Single-Frame Lagrangian Tracking of 3-D Acoustic Streaming Flows using Digital Defocusing Micro-Particle Streak Velocimetry

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ABSTRACT

In this study, a single-frame particle streak velocimetry technique is applied to the classic DDPIV(Digital Defocusing Particle Image Velocimetry) concept to achieve a single-frame 3-D Lagrangian tracking of particles in microscopic flows. The shortcoming of images suffering low signal-to-noise ratio due to pinholes can be avoided. With the streak-resolving algorithm, allows extended exposure time when streak images are taken, and the single-frame approach also eliminates the need for high-cost and complicated synchronization hardware for double-pulse frame-straddling light sources. For each long-exposure, color-coded images received from each pinhole equipped with red, green, or blue color filters, the streak-resolving algorithm is applied first to find each streak on the separate color channel, followed by a one-time triplet-matching process to group the red, green and blue streak projections. From the streak triplets, 3-D reconstruction can be done on all the resolved points on the streak, and trajectory fitting can then be applied to resolve the tracer particle trajectories in the field of view with temporal history. This procedure was applied for visualizing a microscale 3-D acoustic streaming flow pattern induced by a longitudinal spine-shaped fin oscillating at 12kHz. The height of the channel is 1mm with a spine of 0.3mm height and a 30 ◦ tip angle. Resolved flow fields show that the particle streak images can be resolved with the same level of accuracy as the particle tracking method, while the throughput of velocity vectors can be significantly higher due to multiple velocity vectors being resolved from each streak triplet. The methodology has the potential to be applied to various applications that can capture long-exposure images and possibly resolve higher-order information such as acceleration and forces applied on the particles or the flow.

1. Introduction

Particle Streak Velocimetry (PSV) is a method of analyzing the velocity field by taking long streak images with continuous light and long exposure time. It is a quantitative measurement of the flow field that is different from Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV). PSV can get particle trajectory and flow direction from just one image which can be captured with continuous lasers and long exposure time. For these long streak images, the two-frame methods like PIV and PTV have difficulties in determining the correct velocity vectors because the particle trajectory could be a long and curved trace due to the high-velocity gradient, and displacement of the particle between the two frames can deviate significantly from the true tangent velocity vector due to the longer exposure time so the small-time interval approximation fails. For PTV algorithms the long-exposure images cannot be used because PTV relies on finding the peaks accurately to precisely determine the center position of the particles, which is difficult to achieve for the long streak trajectory[1]. Because of the relatively low hardware cost and improvement of the computational technology, PSV became attractive again and some researchers revisited this idea with the new technological improvements. Grayver and Noir[2] use Convolutional Neural Networks (CNN) to infer the displacement and azimuth of straight traces, but there is a possibility of incomplete traces due to the image cuts, resulting in unrecognizable traces and reduced detection accuracy. Tsukamoto and Funatani [3] used coded illumination to make the single-frame streak into three segments and form asymmetric streak traces with the first two short and the third one long to determine the flow direction. The displacement is calculated from the centers of gravity of the first and the third streaks, and the particle velocity can be measured by visualizing the path line with the resolved streaks. The three-feature trajectory may not be detected correctly in the binarization process might impact the detection rate. These algorithms can only detect and analyze straight trajectories for one velocity vector per streak, which does not work very well for long and curved streak images.

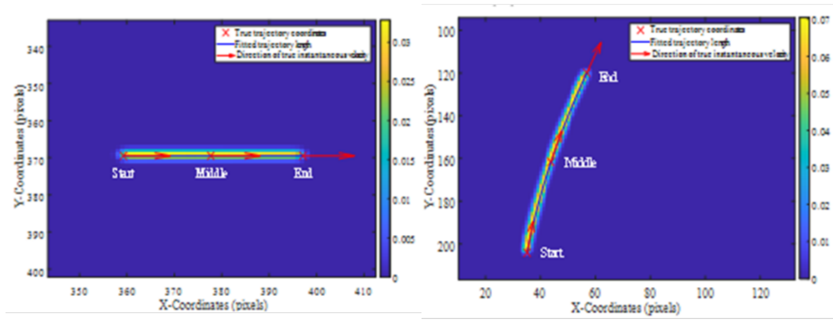
To explore the possibility of analyzing the curved streak, Qureshi and Tien[4] developed a novel streak-resolving algorithm for a single frame to resolve the velocity field. The main idea is to apply a least-square fit of the time integral of a Gaussian-shaped synthetic particle moving in the measurement field of view to fully resolve the time history of the particle's trajectory. This method applied to the Lagrangian tracking of a single particle streak trajectory not only can analyze the straight trajectory but also can be used for the curved trajectory with single image frame. As shown in Fig.1, at the start, middle, and end points of the streak, it was shown that whether a streak is straight or curved, the local velocity vector can be resolved with good accuracy. This scheme was validated with synthetic flow fields of straight parallel flow and highly rotational Hill's vortex flows. The results show that the residual errors and the measurement uncertainty are negligible for the noise-free images, and up to 5%-10% for the case with corresponding error levels. A similar idea is also proposed by Fan et al. [5, 6] as a method of high spatial resolution two-dimensional phosphor particle streak velocimetry (phosphor particle streak velocimetry, phosphor-PSV) technology. With the pulsed laser light to stimulate the phosphor particles in the flow, the decay of the excited phosphor forms a particle streak to be recorded by the camera. The streak is resolved by fitting a temporal integration of a Gaussian-shaped particle image moving in space, but the trajectory is considered linear so that the integration has a closed form for fitting. A segmentation method based on image dilation was proposed for image segmentation, and the results show that when the Signal-to-noise ratio (SNR) is greater than 20, the particle size constant σ is greater than 0.3 pixels, and the displacement ($v\tau/\eta$) is greater than 1 pixel, the mean error value and the root mean square error of the velocity measurements are less than 5%.

Some researchers revisited the PSV idea and applied it to volumetric velocimetry techniques to resolve 3-D flows. Voss et al.[7] proposed a bichromatic particle streak velocimetry (bPSV) to detect three-dimensional flow fields. A camera was used to record the flow region illuminated by two lasers with different wavelengths at different depths. The depth positions of the particles were then determined from the light intensity of the particles, and the particle trajectory and therefore the flow velocity of the fluid can then be determined by the recorded images with a long exposure time. Defocusing Particle Streak Velocimetry (DPSV) was proposed by Wang et al [17] to resolve the out-of-focus particle motion using long exposure time and large magnification photography. They construct an algorithm for the defocusing characteristic parameter σ and apply it to the measurement of straight and curved streak trajectories in a three-dimensional velocity field, and then fit the intensity of the streak to obtain particle trajectories. Dong et al. [18] extended DPSV as the basis for their experiments added the calibration procedure and introduced the σ as the out-of-focus characteristic parameter for determining the Z position. In these studies, only straight streaks are used from a single particle streak.

Since particle streaks can be resolved based on the assumption of Gaussian-shaped particle images, it might be possible to combine the streak-resolving algorithms with those volumetric methods utilizing the multiple-view concept to develop a PSV-based scheme for volumetric methods. Digital Defocusing Particle Image Velocimetry (DDPIV) [8, 9] is one of these methods suitable for the implementation. It has a simple concept and can still be an efficient method in micro-scale flows [10]. The color-coded configuration by Tien et al.[11-13] is a suitable choice for this implementation in microscopic flow, since the three streaks of the same particle can be recorded together in the same color camera with much less chance to be interfering with other streaks. The PSV method also reduced the problem of the DDPIV/PTV methods, which is the requirement of relatively higher illumination intensity to work for high-speed flows, since the use of pinholes significantly reduces the light entering the image sensors.

In this study, an attempt to combine the concepts of the DDPIV and streak-resolving scheme proposed by Mumtaz and Tien[4]], called Digital Defocusing Micro-Particle Streak Velocimetry (DDμ-PSV), is explored experimentally. With the streak-resolving scheme, triplet particle streak images recorded by μ-DDPIV configuration are processed and the full temporal history of the 3-D trajectory of the corresponding particles can be realized. The method is applied to observe the 3-

D flow patterns generated by an acoustofluidic device that utilizes a single-spine in a micro-channel to induce 3-D acoustic streaming. to observe the three-dimensional flow field of particles.



(a) (b)

Fig.1 Resolving streak temporal information by PSV[4]: (a) Straight streak. (b) Curve streak. The red cross marks show the start、middle and end points resolved in the same streak. The blue line indicates the fitted trajectory by the streak-resolving algorithm. The red arrowheads show the direction of resolved instantaneous velocity vectors.

2. Experimental Methods

The experimental setup of the current study is shown in Fig. 2. An inverted microscope (WI-400) with a single-color CMOS camera (MQ013CG-ON) was used for imaging. The light sources are three continuous single-wavelength LEDs with customized lens tubes. The wavelengths are R-620 nm, G-520 nm, and B-450 nm, respectively. They are placed at an angle of 120 degrees apart from each other from the top view of the microchannel area to be measured. A three-pinhole mask attached with corresponding color filters (From Roscolux Swatchbook filter set, R is #2001, G is #4490 and B is #80) is placed in the 10X objective lens, and each of the light sources is aligned to pass through the area to be measured and enters the objective lens to the color camera through the corresponding pinhole and color filter. With this hardware setup, the depth of each particle can be determined by the pattern of the triangular pattern formed by the color-filtered particle images exposed on the image plane, as explained in Fig. 3.

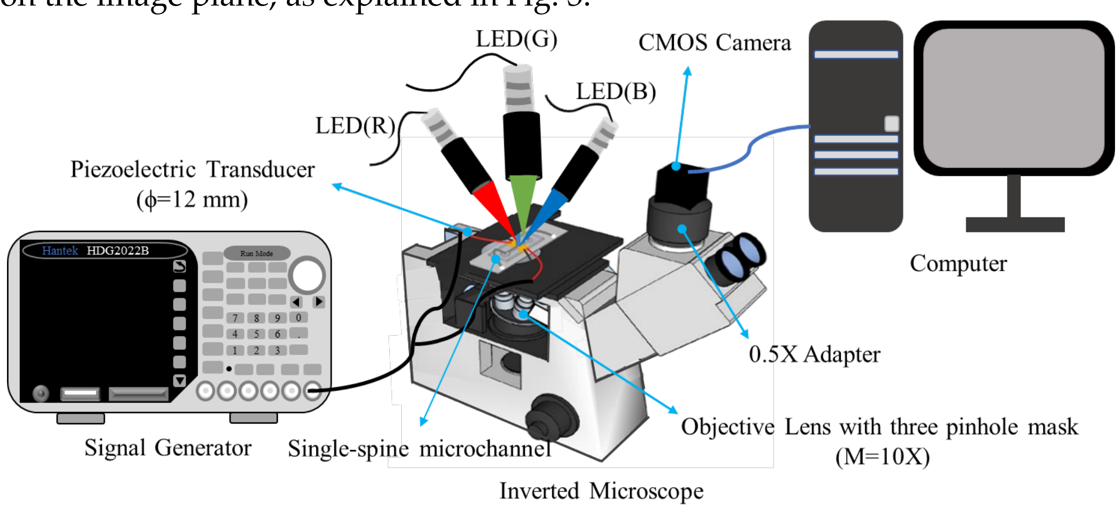


Fig. 2 Experimental setup of the current study

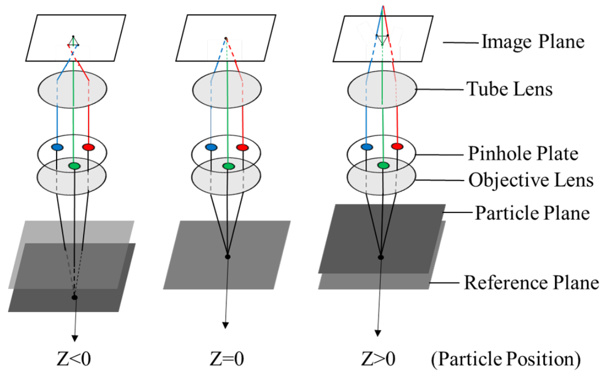


Fig. 3 Illustration of the concept of $\mu-$DDPSV shows the triplet exposure image formation of the particle at different depth locations from left to right: When Z<0, focuses and extends to form a triplet image on the imaging plane. When Z=0, Focuses on the imaging plane to form a single image exposure when the triplet images overlap. When Z>0, lights pass through the imaging plane and then focus to form the triplet images that have a triangular pattern opposite to the left sub-figure.

After the raw image is captured by the $\mu-$DDPSV hardware, a three-stage post-processing procedure is adopted to resolve the streak velocity. In the first stage, the raw color image is separated through a color separation algorithm based on a decorrelation scheme to eliminate the cross-talk between the color filters[12], and the streak images of each color channel is the then processed using the streak-resolving algorithm developed previously[4] to obtain the full temporal history of the individual streak positions of the corresponding color channel. The two-dimensional Gaussian intensity distribution of a single particle image located at $(, y_0)$ in the Field of view (FOV) is

$$G(x, y) = I_0 \exp\left[\frac{-(x-x_0)^2-(y-y_0)^2}{2\beta^2}\right] \quad (3)$$

where I_0 is the peak intensity, σ is the particle image diameter, and $\sigma = 4\beta$ (depends on the intensity value of e^{-2}). To describe the temporal history of the moving particle image, the time integral of equation (3) with respect to time within the exposure time is done as follows:

$$G_\sigma(x, y) = \frac{1}{t-t_0}\int_{t_0}^{t} G\{[x-(x_0-x(t))],[y-(y_0-y(t))]\}dt \quad (4)$$

$G_\sigma(x, y)$ is the trace intensity curve, $x(t)$ and $y(t)$ correspond to the x and y (image) coordinates of a corresponding particle streak within the exposure time range from t_0 to t, respectively. $x(t)$ and $y(t)$ of each color channel can be fitted separately by a multivariable least-square fit scheme assuming the trajectory can be represented by a 7th-order polynomial [4],

$$x_{ji}(t_k) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5 + a_6 t^6 + a_7 t^7 \quad (5)$$

$$y_{ji}(t_k) = b_0 + b_1 t + b_2 t^2 + b_3 t^3 + b_4 t^4 + b_5 t^5 + b_6 t^6 + b_7 t^7 \quad (6)$$

where i indicates the red (R), green (G), and blue (B) color channel, j is the N^{th} particle streak and k is the k^{th} exposure time point. The exposure time t is normalized to a 0 to 1 range and can be used to calculate at any specific t_k for the particle image center location (x_{ji}, y_{ji}).

In the 2^{rd}-stage, the middle time point at $t = 0.5$ is chosen to calculate all the particle image positions at each color channel, and then the triplet-finding based on the epipolar-line-search method [Tien] is performed to match all the possible triplets in the three R, G and B streak images. Once the triplet-matching relationship is established, from these matched R, G, and B streaks at specific time points t_k, $\left(X_j(t_k), Y_j(t_k), Z_j(t_k)\right)$ can be reconstructed with the image coordinates $(x_{ji}(t_k), y_{ji}(t_k))$ by the same reconstruction method described in Tien et al.[12]. In the current study, a minimum of 7 points (k=0~6) are reconstructed and the full temporal 3-D particle trajectory X_p $(X(t), Y(t), Z(t))$ of a streak image can be found using the following equations

$$X_j(t) = A_0 + A_1 t + A_2 t^2 + A_3 t^3 + A_4 t^4 \quad (7)$$

$$Y_j(t) = B_0 + B_1 t + B_2 t^2 + B_3 t^3 + B_4 t^4 \quad (8)$$

$$Z_j(t) = C_0 + C_1 t + C_2 t^2 + C_3 t^3 + C_4 t^4 \quad (9)$$

where the coefficients A_l, B_l and C_l are found by the standard 5^{th}-order polynomial fit scheme, respectively.

In the 3^{rd} stage, after obtaining the full temporal history of the particles' three-dimensional positions, with the time t as the variable describing the trajectory, X_p $(X(t), Y(t), Z(t))$ is equivalent to the displacement of the particle and it is possible to calculate the velocity at any point on the trajectory X_p by differentiation to obtain the Lagrangian velocities:

$$u(t) = \frac{dX_j(t)}{dt} \quad (10)$$

$$v(t) = \frac{dY_j(t)}{dt} \quad (11)$$

$$w(t) = \frac{dZ_j(t)}{dt} \quad (12).$$

In the current study, the desired time point t_m is calculated at $t = 0, 0.5,$ and 1, which correspond to the initial, middle, and final points of individual particle trajectories of one single image frame. The microchannel was designed with a single longitudinal spine, as shown in Fig. 4, and was molded with Polydimethylsiloxane (PDMS) and combined with a slide, with tubes at both ends of the channel as the entrance and exit. In this study, two piezoelectric discs of 12mm diameter were attached to the top sides of the single-spine microchannel using ultrasonic gel (LAITEST LUBRICATION JELLY XY-35) to drive the acoustic streaming, as shown in Fig. 5. A signal generator was used to provide the driving signal to the piezoelectric discs to oscillate the latter. The signal was set at a pulsing frequency of 12 kHz with a peak-to-peak voltage of 20 volts to generate the acoustic streaming vortices. The flow patterns in the FOV shown in Fig. 5 were observed and recorded. The tracer particles used in the current study are 1.75 μm PS particles (Polysciences, Fluoresbrite® BB Carboxylate Microspheres 1.75μm), and the suspension solution was made by mixing with Deionized (DI) water at concentrations of 20, 40 and 65 ppm, respectively, which are in terms of the weight percentage, to find out the better imaging results. Fig.3 Experimental setup of the DDμ-PSV system.

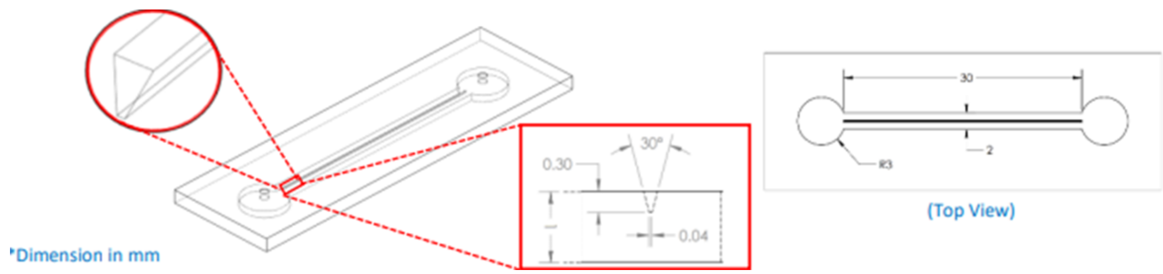


Fig. 4 Schematic Diagram of the microchannel used in the current study. (Unit: mm) (a) Single-spine microchannel. (b) Zoom-in view of the single-spine design. (c) the detailed dimension of the single-spine design diagram.

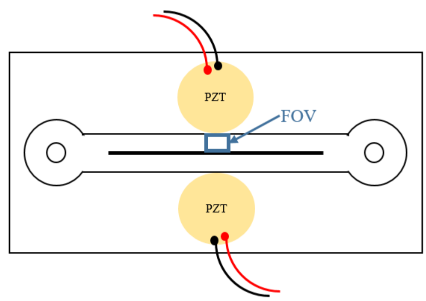


Fig. 5 Schematic Diagram to show the placement of the piezoelectric discs at the microchannel and the FOV of the camera in the current study.

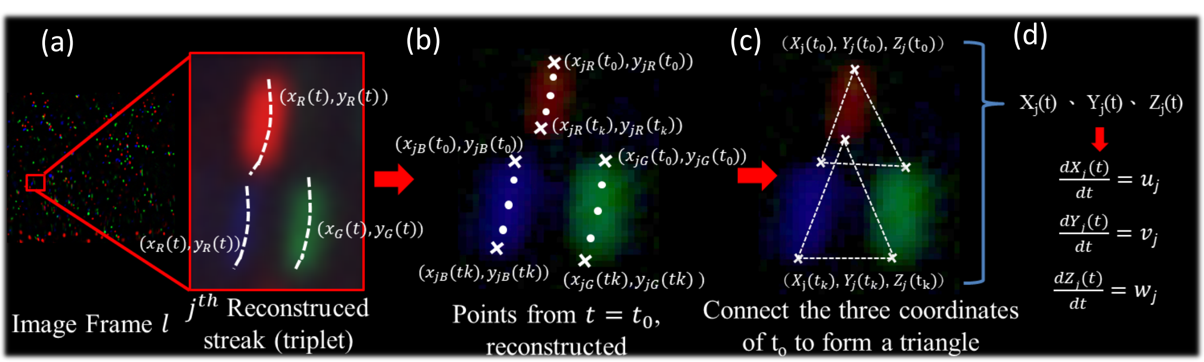


Fig. 6 Post-processing of the μ −DDPSV streak images. From left to right: (a) The three R, G, and B streak images from each color channel. (b) The process to resolve each streak by streak-resolving algorithm and identify of the R, G, and B triplet of the same particle by matching the middle point of the streak in each color channel. (c) Reconstruct the 3-D particle position $\left(X_j(t_k), Y_j(t_k), Z_j(t_k)\right)$ for each time point. (d) Fully reconstruct the 3-D particle trajectory and velocity for each particle.

Fig. 7 shows the operating parameters and the pre-processing of raw images during the single-spine test. The field of view (FOV) is set at the middle section of the microchannel, as shown in Fig. 7(a). During the experiment, this FOV allows us to observe the 3-D flow patterns on the upper half of the channel to reduce the blooming effect from the three LEDs due to the different incident angles. The focal plane is set at 310 μm below the floor of the microchannel. Because the measurement range of the current μ −DDPSV system is set to 320 μm, this focal plane setting is sufficient to capture most of the acoustic streaming flow patterns near the spine.

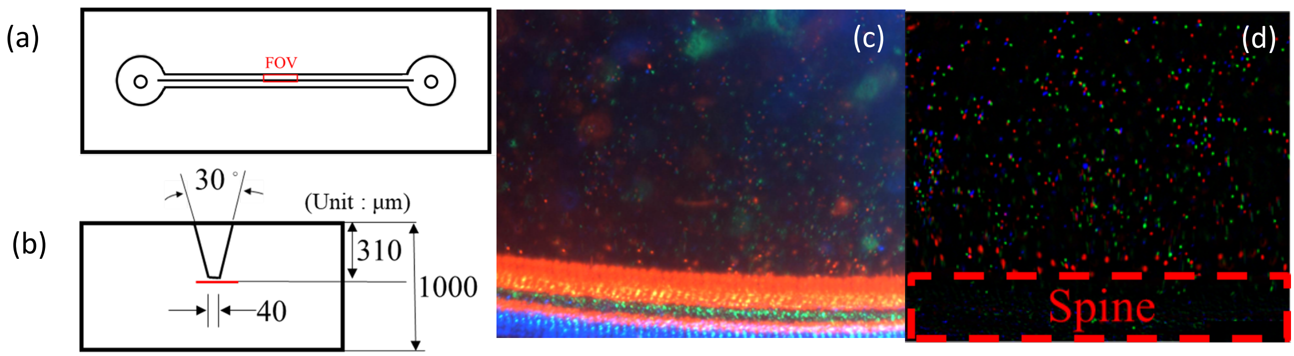


Fig. 7 The Imaging setting and pre-processing of raw images: (a) The field of view (b) the focal plane in the single-spine acoustofluidic microchannel in the current study. (c) The raw image was taken at the FOV and focal plane set in (a) and (b). (d) The pre-processed image is ready to be processed by the post-processing scheme.

3. Results and Discussion

The μ −DDPSV system was tested with a no-spine microchannel of the same geometry without the acoustic streaming activation to validate its functionality. Fig. 8 shows the reconstructed particle field of the flow resolved by the current setup from 71 frames with low particle image density and medium exposure time of 45ms. In Fig. 8 (a) and (c), the X-Y views show that the straight movement of the particles is resolved correctly, and a large amount of connected particle trajectories can be achieved with the single-frame tracking nature of PSV. In Fig. 8 (b) and (d), the X-Z views of the resolved particle field show that the particles close to the center of the channel have more straight trajectories, while the particle trajectories on top and bottom of the channel are moving more randomly. This is possibly due to the Brownian motion can cause the particle to deviate from the straight flow path more as the axial velocity is lower closer to the wall.

Fig. 9 is the resolved particle field using the setup in the current study. The experimental conditions are set to the single-spine channel with the acoustic streaming activated at 20V, 12kHz, with higher particle image density at 100 ms exposure time from 100 frames. In Fig. 9 (a) and (c), the X-Y views clearly show the effect of the acoustic streaming, and particle trajectories show that the acoustic streaming is moving toward the base of the spine. Away from the spine, the acoustic streaming is weaker and particle tracks may deviate from the acoustic streaming patterns and settle down by gravity. In Fig. 9 (b) and (d), the Y-Z views of the resolved particle field show the particle trajectories influenced by the acoustic streaming. Particles are first moving toward the base of the spine, rise with a steep angle, and then accelerate away from the spine. This is similar to the 2-D acoustic streaming around the solid triangular shape obstructions shown in many previous studies. Particles at the lower left corner at the far side of the acoustic streaming flow loop, and particles become more easily influenced by gravity and fall to the floor.

Fig. 10 shows the reconstructed velocity field calculated from single frames. tn marks the normalized time point in a single exposure. Each streak produces 25 velocity vectors, calculated from the equation (10)-(12). The velocity field obtained from the streaks agrees with the observation from the resolved 3-D velocity field and therefore shows that the current setup of DDμ-PSV can be applied to resolve rotational flow with single frames.

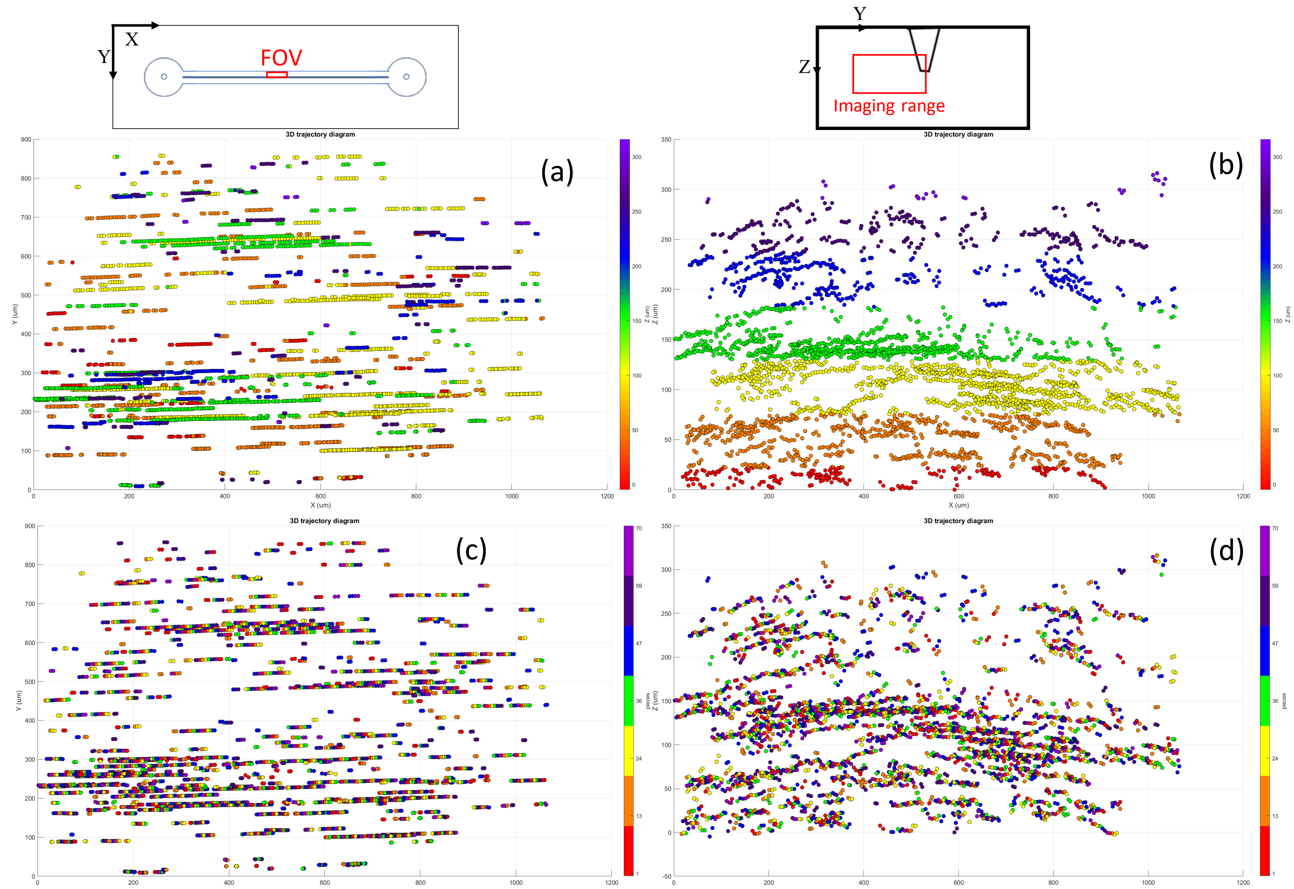


Fig. 8 Reconstructed particle field of the no-spine channel: (a) Resolved particle distribution viewed in X-Y plane with indexed color indicating the Z position. (b) Reconstructed particle distribution viewed in the X-Z plane, with indexed color indicating the Z position. (c) Reconstructed particle field viewed in the X-Y plane, with indexed color showing the frame number. (d) Reconstructed particle field viewed in the X-Z plane, with indexed color showing the frame number.

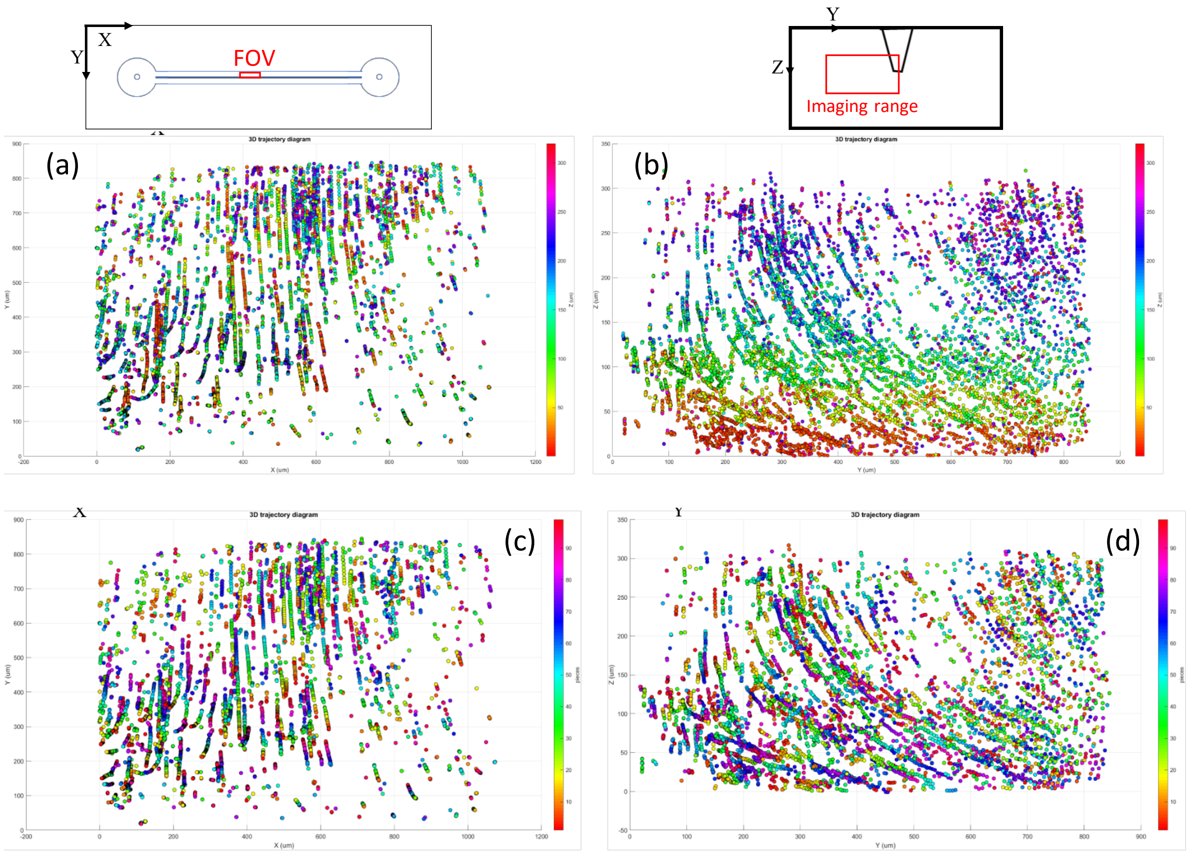


Fig. 9 Reconstructed particle field of the single-spine channel with the acoustic driving turned on: (a) Resolved particle distribution viewed in X-Y plane with indexed color indicating the Z position. (b) Reconstructed particle distribution viewed in the X-Z plane, with indexed color indicating the Z position. (c) Reconstructed particle field viewed in the X-Y plane, with indexed color showing the frame number. (d) Reconstructed particle field viewed in the X-Z plane, with indexed color showing the frame number.

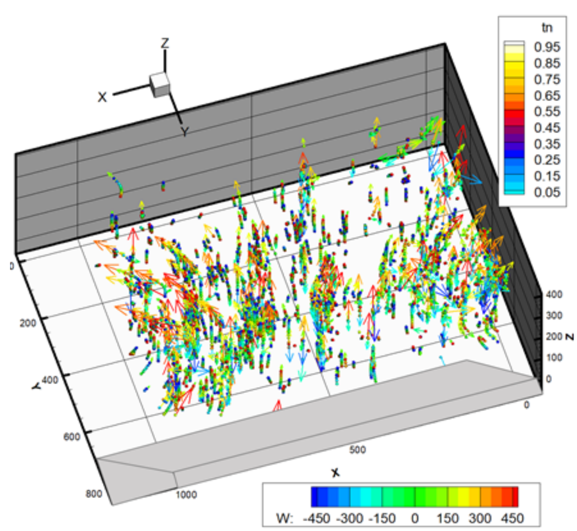


Fig. 10 Reconstructed velocity field of the single-spine channel with the acoustic driving turned on.

4. Conclusions and Future Works

The DDμ-PSV system concept that can capture the 3-D microscale flow patterns with streak images was developed and validated. With appropriate particle concentration and exposure time settings, it is possible to resolve 3-D rotational flow in microscale. can be obtained for further analysis. The results of visualizing a microscopic acoustic streaming flow induced by a single longitudinal spine show that it is possible to generate a rolling 3-D flow pattern on each side of the spine. Particles moving at higher speeds might be captured if the exposure time is extended. Follow-up studies on how to quantitatively determine the system performances and the optimum recording parameters are underway to understand the capability of this technique for imaging faster microscopic flows. Other challenges of this technique such as resolving overlapping long streaks at high streak concentrations, which increases the difficulty in the analysis should also be addressed in future studies.

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