment.

Once the adjustments are made for a given laser system, however, the TTL coincides correctly with the pulse peak. Indeed, it was observed that the shape of the second pulse did not change throughout the acquisition sequences, but only experienced a movement in the timing as it moved closer or farther from the first pulse.

The digital measurement of the TTL pulses results in the timing for the rise and fall of each pulse. The correlation of the up (or down) time for each pulse can then be converted into a measurement of the pulse Δt.

During a sequence of pulses, the corresponding digital timing recording can be used to create an instantaneous Δt correction for every image pair in a PIV recording sequence. This is due to the basis for determining a PIV field. Since the timing is assumed to be equal to the assigned $(\Delta t)_a$, the PIV processing scheme calculates the relative movement of particles between two successive frames that are illuminated by the laser pulses. Consequently, velocity $\boldsymbol{u}$ would be determined as the following:

$$u = \frac{dx}{dt} = \frac{\Delta x}{(\Delta t)_a} \tag{1}$$

For a given movement (Δx) and the measured timing Δt a simple correction is made for calculation of the corrected velocity $\boldsymbol{u}_c$

$$u_c = \frac{dx}{dt} = \frac{\Delta x}{\Delta t} \times \frac{\Delta t}{(\Delta t)_a} \tag{2}$$

3. RESULTS

In order to determine the effectiveness of the proposed laser pulse timing correction, the high frequency PIV data was compared to that taken from a hotwire anemometer in the wake of the cylinder placed in the wind tunnel, as described in Section 2. To check the spectral energy distribution in the fluctuating flow field of the wake behind a cylinder, both the PIV and the hot-wire measurements were conducted at the same sampling rate of 5 kHz and for the same duration of one second, ensuring the same frequency resolution for both measurements. Furthermore, as the HWA measures the in-plane velocity component, PIV data are processed such to generate the same quantity.

Lastly, the time-resolved flow fields (PIV) and the 'point' measurements (HWA) are segmented in ten subsets. Power spectrum of the velocity magnitude fluctuations is calculated for each subset, and the final spectrum is obtained by the averaging of individual spectra, for suppression of random noise. Figure 5 shows the final power spectra for a representative flow condition over the cylinder (Re ~ 17500), with the spectra for the uncorrected and corrected PIV, and the HWA. It is clear that each of these three methods capture the same shedding frequency of the cylinder wake.However, it is also shown that there is a large difference in energy distribution between the power spectra of the corrected and uncorrected PIV fields, when compared with the HWA spectrum. As already discussed, inaccuracy in the laser timing is affecting the magnitudes of the measured instantaneous velocities in the uncorrected PIV fields. As such, when the uncorrected velocity fields are analysed, their spectral energy significantly overestimates the HWA-based levels, across all the scales. Contrary to this case, once the proposed timing correction is applied, the corrected PIV power spectra aligns much closer to the HWA spectra, although still somewhat overestimating the HWA spectral distribution. It is argued that there might be additional secondary causes for this residual discrepancy, possibly related to either PIV or the HWA measurements.

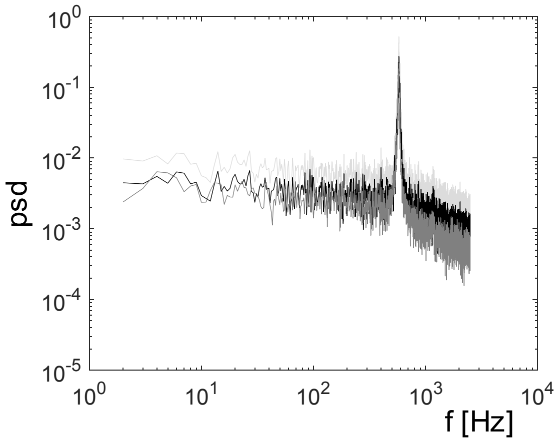

Figure 5. Power spectra of the velocity fluctuations measured by the HWA (dark grey) and the uncorrected (light grey) and corrected (black) PIV measurements.

Additional comparison between the corrected PIV measurements and the HWA is shown in Figure 6, where the measured Strouhal number of the wake vortices is plotted for both measurement techniques, while the Reynolds number is varied. Besides the Strouhal number distribution, three representative power spectra, determined by each measurement technique, are included for comparison in inset plots. As the Reynolds number increases, there is a decrease in the Strouhal number, which approaches a value of 0.2 within the measurement range.

Such a distribution of the Strouhal number with the increase in Reynolds number, within the current testing range, can be compared to the results by West and Apelt in 1982 [8], who also considered different levels of cross-section blockage by a cylinder. When the current Reynolds number range ($5000 < Re_D < 17500$) and the cylinder blockage (12.5 %) are taken into account, the Strouhal number distribution shown in Figure 6 appears as a smooth extension of the equivalent distribution by West and Apelt [8] for the blockage of 12.3% and $Re_D > 20{,}000$.

Hence, not only do the corrected PIV and HWA spectra yield the same Strouhal numbers (within less than 2%), but they are both in agreement with prior work on the shedding frequencies off of cylinders in similar test configurations with significant blockage in the test section. As already mentioned in discussion of Figure 5, even the timing-uncorrected PIV reasonably well resolves the dominant frequency of the signal, and the main advantage of the proposed correction is rather related to improvement of the broadband distribution of the spectral energy of the flow field velocity fluctuations within the bandwidth of the laser repetition frequency. This proposed approach further enables utilization of PIV flow measurements for spectral analysis of the measured flow fields, beyond just the dominant frequency detection.

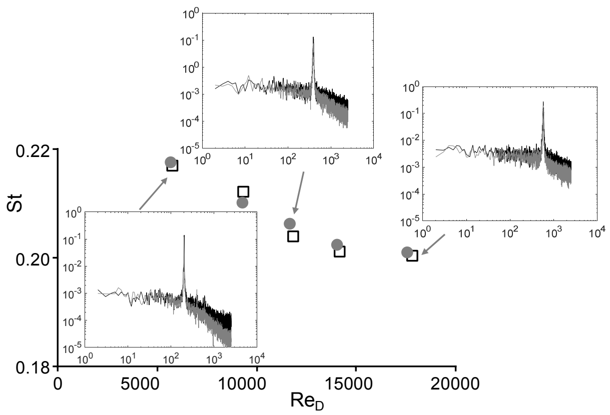

Figure 6. Strouhal number of the cylinder wake with Reynolds number measured by the HWA (circle) and PIV (square), and three characteristic pairs of spectra of the velocity fluctuations (HWA in dark grey, PIV in black).

4. CONCLUSION

A methodology is developed for the real-time measurement and the processing correction of double-pulse laser timing inconsistencies in order to prevent error propagation into both the time-averaged and spectral content of flow field measurements. Electronic timing, designed on the commercially-available high-speed lasers, may not account for all the physical delays associated with the laser operation, which can ultimately introduce unknown and unaccounted for timing errors within a PIV acquisition sequence. With increasing temporal capabilities of laser-illuminated, particle transit-based measurements, small fluctuations in the pulse timing can significantly increase the error when the pulse separation decreases and the repetition rates increase. The proposed feedback methodology measures the instantaneous pulse separations by the custom-designed circuitry and converts each pulse peak to a digital TTL pulse. Each PIV sequence of image pairs is then associated with its corresponding sequence of the TTL pulses, which are incorporated into the PIV processing methodology to create a set of correction factors for the actual separation time of the PIV snapshot pairs and to ultimately adjust the instantaneous velocity values. Although the correct dominant frequency appears to be captured even in the uncorrected PIV velocity fields, applying the proposed correction factors to the measured PIV acquisition sequence clearly adjusts the spectral distribution of the velocity field, as directly compared to that obtained in the hot-wire measurements. The corrected particle transit times, and ensuing spectral content, match well with the HWA measurements. Furthermore, the measured Strouhal number behind a shedding cylinder is correctly determined by both the corrected PIV and HWA measurements. These results show the feasibility of this methodology to accurately capture and then correct errors in PIV measurements due to laser pulse timing errors.

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NOMENCLATURE

D	cylinder diameter
H	test section height
W	test section width
$\boldsymbol{u}$	typical velocity vector
Re_D	Reynolds number
St	Strouhal number
τ	time

Greek symbols

Δt	pulse separation in (μs)
τ	time

Subscripts

D	cylinder diameter
a	assigned pulse timing
c	corrected velocity vector

МЕРЕЊА РАЗМАКА ИЗМЕЂУ ЛАСЕРСКИХ ПУЛСЕВА ЗА СПЕКТРАЛНУ АНАЛИЗУ СТРУЈАЊА ФЛУИДА ПУТЕМ ПИВ

К. Питерсон, Б. Вукашиновић, А. Глејзер

Методологија повратне везе је развијена за кориговање грешака у тајмингу ласерских система који користе пулсеве у пару високих фреквенција. Са сталним развојем неинтрузивних техника мерења као што је ПИВ, постоји растућа потреба за истовремену високу резолуцију мерења и у просторном и временском домену, што би омогућило њихову примену за спектралну карактеризацију струјања флуида. Ова примена условљава да је тачност и стабилност тајминга између сваког пара ласерских пулсева код ласерских система високих фреквенција од изузетне вазности јер се одступања у тајмингу директно преносе на греске у изведеним векторима брзине струјања, а идиректно и у све изведене параметре, укључујући и спектралну анализу струјања. Овај рад предлаже методологију повратне везе којом се коригују овакве грешке у току мерења. Такође, предложена методологија је демонстрирана на примеру вртложног трага цилиндра, и резултати су упоређени са одговарајућим мерењима усијаним влакном.