Shake-The-Box for multi-pulse systems: 3D Lagrangian particle tracking in high speed flows

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Due to current hardware limitations in terms of maximum acquisition frequency, long time-resolved sequences suitable for STB processing can be obtained only for relatively low flow speeds, typically limited to approximately $40\,m/s$. When dealing with larger flow velocities, typical of industrial and aerodynamic applications, dual-frame PIV systems are employed, where two-pulses are recorded with a short time separation of a few microseconds.

Multi-pulse acquisition systems obtained by synchronizing the recordings of multiple dual-frame systems in a staggered fashion enable the recording of short time resolved sequences, consisting typically of four recordings [14][10][2].

In order to benefit from the advantages offered by Lagrangian particle tracking (LPT) at high seeding density (accurate particle position-velocity-acceleration and highly spatially resolved ensemble statistics – see Sec. 11.9.5 - among others) a novel STB approach for multi-pulse sequences has been proposed by [12]. To compensate for the lack of a large number of time-resolved realizations the method makes use of an iterative strategy where the sequential application of the Iterative Particle Reconstruction technique (IPR [17]) and particle tracking is used to progressively reduce the complexity of the object to be reconstructed (by the stepwise reduction of the perceived seeding density) and increase the number of successfully retrieved particle tracks. A performance assessment of the STB multi-pulse method has been presented by [11], while experimental applications can be found in [12] and [6].

Iterative multi-pulse Shake-The-Box strategy

Several techniques have been proposed in order to separate the four pulses generated by a dual double-pulse laser illumination system; [10] suggested the use of three independent imaging systems, while the use of polarized light has been proposed by [9] and [14] where the lasers emit light with two polarization states and two imaging systems are equipped with the respective polarizing filters. The use of frame-optimized exposure cameras (FOX [5]) to implement a timing based pulse separation strategy has been suggested in [12].

Alternatively, a multi-pulse recording strategy based on the use of a single acquisition system and multi-exposed frames (e.g. two time instants recorded on frame 1 and two on frame 2 to obtain a four-pulse recording sequence) be envisioned in order to significantly simplify the experimental setup at the cost of a reduced instantaneous spatial resolution (i.e. particle image density).

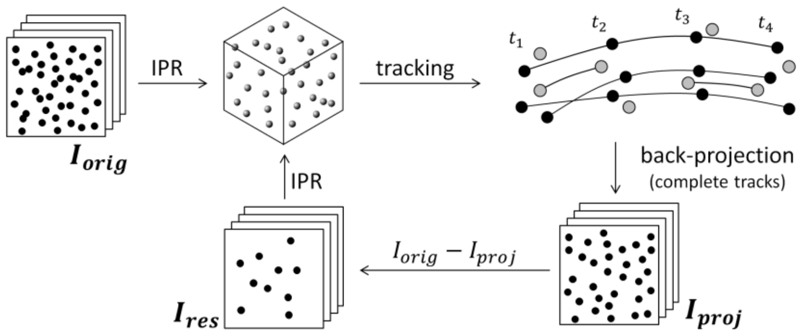

Fig. 1: Iterative STB processing strategy for multi-pulse sequences.

Independently of the chosen pulse separation technique, the Shake-The-Box method can be implemented in an iterative fashion to reconstruct and track the particle tracers along the short recording sequences. The processing strategy is depicted in Fig. 1. Four pulses are considered here (t_1, t_2, t_3 and t_4); an uneven time separation between the recordings can be chosen in order to increase the measurement dynamic range without affecting the performances of the tracking technique (see Sec. 11.9.5).

The recorded images (I_{orig}) are reconstructed for each pulse by means of IPR and particle tracking is performed across the four-pulse sequence. During the tracking, the partner matching scheme can be aided using a predictor for the velocity field, typically obtained by means of Particle Space Correlation of subsequent IPR reconstructed fields (PSC [11]).

After the tracking step is performed, particles that could not be tracked over the complete four-pulse sequence are rejected (gray dots in Fig. 1); as most *ghost particles* are inconsistent with the flow motion and fail to produce coherent tracks this step ensures that most of retained tracks (black dots) refer to actual particles. Furthermore, when two independent imaging systems are employed, the chance of producing *ghost tracks* is drastically reduced [4]. The retained particles are then back-projected onto the image plane to form projected images (I_{proj}); these are subtracted from the original recordings to obtain residual images (I_{res}). These steps constitute a single STB iteration; the images of particles which have not been reconstructed by IPR (e.g. due to particle image overlapping situations) or failed to be matched during tracking (e.g. due to inaccurate predictor or inadequate search radius) remain in the residual images.

These residual images are then used to perform a further STB iteration, as depicted in Fig. 1; these images typically exhibit a lower particle image density, therefore offering a less complex reconstruction and tracking problem. As a consequence, the iterative application of STB is expected to enable the recovery of previously undetected particles, potentially overcoming the limitations in terms of seeding density imposed by the use of particle reconstruction alone (typically $0.05\ ppp$ for IPR).

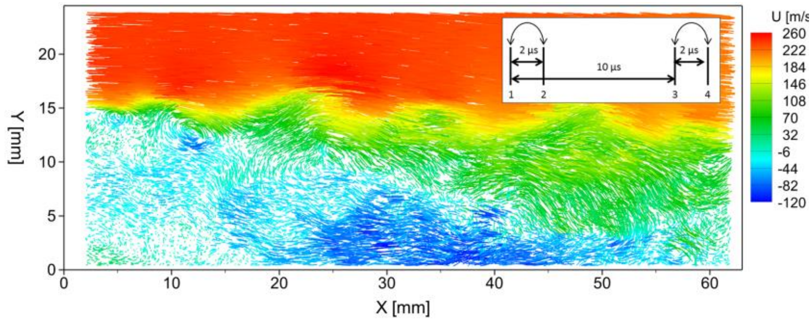

Fig. 2: approximately $\mathbf{26,000}$ ground-truth reference tracks within the investigated domain; tracks are color-coded by the stream-wise velocity component; the four-pulse timing sequence is depicted in the top-right corner.

Performance assessment of multi-pulse Shake-The-Box

A performance assessment of the STB applied to multi-pulse recordings based on synthetic experiments has been proposed by [11]; the effect of image noise and seeding density has been investigated, as well as the reconstruction and tracking parameters.

Within the framework of the European FP-7 project NIOPLEX, a synthetic multi-pulse experiment has been generated, among other cases, to assess the suitability of multi-pulse data in delivering accurate material acceleration measurements suitable for the extraction of instantaneous pressure fields via the momentum equation. A more detailed description of the test cases and the techniques employed for pressure determination can be found in [15]. Results from a Zonal Detached Eddy Simulation (ZDES [3]) of a transonic flow over an axisymmetric step are used to produce synthetic particle images from a four-camera 3D imaging system. The flow has a Mach number of 0.7, resulting in a free stream velocity of $226\ m/s$ ($Re_D = 1.3 \cdot 10^6$). The measurement domain of the synthetic experiments encompasses $60 \times 24 \times 4\ mm^3$ along the stream-wise (X), wall-normal (Y) and span-wise (Z) directions respectively; the step height is $15\ mm$. Tracer particles are randomly generated within the 3D domain in order to produce camera images with a particle image density of approximately $0.05\ ppp$; ideal and noisy images are generated to simulate experimental imaging conditions.

A series of 21 statistically independent instantaneous four-pulse sequences is generated for both cases; an example of the instantaneous ground-truth reference track field is shown in Fig. 2 where the particle tracks have been color-coded based on the value of the stream-wise velocity component. The origin of the coordinate system is placed at the lower corner of the step. The four-pulse image acquisition timing sequence is depicted in Fig. 2; an uneven spacing of the pulses is applied in order to extend the measurement dynamic range and allow for the evaluation of more accurate particle material acceleration.

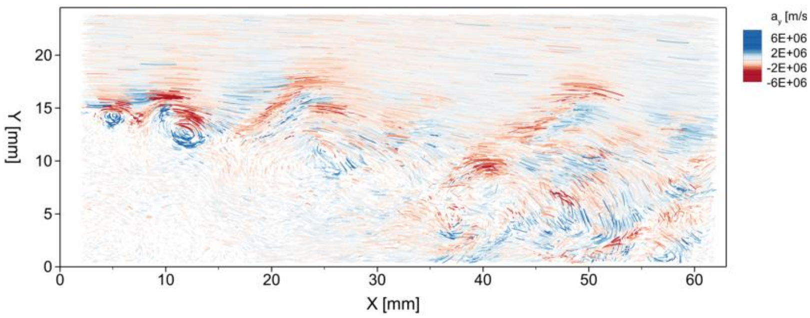

Fig. 3: instantaneous STB result for the noisy particle images case. Tracks are color-coded with the value of the material acceleration along the Y axis.

A detailed description of the STB parameters and tracking strategies, adapted to cope with the uneven time separation between the pulses by means of a predictive scheme for particle matching, can be found in [11].

The performances of STB are evaluated at the mid-point of the tracks where the maximum accuracy of the fit to the particles trajectories [7] is attained; results are obtained averaging across the 21 time instants. Unlike for the reference particle position and velocity, a ground-truth value for the material acceleration is not directly available from the ZDES simulation results. As a consequence, the reference material acceleration is obtained applying a fit to the ground-truth particle locations.

An example of the instantaneous STB result is shown in Fig. 3 for the noisy case, where the particle tracks are color-coded based on the acceleration component along the Y axis.

For each reference particle, a search area having $1\ px$ radius is located at the peak position; if at least one STB particle is found within the search area, the particle is considered as detected and the mean and root-mean-square (rms) errors in terms of particle position are evaluated as:

$$\Delta_p = \frac{1}{N_{tr,a}} \sum_{1}^{N_{tr,a}} \left| \vec{x}_{tr,a} - \vec{x}_a \right| \qquad rms_p = \sqrt{\frac{1}{N_{tr,a}} \sum_{1}^{N_{tr,a}} \left(\vec{x}_{tr,a} - \vec{x}_a \right)^2} \tag{1}$$

When no particle reconstructed from STB is found in the vicinity of the reference particle, this is listed as undetected. The velocity and acceleration errors are evaluated as in equation 1, where the position vector $\vec{x}$ is replaced by the velocity and acceleration vectors $\vec{v}$ and $\vec{a}$; results are summarized in Table 1.

The number of *ghost* particles is computed searching for reference particles in the area surrounding each reconstructed particle. When no actual particle is found the peak is considered as a *ghost*; results refer only to *ghost* particles that produced a four-pulse track.

For the clean case a converged state, in terms of number of detected tracks, is reached after two STB iterations only, while five iterations are needed for the noisy case. Up to 99% of the reference particles are identified by STB in the con-

Table 1: velocity and acceleration errors and dynamic ranges for tracks detected by STB.

	clean	noisy
Δ_v $[px/\Delta t]$	0.018	0.042
rms_v $[px/\Delta t]$	0.026	0.053
DVR	467	223
Δ_a $[px/\Delta t^2]$	0.025	0.073
rms_a $[px/\Delta t^2]$	0.04	0.087
DAR	23	10

verged state; the number of iterations needed to reach this condition depends upon image quality (e.g. noise level) and seeding density.

For both the clean and noisy cases, the fraction of tracked ghost particles is lower than 1%.

Following [1], the dynamic velocity (DVR) range of the measurement can be estimated as the ratio between the maximum velocity magnitude within the investigated domain and the velocity rms error; the same approach can be followed to compute the dynamic acceleration range (DAR). Concerning the clean case, a DVR and DAR of 467 and 23 respectively are found. For the more realistic case of noisy particle images the dynamic velocity range equals 223 while the dynamic acceleration range is 10; the values of the dynamic ranges are comparable to the ones indicated by [13] concerning time-resolved data.

The performances of the iterative STB approach in terms of fraction of detected tracks and velocity and acceleration errors suggest the suitability of multi-pulse systems in providing access to the measurement of the material acceleration, in particular when a variable time separation between the pulses is adopted to increase the dynamic range of the measurement.

Application of STB to multi-pulse experimental data

Experimental applications of the Shake-The-Box for multi-pulse systems can be found in [6] and [12]. The investigation of a transonic jet in air at Mach 0.84 by means of a four-pulses system and STB is described in Sec. 11.9.5.

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