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Particle Displacement Tracking for PIV

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PARTICLE DISPLACEMENT TRACKING FOR PIV

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Abstract

A new PIV data acquisition and analysis system, which is an order of magnitude faster than any previously proposed system has been constructed and tested. The new Particle Displacement Tracking (PDT) system is an all electronic technique employing a video camera and a large memory buffer frame–grabber board. Using a simple encoding scheme, a time sequence of single exposure images are time coded into a single image and then processed to track particle displacements and determine velocity vectors. Application of the PDT technique to a counter–rotating vortex flow produced over 1100 velocity vectors in 110 seconds when processed on an 80386 PC.

Introduction

Particle Imaging Velocimetry (PIV) is a very useful tool in the study of transient fluid flow phenomena. Many classes of engineering problems satisfy the in–plane velocity requirements of the technique. The processing techniques for reducing PIV data have traditionally been tedious and time consuming. Hence, much effort continues to be devoted to developing more refined and expedient data reduction techniques. In this work a new approach to PIV data reduction is presented which uses a simple space domain particle tracking algorithm.

In PIV, pulsed light sheets are used to record the in–plane positions of particles entrained in the flow at two instances in time.[1] Low particle concentrations are used to ensure that individual particle images are clearly resolved.[2] Subsequent processing of the photographically recorded particle images yields a 2–D velocity vector map across an extended planar cross section of the flow. A common data reduction technique is the beam readout technique.[3-4] Other techniques involve digitizing small sections of the photograph and performing numerically intensive computations or employ image processors to detect velocity vectors.[5-6] All of the photographic recording PIV techniques offer high precision estimates of the velocity, but require extremely long processing times even on specialized array processors. Chemical processing of the exposed plates is a cumbersome and tedious process. The photographic plates must also be stored and catalogued.

Other PIV work has focused on developing all electronic acquisition and processing systems. Electronic recording and processing offers the advantages of no chemical processing steps, and no large volumes of photographic plates to catalog, store, or break. The most attractive features are system integration and simplicity. In a electronic PIV system, all of the data acquisition and processing can be performed on a single computer. No media conversion is required. The comparatively low resolution of video cameras to that of photographic film limits the spatial resolution of electronic PIV recording techniques. However, if small (50×50 mm) cross sections of the flow are imaged, the spatial resolution of video cameras is acceptable.

All of the electronic PIV work has been concerned with resolving individual particle images and/or particle streaks. In some of the previous electronic PIV work, particle streaks were digitally recorded and later image processed to estimate the streak lengths.[7] Combinations of streaks and dots have also been employed to determine the velocity vector direction.[8] Other electronic PIV systems use multiple exposures (> 2) on a single image, and then rely on the operator to visually recognize particle displacement records.[9] The recognized particle image sets are marked using an image processor cursor and stored in the computer.

The Particle Displacement Tracking (PDT) technique uses a time sequence of single exposure images to determine direction information and to track particles. Time sequences of particle images to estimate velocity have been previously proposed and analyzed in computer simulations.[10-11] However, cross–correlation and FFT techniques were used to obtain velocity magnitude, which are both computationally intensive operations. The cross–correlation technique yields the velocity vector direction information in conjunction with the vector magnitude. In the FFT approach, the sequence of single exposure particle image frames are linearly superimposed to generate a single multiple exposure record, which is then Fast Fourier Transformed to estimate the velocity vector magnitude. The sequence of single exposure images is used as a phase reference, so that the direction information can be inferred.

The PDT technique has evolved from a previous work on a 'Vector Scanning' space domain processing technique.[12] In this previous work, a sequence of single exposure images were used to estimate velocity vectors. A particle displacement pattern was selected, and then scanned through the entire image. The only difference between the PDT technique and the previous work is the algorithm used to detect the occurrence of velocity vectors. The PDT system is an order of magnitude faster than the previous vector scanning technique.

The Vector Scanning and PDT techniques are the only fully automatic electronic PIV systems yet devised. In all other PIV systems, some operator intervention or supervision is required either at data recording or during data reduction. In the Particle

Displacement Tracking (PDT) system, no operator intervention is required in the data reduction process as long as good quality, high contrast PIV images are recorded. If the contrast is not optimal, then the appropriate threshold level to eliminate the background level is the only operator intervention required.

The PDT technique uses a simple algorithm which utilizes the time sequence of particle image fields to determine both the velocity vector magnitude and direction, without numerically intensive operations. All computations can be performed on a PC. The PDT technique is demonstrated on a counter–rotating convection vortex flow. Over 1100 velocity vectors were detected in a 50×100 mm field of view and completely processed on an 80386 PC in 110 seconds.

Particle Displacement Tracking

The Particle Displacement Tracking (PDT) technique is applicable only to low velocity PIV fluid flow systems. In the PDT system, a cw laser source is used to generate a light sheet, and a video array camera/frame–grabber board records the particle image data. The frame–grabber board is used to acquire five video fields equally spaced in time from the RS–170 video source. The choice of five fields minimizes the error rate in subsequent processing.[12] The time interval, ΔT, between recorded fields is 1/60 second at the minimum, and essentially unlimited at the maximum time interval, which corresponds to the minimum velocities. The actual value of ΔT is selected according to the fluid velocities of interest. The particle seeding number density is selected so that the individual particle images are clearly imaged. The recorded particle images do not overlap.

The five video fields are then individually processed to determine the centroid location of each particle image on each video field in the sequence. The particle image centroids are estimated to within ± ½ pixel.[12] Although the particle positions are actually estimated to sub–pixel accuracy, at this point in the PDT development the need for high precision particle position estimates is not required. A simple boundary following algorithm with centroid estimation is used to estimate the particle locations. The details of the centroid processing are discussed in reference 12. The single pixel particle centroid estimates from all of the particle images recorded in the five field sequence are combined into a single 640×480×8 bit square pixel image. The time history of each particle image is encoded in the amplitude of the pixel marking the position of the particle centroid. The pixel amplitudes are coded according to the time order in the five field sequence. All of the particle centroids from video field #1 are encoded into the composite image as pixels with amplitudes 2^1. Similarly, particle centroids from video field #2 are encoded with amplitude 2^2. By amplitude coding the pixel locations of the particle centroids, a single image is generated which contains the time history displacements of all the particles recorded in the five field sequence over a total time interval of $4\Delta T$. Figure 1 shows two particle image displacement records encoded into a 100×100 pixel image. The amplitudes of the pixels marking the centroid positions increase from 2^1 at T=0, and 2^5 at $T=4\Delta T$. Amplitude coding unambiguously defines the particle's direction of travel. The amplitude coding also decreases the probability of mistakenly identifying a particle image from a different particle as being part of another particle displacement record. Another advantage of using single exposure particle images fields is the elimination of particle image overlap, which typically restricts the lower limit of velocities which can be measured. By individually processing the particle image fields, particle images with large diameters relative to their displacement between exposures are easily tolerated. The only constraint on the minimum velocity is that the particle must travel at least one pixel between exposures.

The time history image serves as the input to the PDT algorithm. The PDT algorithm begins by scanning the time history image and storing the locations of all pixels with amplitude 2^1, which corresponds to all particle positions at the initial field in the sequence. The particle positions at T=0 serve as the starting point for the displacement tracking. By determining the displacement of the particle from its initial position, the velocity information of the flow is inferred.

For each initial particle position, a circular search region is defined around the 2^1 amplitude pixel. Inside the search region, the coordinates of all pixels with amplitudes equal to 2^2 are scanned and stored. The 2^2 amplitude coded pixels correspond to the particle positions at $T=1\Delta T$, or exposure #2. The detected 2^2 amplitude pixels within the search region are now each successively analyzed. The distance and angle between each 2^2 amplitude pixel and the search region center 2^1 amplitude pixel is computed and used to project where the 2^3, 2^4, and 2^5 amplitude pixels are located which correspond to the 2^1 and 2^2 amplitude pixel particles; see figure 2. If the projected pixel locations for the 3rd, 4th, and 5th particle images contain the corresponding amplitudes (2^3, 2^4, 2^5) then a complete particle displacement record has been detected. The velocity vector associated with this particle is computed from the distance between the initial and final particle locations (2^1 and 2^5 amplitude pixels), and the sum of the four inter–exposure intervals ($4\Delta T$). The detected particle pixel amplitudes are then set to zero. If the projected particle locations detect the incorrect pixel amplitude or zero amplitude, then the 2^2 amplitude pixel within the search region is not the actual second image of the 2^1 amplitude pixel at the center of the search region. Each 2^2 amplitude pixel within the search region is examined until a complete particle displacement pattern is detected or all of the 2^2 amplitude pixels are exhausted. If no match is found, the algorithm continues on to the next initial particle position 2^1 amplitude pixel. In summary, for each 2^1 amplitude pixel, a circular search region is defined about that particle. All 2^2 amplitude pixels within the search region are assumed to be the position of the initial particle at the second exposure, and thus used to predict the successive locations of the particle at time sequence exposures 3, 4, and 5. No preknowledge about the flow system is required. The PDT system assumes that 2^2 amplitude pixels in the neighborhood of the initial 2^1 amplitude pixel are the most probable particle displacements between video fields #1 and #2 in the five field sequence. The maximum allowable particle displacement between exposures has previously been determined to be 10 pixels for sharply turning flows.[12] Ten pixel displacements between exposures minimizes the deviation of the particle path from a linear trajectory. Therefore, the search region size is defined to be a circle of radius 10 pixels; see figure 2.

The positioning error on the discrete grid must be accommodated in the PDT processing. As previously mentioned, the boundary processing technique provides particle centroid estimates to within $\pm \frac{1}{2}$ pixel on the 640×480 pixel time history image. For each projected particle position (for exposures 3, 4, 5) a 3×3 pixel search region is defined. The 3×3 search regions are centered on the projected positions; see figure 2. The expanded regions allow for the positioning error of $\pm \frac{1}{2}$ pixel. However, when a complete particle displacement pattern is detected, the exact location of the amplitude coded pixel within the 3×3 region is determined and used to determine the velocity vector magnitude. The velocity vector angle is computed from the position of the 2^1 and 2^5 amplitude pixels.

There are two sources of error in the PDT estimated velocities: 1) the particle positioning error; and 2) the time interval error. The time interval error is minimal, since the frame–grabber board is genlocked to the RS–170 video signal from the video camera. The major source of error is from the particle centroid estimates. The total relative error in the measured velocity is given by:[12]

$$\frac{\sigma_U}{U} = \left[\left[\frac{\sigma_X}{X}\right]^2 + \left[\frac{\sigma_T}{T}\right]^2\right]^{\frac{1}{2}} \tag{1}$$

where U is the estimated mean velocity magnitude, X is the total particle displacement from the first to last exposures, T is the sum of the four time intervals $4\Delta T$, σ_X is the rms error in the total particle displacement, and σ_T is the timing error. For the $\pm \frac{1}{2}$ pixel positioning error, the rms error in the total displacement is simply $1/\sqrt{2}$ pixels. A nominal estimate for the time interval error is one video scan line per acquired field, or roughly $5 \times 65 \mu$sec. Hence, for a 40 pixel total displacement and a total time interval of 2 seconds, the relative error in the estimated velocity is:

$$\frac{\sigma_U}{U} = \left[\left[\frac{1/\sqrt{2}}{40}\right]^2 + \left[\frac{325E-6}{2}\right]^2\right]^{\frac{1}{2}} \tag{2}$$

or

$$\frac{\sigma_U}{U} = 0.018$$

which is dominated by the positioning error. For the worst case corresponding to only a 4 pixel total displacement, the relative error in the estimated velocity magnitude is a factor of 10 larger, or $\sigma_U/U = 0.18$.

The error in the estimated velocity vector angle is similar to the magnitude error. The angular error is given by:[12]

$$\sigma_\theta = \text{ARCTAN}\left[\frac{\sigma_X}{X}\right] \tag{3}$$

where X and σ_X are the particle displacement and rms error in the particle displacement, respectively. Using the same displacement of 40 pixels, the angular error is:

$$\sigma_\theta = \mathrm{ARCTAN}\left[\frac{1/\sqrt{2}}{40}\right] \tag{4}$$

$$\sigma_\theta = 1.0^\circ$$

The worst case for the angle estimates is for the smallest displacements. The minimum displacement of 4 pixels yields an error of $\sigma_\theta = 10.0^\circ$.

A unique feature of the PDT technique is afforded by the use of a large memory buffer frame–grabber board which can digitize individual fields at 1/60 second intervals and store 25 sequentially acquired video fields. The 25 fields are grouped in successive sets of 5 fields and processed by the PDT technique described above. The five groups of 5 successive fields produce five 2–D velocity vector maps. Particles are tracked across all five groups, for all 25 fields. Hence, the composite 2–D velocity vector map will track particles for all five sampling intervals. Particles tracked for all 25 fields will be represented by a string of velocity vectors oriented head to tail, which indicates the particle path over the total measurement time of 24ΔT. Alternatively, the five 2–D velocity vector data sets can be successively displayed quickly on a computer screen to elucidate the flowing fluid pattern. Flowing fluid five frame movies of a time stationary flow system have been constructed; unfortunately, they cannot be displayed in this paper.

Equipment

The flow system used in this validation of the PDT technique is a prototype configuration of a future space shuttle mission called the Surface Tension Driven

Convection Experiment (STDCE). The purpose of the experiment is to study the behavior of heated free surface fluid flows in the absence of gravity. In the STDCE configuration discussed here, a 1cm diameter tubular heater is inserted into a cylindrical reservoir filled with silicone oil and seeded with 200μm pliolite particles. The silicone oil is index matched to the plexiglas reservoir. The reservoir width to height dimensions are 2:1, the width being 10cm. A 5 mW HeNe laser is used to provide a 1mm thick light sheet, which illuminates a radial cross section of the reservoir from the top; see figure 3. In operation, the tubular heater drives a toroidal convection cell flow, whose cross section appears as two counter rotating convection vortices. A Silicon Intensified Target (SIT) camera, oriented at 90‡ to the plane of the light sheet, is used to supply RS–170 video signals of the particle images. The exposure time of the SIT camera is 1/60 second.

An EPIX 4–MEG video frame–grabber board digitizes and stores the PIV images. The frame–grabber board is equipped with a 12.5MHz A/D oscillator so that interlaced 640×480 square pixel frames are digitized. The frame–grabber board can be configured to digitize individual fields or frames. In field mode the minimum sampling time is 1/60 second. When acquiring video fields, 27 fields can be acquired and stored in the 4 Megabyte on–board memory buffer. However, by using just fields, the vertical resolution is halved, producing a 640 pixel × 240 line image. The 240 lines are the even or odd fields from the RS–170 interlaced video signal. The reduced vertical resolution decreases the accuracy of the particle centroid estimates in the vertical direction, compared to the horizontal direction. The reduced vertical sampling is not a significant effect if the particle images encompass several pixels across their diameters.

The data acquisition software allows the selection of the inter–field acquisition time interval in multiples of 1/60 second. For low velocity flows many video fields are allowed to elapse between successively acquired images. For faster flows, adjacent fields can be acquired resulting in the minimum ΔT of 1/60 second. When acquiring adjacent fields, a gated camera is required to obtain sharp particle images, otherwise particle streaks will be recorded instead. For a 100×100 mm field of view, the image scale is roughly 175μm/pixel. At the minimum inter–exposure interval of 1/60 second, the maximum measurable velocity is roughly 100 mm/second.

The data acquisition and PDT processing are all performed on a 25MHz 80386 computer with a Weitek 3167 coprocessor. All of the PDT processing routines are written in Fortran 77 and compiled with a 32 bit Weitek supported compiler. Video images are stored on the hard disk and later transferred to removable cartridge disks for archiving.

Results and Discussion

A VHS video tape was made of the counter rotating convection vortex flow. Two 25 field data sets were digitized from the video tape. Each set of 25 fields were used to generate five sets of time evolved velocity vector maps. The first data sequence was obtained using a ΔT of 60 fields or 1 second intervals between successively acquired fields. The second data sequence was acquired with a ΔT of 30 fields, or 1/2 second intervals. Using two data sequences will effectively double the dynamic range in the measured velocity magnitudes. The PDT technique limits the maximum particle displacement between acquired fields to 10 pixels, thus the dynamic range is 10:1 for a single sequence. By digitizing two sequences with a ΔT ratio of 2:1, the dynamic range of the combined 2–D velocity vector maps will be doubled, or 20:1.

A sample image field obtained from the PDT system is shown in figure 4. Only the region within the fluid reservoir is shown, which corresponds to a digitized image size of 580 pixels × 143 lines. The scale of the digitized image is 172 μm/pixel. The recorded particle images were approximately $\leq$10 pixels in diameter, and their recorded intensities spanned essentially all of the 0–255 dynamic range. The tubular heater used to drive the flow was not placed exactly in the center. The amount of decentration is not obvious in figure 4, but will be evident in the 2–D velocity vector maps.

The acquired data sequences were boundary processed to determine the particle image centroids. A threshold level of 10 grey levels was used for all of the boundary processing.[12] For data sequence #1 the total boundary processing for all 25 fields was 45 seconds and approximately 320 particle centroids were detected on each field in the sequence. For data sequence #2, the total boundary processing time was 45 seconds with roughly 265 particles detected per video field. Next, the PDT processing was performed on the 10 time history encoded files generated from the boundary processing stage. The total PDT processing time was 16 seconds for all 10 images, or roughly 1.6 seconds per time history file. Hence, for a single five field image sequence, the total boundary processing/PDT processing time is roughly 11 seconds per data set. In the current discussion, each data sequence of 25 fields contained five data sets. For data sequence #1, a total of 629 velocity vectors were found; see figure 5a. For data sequence #2, 485 velocity vector were detected; see figure 5b. The velocity magnitude scales in both figures 5a and 5b are identical. In both 2–D velocity vector maps, sets of velocity vectors tail to head are observed. These are the velocity vectors from particles which were tracked over all 25 fields. The continuous tracking of particles can be used to make movies of the evolving flow as described above.

In the counter rotating flow, the velocity is lowest in the lower outside edges of the reservoir. The highest velocities occur next to the tubular heater near the fluid surface. Data sequence #1, with ΔT=1 second, shows more of the slow velocity vectors in the outside corners of the reservoir, and few velocity vectors next to the heater near the fluid surface. Data sequence #2, with $\Delta T=1/2$ second, contains fewer slow velocity vectors in the outside corners of the reservoir, but does show the higher velocities next to the heater near the fluid surface. The two data sets are combined in figure 6. A good sampling of both the high and low velocity vector magnitudes are contained in the combined data set. Figure 6 contains a total of 1114 velocity vectors. The minimum and maximum measured velocities were 0.17 ± 0.03 mm/s and 3.8 ± 0.06 mm/s , respectively. The error in the measured velocity vectors is proportional to the reciprocal of the total displacement.[12] The measured dynamic range in velocity magnitude for the combined data sequences was 22:1. The dynamic range is higher than expected due to the use of the 3×3 pixel search regions about the projected particle positions. The 3×3 pixel regions allow for 11 pixel displacements. There are a few falsely identified velocity vectors in figures 5a and 5b. The false identifications have occurred in regions of small displacement and high particle concentration. Some of the velocity vectors in the lower portion of the cell point downwards. These are not necessarily all false vectors, but are large particles which are settling out of the fluid. The falsely identified velocity vectors can be eliminated using smoothing techniques.

The randomly sampled data obtained using the PDT processing technique can be replotted on a regular grid using a simple interpolation technique. The 11 nearest neighbors to the grid point are used in a least squares estimate of the grid point velocity magnitude and direction. A 2–D, 32×32 interpolated grid of velocity vectors from the combination of data sequences #1 and #2 is shown in figure 7. The interpolated data clearly show the features of the counter–rotating vortex flow. The flow field is very symmetric about the tubular heater. The maximum velocities are observed along the fluid surface adjacent to the heater. The contribution from any falsely identified velocity vectors is diluted by the interpolation technique, yielding a good overall representation of the fluid pattern.

Conclusions

The PDT technique has been shown to be a fully automated electronic PIV data acquisition and analysis system. Video cameras have been shown to provide reasonably accurate velocity vector estimates. By using a large memory buffer frame–grabber board, 25 field image sequences are acquired and five frame movies can be generated. Alternatively, all five 2–D velocity vector maps can be combined into a single 2–D velocity vector map. All of the data acquisition and processing were performed on an 80386 PC. No array processors or other processing equipment was required. The total processing time was 11 seconds per data set. Ten data sets were processed and combined to produce a 2–D velocity vector map containing 1114 velocity vectors. Work is continuing on the PDT technique to make high velocity (>10m/s) measurements just as fast and simple as demonstrated herein. Also, the accuracy of the velocity estimates can be improved by encoding the sub–pixel particle positions in the amplitude coding.

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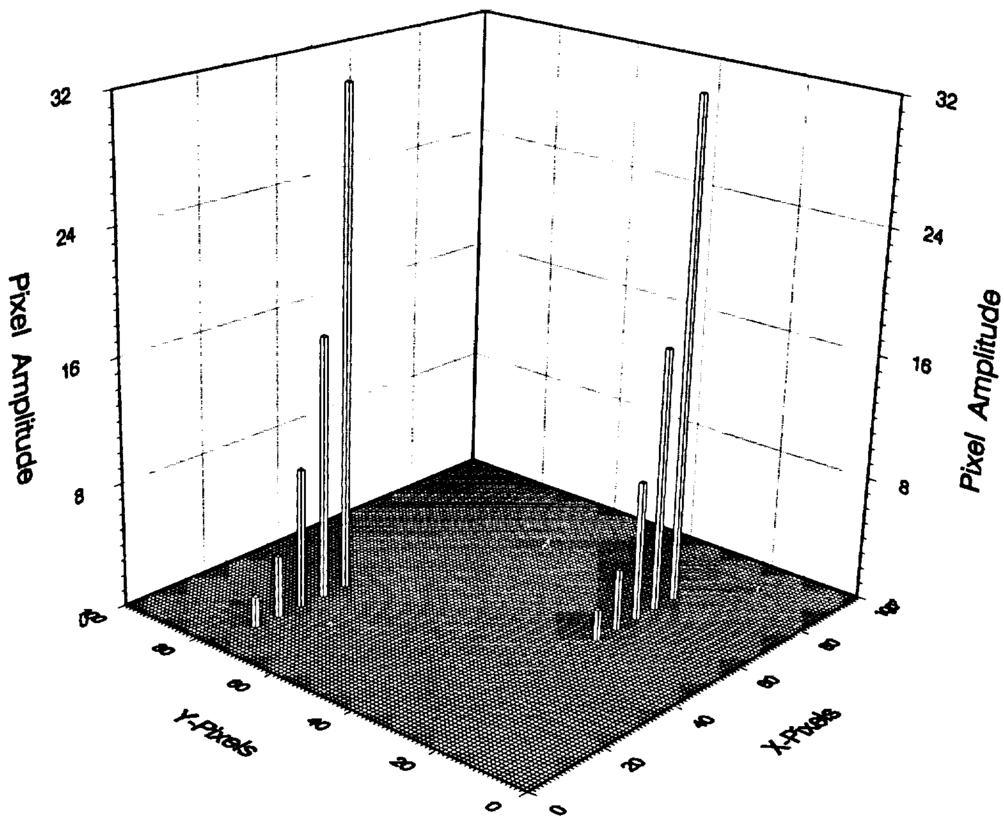

Figure 1 Two amplitude coded particle displacement patterns are shown in a 100×100 pixel grid. Particle positions from the video fields are determined to within a single pixel. The time order of a detected particle is coded in the pixel amplitude. Particles from field #1 are given amplitude 2^1, particles from field #2 are assigned amplitude 2^2, and so on for all five fields.

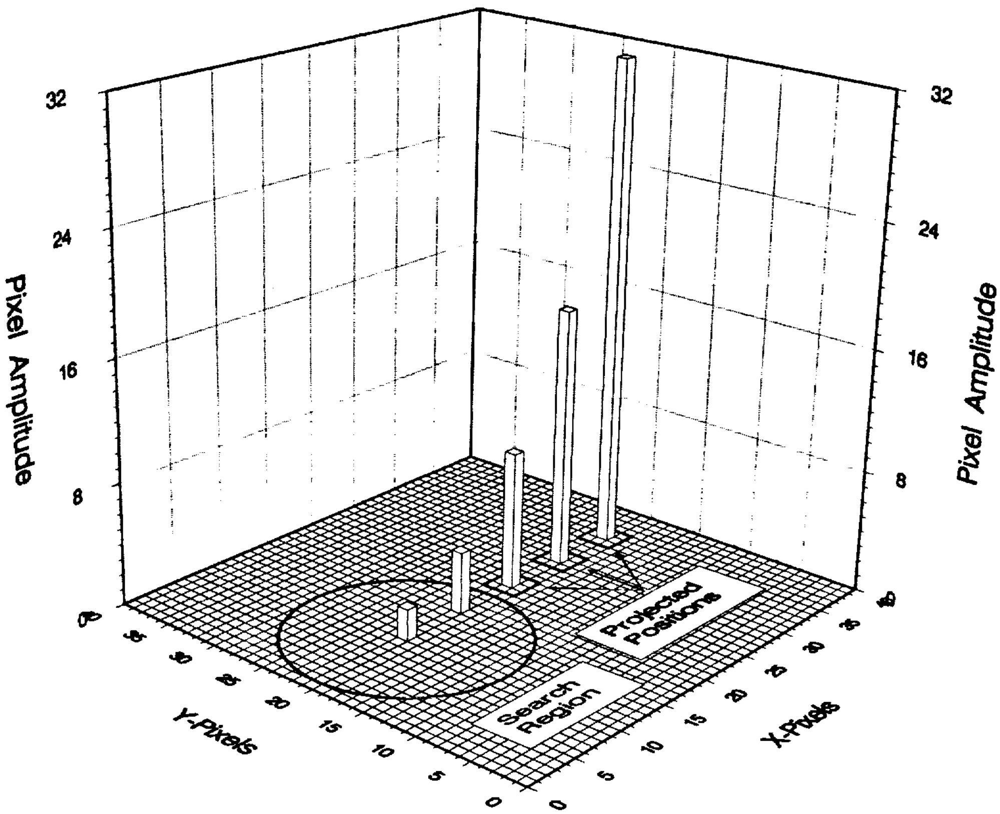

Figure 2 The PDT technique determines velocity vectors by defining a circular search region around each 2^1 amplitude pixel. All 2^2 amplitude pixels within the search region are detected. The distance and angle from the 2^1 amplitude pixel and all detected 2^2 amplitude pixels is used to project where the subsequent 3rd, 4th, and 5th exposure particle images will occur. The projected 3×3 pixel search regions are indicated in the figure.

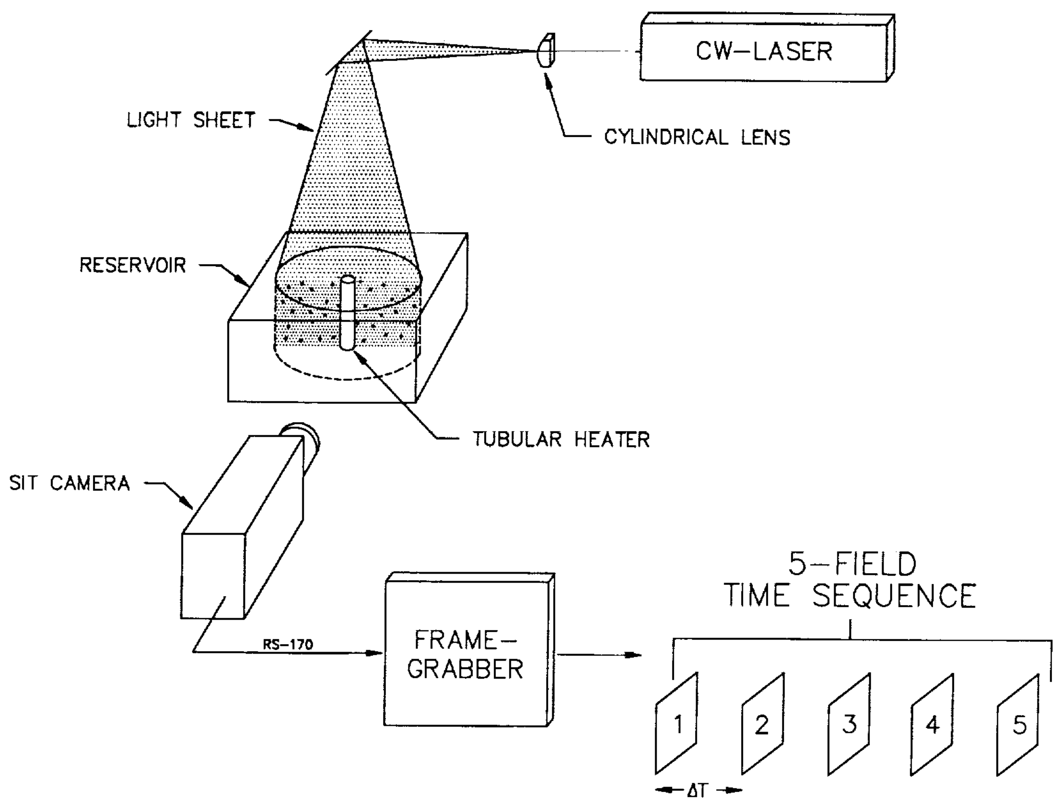

Figure 3 Schematic view of the light sheet illumination, fluid flow reservoir, and data acquisition and processing system. The tubular heater in the reservoir drives the flow. The frame–grabber board digitizes a sequence of video fields separated by ΔT, which is defined in integral multiples of 1/60 second.

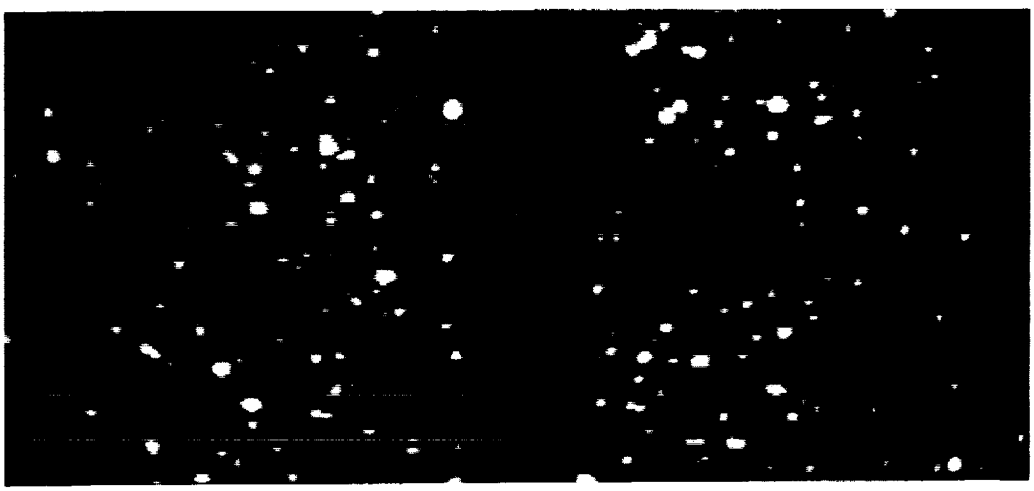

Figure 4 A sample video field acquired from the flow system. The particle images are 10 pixels and less in diameter. The image includes only the bounding edges of the fluid reservoir. The dark band in the center region of the reservoir marks the location of the tubular heater.

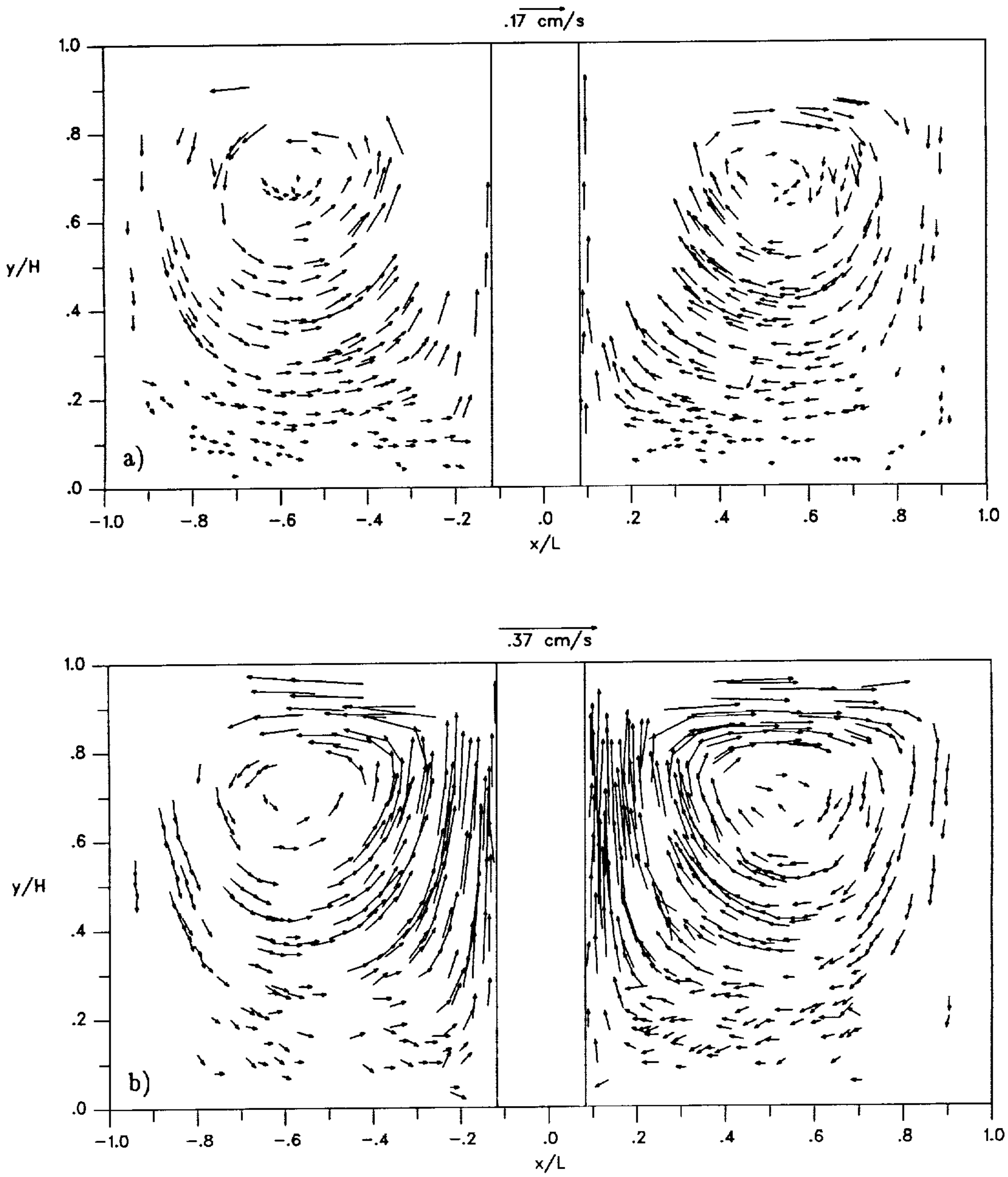

Figure 5 2–D velocity vector plots from the PDT processed data. The fluid surface is at a normalized height of 1. The velocity scale indicates the maximum velocity measured in the data sequence. Velocity vectors in the lower portion of the reservoir that cross paths are from larger particles which are not accurately following the flow. The location of the tubular heater is depicted by a blank rectangular region. The heater was not exactly centered in the reservoir. a) Data sequence #1. A total of 629 velocity vectors are shown. b) Data sequence #2. A total of 485 velocity vectors are observed in this plot. The highest velocity regions are next to the heater near the fluid surface.

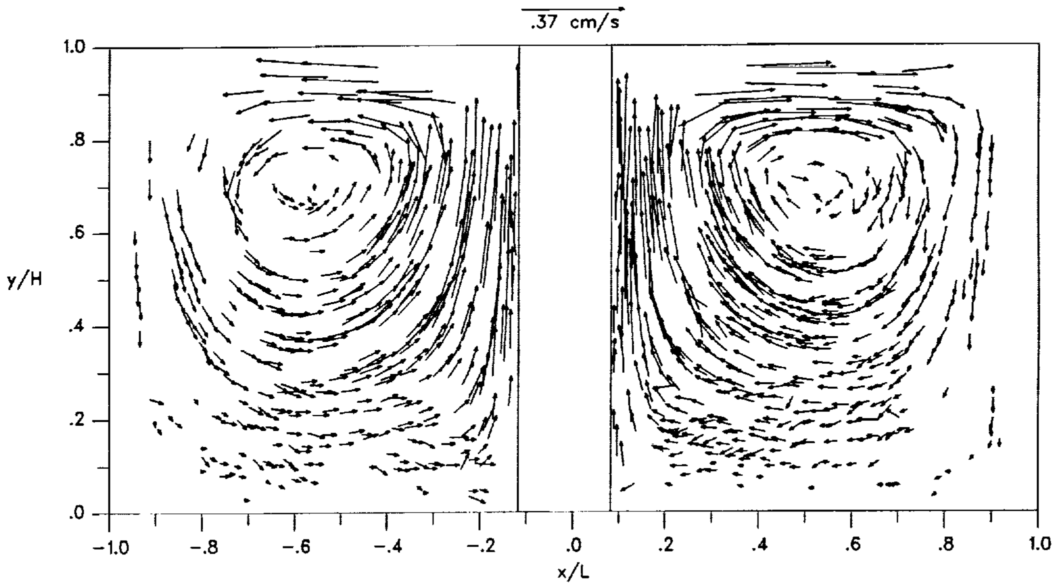

Figure 6 Combined data sequences #1 and #2. A large dynamic range of velocities have been recorded. Many sets of tail to head velocity vectors are observed, indicating particles which were tracked over the entire sampling period.

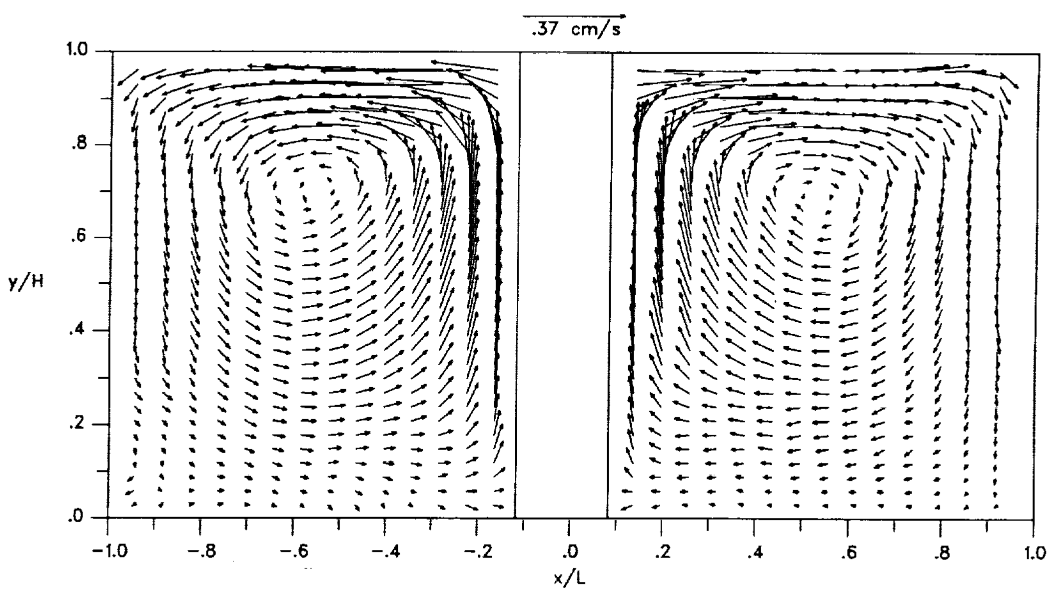

Figure 7 Interpolated 2–D velocity vector plot. The combined data from sequences #1 and #2 have been interpolated over a 32×32 grid. The interpolated data clearly show the counter rotating flow pattern.

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16. Abstract

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