Fuzzy Logic Enhanced Digital PIV Processing Software

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ABSTRACT

Digital Particle Image Velocimetry (DPIV) is an instantaneous, planar velocity measurement technique that is ideally suited for studying transient flow phenomena in high speed turbomachinery. DPIV is being actively used at the NASA Glenn Research Center to study both stable and unstable operating conditions in a high speed centrifugal compressor. Commercial PIV systems are readily available which provide near real time feedback of the PIV image data quality. These commercial systems are well designed to facilitate the expedient acquisition of PIV image data. However, as with any general purpose system, these commercial PIV systems do not meet all of the data processing needs required for PIV image data reduction in our compressor research program. An in-house PIV PROCessing (PIVPROC) code has been developed for reducing PIV data. The PIVPROC software incorporates fuzzy logic data validation for maximum information recovery from PIV image data. PIVPROC enables combined cross-correlation/particle tracking wherein the highest possible spatial resolution velocity measurements are obtained.

INTRODUCTION

Digital PIV provides near real-time flow field measurements through the use of refined data processing techniques combined with continuous increases in computational power and advances in CCD sensor technology. Digital PIV is a planar measurement technique that utilizes a pulsed laser light sheet to illuminate a flow field seeded with tracer particles small enough to accurately follow the flow. The positions of the particles are recorded on a digital CCD camera at each instant the light sheet is pulsed. In high-speed flows, pulsed Q-switched lasers are required to provide sufficient light energy (~100mJ/pulse) in a short time interval (<10 nsec) to record an unblurred image of the particles entrained in the flow. The data processing consists of determining either the average displacement of the particles over a small interrogation region in the image or the individual particle displacements between pulses of the light sheet. Knowledge of the time interval between light sheet pulses then permits computation of the flow velocity. Different data processing schemes are employed depending on the number of exposures per frame and the seed particle concentration. While each technique has some inherent benefits, the appropriate choice depends on the characteristics of the flow and recorded image constraints.

DPIV is being actively used at the NASA Glenn Research Center to study both stable and unstable operating points in the diffuser of a high speed centrifugal compressor. A commercial PIV system is used to provide near real time feedback of the acquired PIV image data quality, which facilitates the expedient acquisition of PIV image data. However, these commercial PIV systems do not meet all of the data processing needs required for PIV image data reduction in our compressor research program. Therefore, an in-house PIV PROCessing (PIVPROC) code has been developed for reducing PIV data. The PIVPROC software incorporates fuzzy logic data validation for maximum information recovery from PIV image data. PIVPROC enables combined cross-correlation/particle tracking wherein the highest possible spatial resolution velocity measurements are obtained. The PIVPROC software also supports batch processing of the large volumes of PIV data collected in the compressor research program.

The PIVPROC software has been used to reduce the data obtained from the successful application of digital PIV in a centrifugal compressor. Measurements have been obtained in the diffuser section of a 431 mm diameter 4:1 pressure ratio centrifugal compressor facility at GRC. Measurements were obtained from 6 to 95% span with the impeller running at the design speed of 21,789 rpm and 4.54 kg/s mass flow. Previous measurements using LDV could not get closer than 50% span to the hub surface in the small height passages (17 mm) in the diffuser. For a more detailed description of the PIV system used for image acquisition in the centrifugal compressor facility see reference 1. A discussion of the unstable operating point data obtained in the centrifugal compressor can be found in reference 2. A once-per-rev signal is used to synchronize the DPIV image capture with the impeller circumferential position. The PIVPROC software is being used to reduce the over 60 gigabytes of PIV image data obtained from the compressor facility. The PIV data are being used to construct phase-stepped, time-averaged velocity vector maps of the compressor flow. The improved data quality obtained via the fuzzy logic based data validation in the PIVPROC software will be presented. Also, particle tracking results will be shown which utilize the cross-correlation processed velocity vector maps as a guide in

the fuzzy logic based particle tracking.

PROCESSING PIV IMAGE DATA

Particle Image Velocimetry (PIV) is a technique for measuring the in-plane two-component velocity field of a flow seeded with tracer particles small enough to accurately follow the flow. A pulsed laser light sheet is used to illuminate the particles entrained in the flow, as shown in figure 1. The light scattered by the particles is collected normal to the plane of the light sheet and is imaged onto a photographic plate or a CCD camera, where the positions of the particles are recorded at each instant the light sheet is pulsed. Basically, there are three types of data reduction techniques used in PIV: auto-correlation, cross-correlation and particle tracking. The choice of a processing technique depends primarily on the available equipment used to record the particle image data and the seed particle concentration.
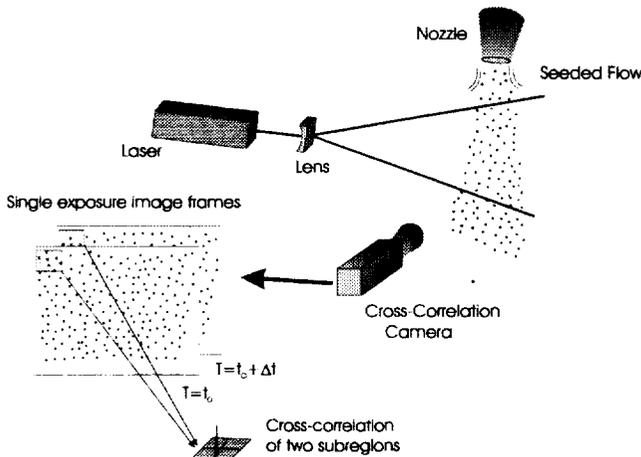

Figure 1 showing the main elements of a PIV system.

Correlation based processing techniques produce spatially averaged velocity estimates. The recorded image frame is divided into small subregions, each containing particle images. By processing the image over a regular grid of small subregions, a velocity vector map is generated. The optimum number of particles per interrogation region for PIV is nominally 10 image pairs[3].

In the auto-correlation technique a single image frame is exposed multiple times (≥ 2) and processed over a regular grid of small subregions. For a multiple exposure image, the average displacement of the recorded particle image pairs is determined by computing the auto-correlation of the subregion.

The 2-D auto-correlation is a symmetric function having a characteristic dc peak at the origin of the correlation plane and two satellite peaks, oriented symmetrically about the dc peak. Figure 2 shows a sample input double exposure subregion and the resulting auto-correlation plane output. The dc peak originates from the correlation of all of the

particle images in the subregion, hence the size of the dc peak is related to both the total number and size of the particles in the subregion[3]. The satellite peaks originate from the average displacement of the particle image pairs between exposures. In order for the displacement peaks to be discernable from the dc peak, the particle displacements must be greater than the average particle diameters across the subregion. This requirement places a dynamic range limitation on the auto-correlation technique. A second shortcoming is in the symmetry of the auto-correlation function. The existence of two diametrically opposed displacement peaks about the dc peak yields a 180 degree directional ambiguity in the velocity vector direction. The directionally ambiguity can be eliminated by imposing a dc offset on the particle image records, whereby the particle images are mechanically shifted between laser pulse firings[4]. Image shifting introduces extra complexity in the experimental setup and also additional errors due to optical path differences resulting from the image shift.
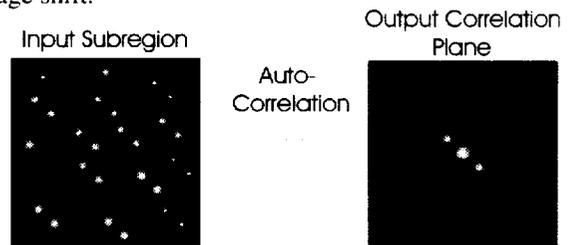

Figure 2: Double exposure input subregion and the corresponding output auto-correlation plane. Note the central dc peak and the symmetry of the auto-correlation function.

The second spatially averaged PIV data reduction technique, cross-correlation processing, is superior to the auto-correlation technique; however, this technique places more difficult demands on the recording system. In cross-correlation PIV, two single exposure image frames must be recorded. The standard convention is to use a cross-correlation camera which utilizes the "frame-straddling" technique first demonstrated on nozzle flows[5]. The cross-correlation operation is similar to auto-correlation where again the image frames are divided into small subregions. However, now a subregion from image #1 (recorded at the first laser pulse) is cross-correlated with a subregion from image #2 (recorded at the second laser pulse) as shown in figure 1. The resulting output on the correlation plane is a single peaked function, where the peak represents the average displacement of the particles across the subregion between the two laser pulses. Figure 3 shows a pair of input single exposure subregions and the resulting cross-correlation output plane. The direction of the displacement is determined unambiguously because the images from exposures 1 and 2 are recorded separately. Since there is no self-correlation peak, even zero particle displacements can be measured, hence, the cross-correlation technique provides a higher dynamic range

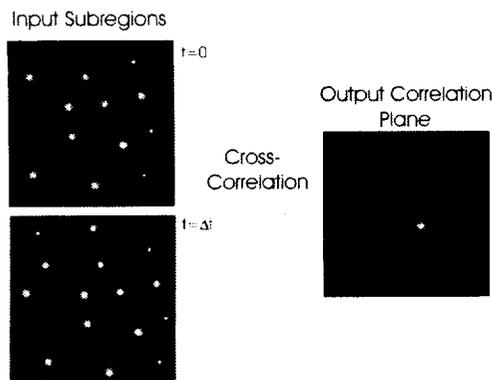measurement capability than the auto-correlation technique.

Figure 3: Two single exposure input subregions and the corresponding output cross-correlation plane. The location of the single bright correlation peak from the origin is the average displacement across the subregion.

In contrast to the spatially averaged correlation techniques discussed above, Particle Tracking Velocimetry (PTV) techniques attempt to identify the displacement of individual particles[5]. Typically, particle tracking techniques require lower seed particle concentrations than are used for correlation based processing. The lower seed particle images yield randomly distributed velocity vector maps with lower accuracy and fewer vectors than correlation processed vector maps.

Both single and double exposure imagery can be used in particle tracking algorithms. Single exposure data are again preferred since knowledge of the particle time history adds direction information, which aids in the tracking process. Most particle tracking techniques require more than two single exposure image frames in order to perform efficiently. For high speed flows, obtaining more than two single exposure image frames is difficult; therefore, multi-frame (>2) tracking techniques are not readily applicable to high speed flows. Correlation techniques succeed by extracting the average displacement of a group of particles in a subregion. In order for tracking techniques to succeed with only two single exposure image frames, information from the surrounding displacements must be used in the tracking operation. There are two approaches for extracting the individual particle displacements based on the surrounding particle displacements: fuzzy logic and neural networks. Fuzzy logic techniques utilize a rule base (flow continuity) for allowed particle displacements[6-7]. Particle pairs close together must move in similar directions and must have similar displacements. Neural Net approaches to data extraction rely on training the nets to identify patterns[8-9]. The nets must be trained on flows similar to those that they will be used to process. Determining the number of layers and training sets required for neural nets is a nebulous problem.

Alternatively, combining correlation and particle tracking techniques has been proposed to create a PIV data processing system which can cover a wide range of flow seeding conditions and offers the potential for "super-resolution" PIV measurements[10]. As mentioned above, particle tracking by itself is typically not capable of successfully tracking particles at the high seed particle densities normally used for auto- or cross-correlation analysis. Conversely, correlation techniques must use large subregion sizes, with a concomitant reduction in spatial resolution, in order to perform adequately in the low seed particle density regimes where particle tracking techniques are normally applied. In the combined technique, correlation analysis is used first to obtain a benchmark velocity vector map, which then serves as a guide for the particle tracking operation. Hence, highly seeded flow field images can be processed with small correlation subregion sizes, and then the spatial resolution of the measurements improved by following with particle tracking. For moderately seeded flow field images, the correlation subregion size is increased so that a good velocity vector map is obtained, and then this is followed by particle tracking in order to obtain high spatial resolution measurements. For low-seed particle concentration cases, the standard particle tracking technique can be used alone. Low seed particle concentrations are where the average distance between particle pairs is larger that the average particle displacements between exposures. The first demonstration of the combined correlation/particle tracking technique was performed on a supersonic nozzle flow[7]. A high seed density flow was processed to obtain over 2300 individual velocity vectors in a 300 mm^2 area.

Using the combined correlation processing/particle tracking technique determines the individual particle displacements for even high seed particle concentration flows, yielding the highest spatial resolution velocity measurements possible. A super-resolution correlation-based technique has been described, which claims spatial resolution on the order of the particle size[11]. This claim does not appear appropriate, since the limiting spatial resolution is physically bounded by the particle displacement between exposures. Hence, the combined correlation processing/particle tracking approach yields the ultimate spatial resolution velocity measurements for seeded flow fields.

FUZZY LOGIC PROCESSOR APPLIED TO PTV
The control of complex processes has been aided by the development of fuzzy control systems. Fuzzy control systems have been used to control traffic flow, appliances, and even subways for optimal energy efficiency and passenger comfort. Fuzzy logic employs a tolerance for imprecision to achieve system control. An exact model for the system inputs and outputs is not required. Fuzzy inference control utilizes membership functions and a rule

base developed by the user to process information. The physical mechanisms underlying the process are irrelevant to the controller. The process of identifying and tracking particles in a flow is a good candidate for fuzzy control since the procedure is not clear cut, but involves some gray area decisions. Fuzzy logic principles have been used to track particles directly in low seed particle concentration flows, to validate correlation peaks in correlation processing, and to perform particle tracking in the combined correlation processing/particle tracking approach for high seed particle concentration flows.

In the discussion that follows, the use of fuzzy logic to track particles in a low seed particle concentration case will be described. The extension of the approach for correlation peak validation and for combined correlation processing/particle tracking is straightforward. In the fuzzy logic particle tracking technique, local particle displacement information is used to identify candidate particle tracks. The fuzzy inference processor is used to determine the most probable particle trajectories based on common sense rules that an observer would use to identify particle tracks.

The experiment is set up such that two single exposure image frames are acquired. The particle centroids on frame #1 are used as starting points for possible particle displacements. The user specifies a search region radius, R_s, typically 10-20 pixels, to search for frame #2 particles. Each frame #2 particle within a radius R_s from the initial particle centroid is a candidate displacement vector. All possible displacements of the initial particle to the second particle locations within the search region are recorded and stored as lists of candidate displacement vectors for each initial particle. Hence, for high data density areas, many initial particles may be competing for the same second exposure particle centroids. At this stage in the processing, the vector field is very convoluted and noisy. The fuzzy inference processor operates on these lists of candidate displacement vectors to determine the most likely displacement vector for each initial particle centroid location.

The list of vectors for each initial particle is compared to all other initial particle displacement vector lists to determine if there is any commonality. If two separate initial particles do claim the same second exposure particle, then all possible vector pairings between the candidate lists for each of these initial particles are compared. The main assumption is that if two initial particles are close enough to interact (claim the same second particle) then the pair of vectors that look the most similar (in direction and magnitude) must be the correct pair of displacement vectors for the two separate initial particles. This assumption also holds for tertiary and higher interactions.

There are four inputs to the fuzzy PTV processor for each vector pair: distance between the vector midpoints in pixels (Sep); average vector magnitude (Mag); difference in vector magnitudes (MagDif); and the sum of the squares of the differences of the x- and y-components of the two velocity vectors (Delta). The first (Sep) and third (MagDif) measures, when combined, act as a velocity gradient measure. The last measure operates in the opposite manner to the dot product. This measure is small when the vectors are similar in magnitude and direction and large when they are different. Each input measure is assigned to a fuzzy set, where the degree of membership for each element in the set varies between 0 and 1. Standard 25-50% overlapping triangular input membership functions are used[6]. The degrees of membership for each input are processed through a rule base of "IF...THEN" blocks. The rule base defines an output fuzzy set. For a given vector pair, up to 16 rules may fire depending on the number of unique combinations of membership values. In lieu of the more common centroiding technique, the fuzzy PTV processor output is computed via the singleton technique with a weighted average, which is computationally simpler.

For example, given two pairs of vectors formed from two initial points competing for the same second particle as shown in table 1 and in figure 4:

	X_i	Y_i	$\overline{V}$ [pixels]	$\theta°$
V_1	100	100	8.5	45
V_2	100	100	11	30
V_3	105	100	6	81
V_4	105	100	7.1	51

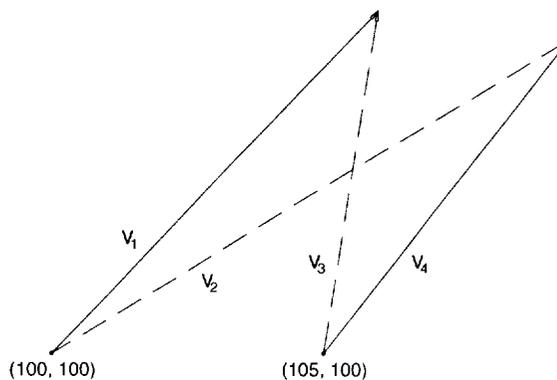Table 1: Sample data for an interacting pair of vectors.

Figure 4: Two pairs of interacting vectors with separate initial points. Dashed line indicates incorrect vectors, solid line denotes correct vectors.

From the data in table 1 we find the following combinations, and their respective input measures to the membership functions:

	Sep	Mag	MagDif	Delta	Confidence
V_1V_3	2.5	7.3	2.5	25	0.24
V_1V_4	4.3	7.8	1.4	2.5	0.67
V_2V_3	1.7	8.5	5	71.6	0.11
V_2V_4	2.6	9.0	3.9	24.4	0.24

Table 2: Fuzzy processor input measures and outputs for sample vector pair combinations

Looking at the first case, V_1V_3 has the fuzzy set memberships: Sep {μ_{small}=0.875, μ_{Med}=0, μ_{Large} =0}; Mag { μ_{small}=0.276, μ_{Med}=0.724, μ_{Large}=0}; MagDif {μ_{small}=0.504, μ_{Med}=0, μ_{Large}=0}; Delta {μ_{small}=0, μ_{Med}=0, μ_{Large}=1}. With these fuzzy sets the following rules are fired:

IF(Sep=Small AND Mag=Small AND MagDif=Small AND Delta=Large) THEN
        Conf_Out$_1$=Med
        μ_out$_1$=MIN(μ_{Sep}=Small, μ_{Mag}=Small,
                    μ_{MagDif}=Small, μ_{Delta}=Large)
END IF

IF(Sep=Small AND Mag=Med AND MagDif=Small AND Delta=Large) THEN
        Conf_Out$_2$=Low
        μ_out$_2$=MIN(μ_{Sep}=Small, μ_{Mag}=Med,
                    μ_{MagDif}=Small, μ_{Delta}=Large)
END IF

The fuzzy "AND" of the memberships in rule #1 gives μ_out$_1$=0.276 and rule #2 gives μ_out$_2$=0.504. Using Conf_Out values of LOW=0.1 and MED=0.5, the corresponding fuzzy processor output for this vector pair is computed as:

$$\text{Confidence} = \frac{\sum_{i=1}^{N_R} \text{Conf\_Out}_i \cdot \mu\_out_i}{\sum_{i=1}^{N_R} \mu\_out_i} \qquad (1)$$

$$\text{Confidence} = \frac{0.5 \cdot 0.276 + 0.1 \cdot 0.504}{0.276 + 0.504} = 0.24 \qquad (2)$$

where N_R is the number of fired rules. The fuzzy processor output confidence level in each vector pair is shown in table 2. For the vector pairs listed, the V_1V_4 pair has the highest confidence level of all the combinations. In the actual implementation of the fuzzy processor, pairings V_1V_3 and V_2V_4 are not permitted since in both of these cases independent initial particles are competing for

the same second exposure particle, hence these pairings will not produce a valid pair of vectors. Initially, all of the vectors are assigned a confidence level of 0. The computed confidence level for the vector pair is compared against the current confidence level for each vector in the pair, and the maximum confidence value is stored for each vector. When all of the interacting vector pairs have been analyzed, the list of candidate vectors for each initial point will have confidence levels relative to one another. The vector in the list with the highest confidence level is assumed to be the most probable vector for the current initial point and is moved to the top of the list.

FUZZY LOGIC PEAK DETECTION
The correlation processing technique requires identification of the correlation peak on the correlation plane corresponding to the average displacement of particles across the subregion. Noise on the images and particle dropout contribute to spurious peaks on the correlation plane, leading to misidentification of the true correlation peak. The subsequent velocity vector maps contain spurious vectors where the displacement peaks have been improperly identified. Typically these spurious vectors are replaced by a weighted average of the neighboring vectors, thereby decreasing the independence of the measurements. In the PIVPROC program, fuzzy logic techniques are used to determine the true correlation displacement peak even when it is not the maximum peak on the correlation plane, hence maximizing the information recovery from the correlation operation and minimizing the number of spurious velocity vectors. Correlation peaks can be correctly identified in both high and low seed density cases. The correlation velocity vector map can then be used as a guide for the particle tracking operation. Fuzzy logic techniques are used to identify the correct particle image pairings between exposures to determine particle displacements, and thus velocity. The advantage of this technique is the improved spatial resolution that is available from the particle tracking operation. Particle tracking alone may not be possible in the high seed density images typically required for achieving good results from the correlation technique. This two staged approach offers a velocimetric technique capable of measuring particle velocities with high spatial resolution over a broad range of seeding densities.

The particle tracking fuzzy inference engine has been used in the PIVPROC program to detect the correct auto- and cross-correlation plane displacement peaks. Ideally, when the image data are of high quality and high seed density the highest amplitude peak on the correlation plane represents the average displacement of particles across the subregion being processed. An example of a high signal to noise case was shown in figure 3. However, particle out-of-plane motion, velocity gradients, image noise, and low particle concentration are all contributing sources for a noise peak to be misidentified as the average particle

displacement across the subregion. In these cases the peak corresponding to the average motion of the particles across the subregion between exposures is not the highest amplitude peak, and possibly not even the second highest amplitude peak on the correlation plane. Figure 4 shows a pair of noisy input subregions and the resulting correlation plane output. Vectors have been drawn on the correlation plane indicating the possible displacement vectors that could be derived from this correlation result. The correct average particle displacement for the subregions is the same as the case shown in figure 3, down and to the right. However, as is observed on the correlation plane, the brightest peak is not the one corresponding to the average displacement across the subregion. The brightest peak is up and to the right, yielding an incorrect estimate of the local flow velocity.
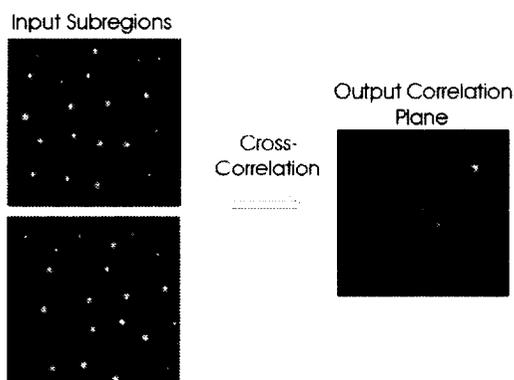
Input Subregions

Figure 4: Noisy input subregions result in spurious peaks on the correlation plane. The brightest peak is not always the correct displacement peak.

In the actual PIV processing, each correlation plane is scanned for the 5 highest amplitude peaks, which are then stored. After all subregions in the image have been processed, the fuzzy inference operation is applied. The five highest amplitude peaks detected on each subregion correlation plane are treated as candidate velocity vectors for that subregion. The fuzzy logic processor uses flow continuity to determine the appropriate correlation peak. The stored correlation peaks from each subregion are compared on a pairwise basis to the surrounding 4 subregion results. The displacement peaks resulting in velocity vectors with the most similar qualities are given the highest confidence weighting. The highest confidence weighting velocity vector for each processed subregion is taken as the correct correlation displacement peak. Hence, the fuzzy inference technique is very similar to the weighted average replacement technique, except that the surrounding velocity vectors are used to identify the correct displacement peak from the correlation information, instead of merely replacing the spurious vector.

A comparison of actual flow field image data processed with and without the fuzzy peak detection is shown in

figure 5. The main flow direction is down and to the right. The vectors with hollow heads represent displacements that were correctly identified by both processing techniques. The original spurious vectors are shown with open line vector heads. The vectors with solid filled heads represent displacements that were initially incorrectly identified, but have been subsequently correctly identified by the fuzzy processor.
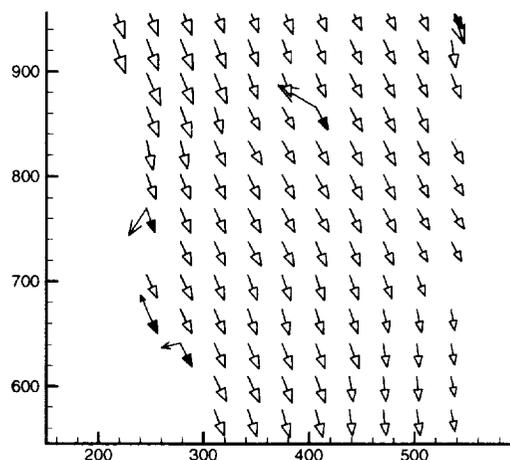

Figure 5: A vector field containing spurious vectors, which have been correctly identified using the fuzzy processor.

CORRELATION PROCESSING COMBINED WITH FUZZY LOGIC PARTICLE TRACKING

The availability of a high quality velocity vector map obtained from the cross-correlation operation offers the opportunity to perform particle tracking on length scales smaller than the correlation subregion size. Instead of using the nearest neighbor and flow continuity approach to track particles, the correlation velocity vector map can be used as a guide for the particle tracking. Using the same two single exposure image frames from the computed cross-correlation step, the first exposure image is scanned for particle centroids. All second exposure particles located within a user specified search region around each first exposure particle are detected and stored. Next, the fuzzy inference engine is employed to determine which detected particle pairings are correct. The first exposure particles and their associated list of candidate second exposure particles are now individually examined. The four nearest neighboring velocity vectors from the cross-correlation vector map to the initial particle location are found and used to compute a spatially weighted mean velocity vector, called a "benchmark vector". The benchmark vector is then used in a pairwise fuzzy comparison with all of the candidate vectors in the list for this initial particle. The candidate vector most similar to the benchmark vector, is assigned the highest confidence weighting. Benchmark vectors are computed for all remaining initial particle locations and used to identify the

most probable velocity vector for each initial particle. Proceeding in this manner the correct particle pairs for all of the initial exposure particles are determined. In practice, the particle pair operation has a success rate of approximately 30%. In some good quality PIV imagery, pair rates higher than 50% are not uncommon.

PROGRAM INTERFACE & PROCESSING

All of the data processing routines used in PIVPROC are written in FORTRAN. The user interface is created and serviced using Microsoft Windows Application Programming Interface (API) function calls. PIVPROC starts out by creating a full screen window with a white client area (workspace). Across the top of the page is the main task bar. All of the data processing, analysis and display features of the program are accessed via the main task bar. Dialog boxes are used to change the image settings and to set the correlation processing parameters. The image settings dialog box enables the user to select the gain of the image and threshold level. The images can also be left/right reversed and flipped vertically. These features are convenient if the image acquisition camera is mounted in a non-standard manner relative to the flow field of interest, or for viewing the illuminated plane through a mirror. The correlation settings dialog box is shown in figure 6. Here the user can set the subregion size, spacing between subregions and subregion image shifting.
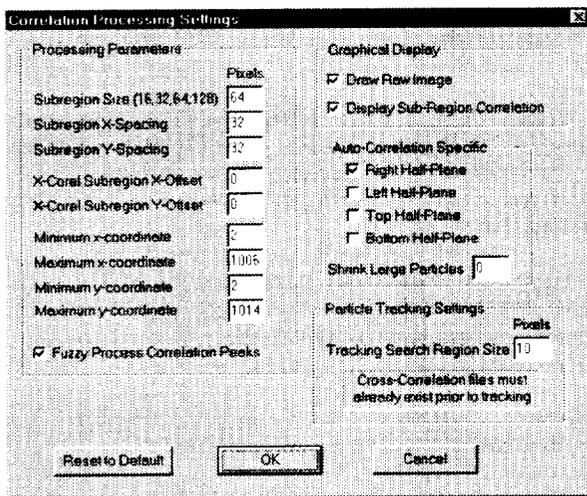

Figure 6: Correlation processing dialog box.

The maximum displacement on the correlation plane is limited by the subregion size. To avoid aliasing in the correlation plane, the displacement search region must be restricted to ¼ of the subregion size[3]. The easiest method for dealing with large displacements is to increase the correlation subregion size. However, this results in substantially increased processing times due to the larger subregions.

The best approach for processing single exposure PIV imagery that have a fairly constant displacement across the

entire image is to use subregion shifting in the data processing procedure[12]. In cross-correlation processing, the second correlation subregion can be spatially shifted with respect to the first subregion by an amount equal to the mean flow displacement between exposures, which keeps the correlation peak at the center of the correlation plane and minimizes any distortion effects caused by the windowing of the FFT based correlation operation. Image shifting has another very important benefit: shifting the second subregion window by the mean flow velocity significantly increases the probability that the particles that were in the first image frame subregion will be in the second image frame subregion. If the number of particles entering and leaving the subregions are reduced, then the false correlation rate is also reduced. Employing subregion shifting also enables the use of smaller interrogation regions (yielding faster processing times), provided the smaller subregions still contain a sufficient number of particles to provide a correlation result. Hence, particle seed concentration determines if the image shifting combined with smaller correlation subregions is a possible processing strategy for a given data set.

In the correlation processing modes, the user can select between Point Processing, Line Processing, Region of Interest or Entire Image. The portion of the raw image loaded into memory that is currently being processed via a correlation operation is displayed at the side of the image. In addition to the image subregion, the output correlation operation on the subregion is plotted, see figure 7. The x and y-displacements of the correlation peak, corresponding to the average particle displacement on the subregion are displayed on the client area below the correlation output.

The Point Processing mode is intended to be a diagnostic mode to determine the optimal image and correlation settings for processing the image. Moving the mouse around on the image space updates the pointer position display just above the image. Each time the left mouse button is clicked, a correlation operation is performed at that location on the image. The image subregion being processed is displayed along with the correlation output plane. A sample of the client area after a Point operation has been performed is shown in figure 7. Note the correlation subregion and output correlation plane to the right of the image. The bright spot on the correlation output plane corresponds to the average particle displacement across the subregion. A peak centered in the correlation plane corresponds to zero velocity across the subregion.

The data shown in these figures is from the application of PIV to the diffuser region of a high speed centrifugal compressor. The nominal flow velocity is 350 m/s and the impeller tip speed is 490 m/s. The time between laser pulses is 1.8 µs. The imaged field of view is approximately 45x45 mm. The light sheet propagates up

through the diffuser passage. The diffuser vanes are not readily observed in the figures.

The Line Processing mode is intended to be a diagnostic tool for looking at flow profiles in the particle image data. Click the left mouse button at two locations on the image and a series of correlations are performed along the line connecting the two mouse click locations, as shown in figure 8. More than one line of correlations can be computed. The image subregion being processed is displayed along with the correlation output plane.

Region of Interest processing mode enables the user to select only a portion of the image to be processed. The Entire Image processing mode processes the entire image. In both of these modes the current subregion being processed and the corresponding correlation output plane are displayed on the screen in real time. A sample of the Region of Interest processing mode output is shown in figure 9, where over 300 valid vectors were found. Spurious vectors are obtained outside the region of the light sheet.

The Particle Tracking operation can only be performed after a correlation velocity vector map is obtained. Using the correlation vector map obtained from figure 9, a particle tracking operation was performed. The resulting particle tracking velocity vector map is shown in figure 10, where over 3400 velocity vectors have been tracked. The particle tracking result has a much higher spatial resolution than the spatially averaged correlation result.

In addition to the correlation and particle tracking operations, the PIVPROC program can be used to edit the velocity vector maps or interpolate the randomly sampled particle tracking data over a uniform grid. The vector maps displayed on the screen can be sent to a printer to generate a hardcopy. In the manual vector removal mode, the velocity vector data are displayed on the screen, and the current location of the mouse pointer is displayed just above the vector plot. Position the mouse pointer over the tail of the velocity vector to be removed. Click the left mouse button and the vector is deleted, both from the screen and from memory.

CONCLUSIONS

A description of the main processing features of a PIV data reduction software package has been presented. The principles of fuzzy logic are used to maximize the information recovery from PIV image data and also to facilitate combined correlation processing/particle tracking. The combined correlation/particle tracking technique yields the highest spatial resolution velocity measurements possible from the PIV image data. A description of the PIVPROC user interface was given, along with examples of the dialog boxes used to set the processing parameters. Examples of using the PIVPROC

software to process PIV image data from a high speed centrifugal compressor have been presented. Particle tracking results were shown to have much higher spatial resolution than the correlation results.

REFERENCES

[1] Wernet, M. P., "Digital PIV Measurements in the Diffuser of a High Speed Centrifugal Compressor", AIAA-98-2777, *Advanced Measurement and Ground Testing Technology Conference*, Albuquerque, NM, June 15-18, 1998.

[2] Wernet, M. P. and Bright, M. M., "Dissection of Surge in a High Speed Centrifugal Compressor Using Digital PIV", AIAA-99-0270, 37th AIAA Aerospace Sciences Meeting, Reno, NV, January 11-14, 1999.

[3] Adrian, R. J., "Multi-Point Optical Measurements of Simultaneous Vectors in Unsteady Flow -A Review", *Int. J. of Heat and Fluid Flow*, Vol. 7, pp 127-145, 1986.

[4] Landreth, C. C., Adrian, R. J., Yao, C. S., "Double Pulsed Particle Image Velocimeter with Directional Resolution for Complex Flows", *Experiments in Fluids*, Vol. 6, pp119-128, 1988.

[5] Wernet, M. P., "Particle Displacement Tracking Applied to Air Flows", *Fourth International Conference on Laser Anemometry*, Cleveland, OH, pp 327-335, August 5-9, 1991.

[6] Wernet, M. P. "Fuzzy Logic Particle Tracking Velocimetry", *Proceedings of the SPIE conference on Optical Diagnostics in Fluid and Thermal Flow*, San Diego, California, July 11-16, 1993.

[7] Wernet, M. P., "Fuzzy Inference Enhanced Information Recovery From Digital PIV Using Cross-Correlation Combined with Particle Tracking", *Proceedings of the SPIE conference on Optical Diagnostics in Fluid and Thermal Flow*, San Diego, California, July 9-14, 1995.

[8] Cenedese, A., Paglialunga, A., Romano, G. P., Terlizzi, M., "Neural Net for Trajectories Recognition in a Flow", *Sixth International Symposium on Applications of Laser Techniques to Fluid Mechanics*, Lisbon, Portugal, July 20-23, pp27.1, 1992.

[9] Grant, I., "Particle Imaging Velocimetry: a Review", *Proc. Instn Mech Engrs*, Vol. 211, Part C, pp 55-76, 1997.

[10] Keane, R. D., Adrian, R. J. and Zhang, Y., "Super-Resolution Particle Imaging Velocimetry", *Meas. Sci. Technol.*, Vol. 6, pp754-768, 1995.

[11] Hart, D. P., "Sparse Array Image Correlation", *Proc. of the 8th International Symposium on Applications of Laser Techniques to Fluid Mechanics*, Lisbon, Portugal, 1998.

[12] Westerweel, J., "Fundamentals of Digital Particle Image Velocimetry", *Meas. Sci. Technol.*, Vol. 8, pp 1379-1392, 1997.
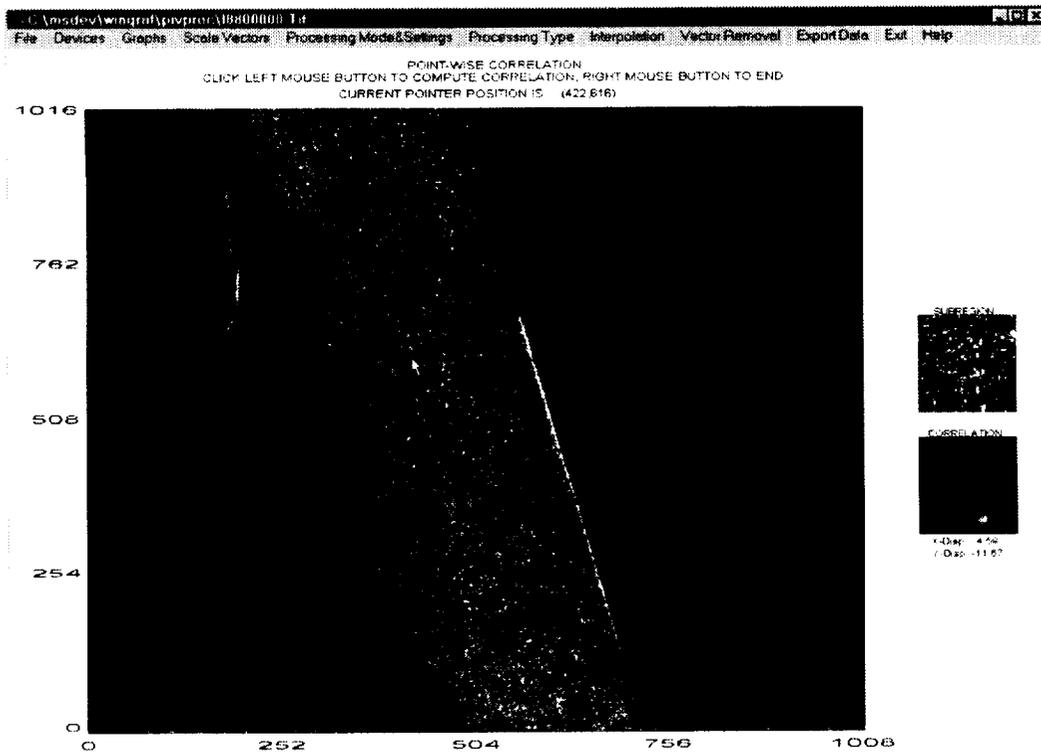
Figure 7: Point Processing mode showing the raw image file. The correlation subregion and correlation output plane are shown to the right of the image. The image data shown are from measurements obtained in the diffuser of a high speed centrifugal compressor. The impeller is observed to the left of the light sheet.
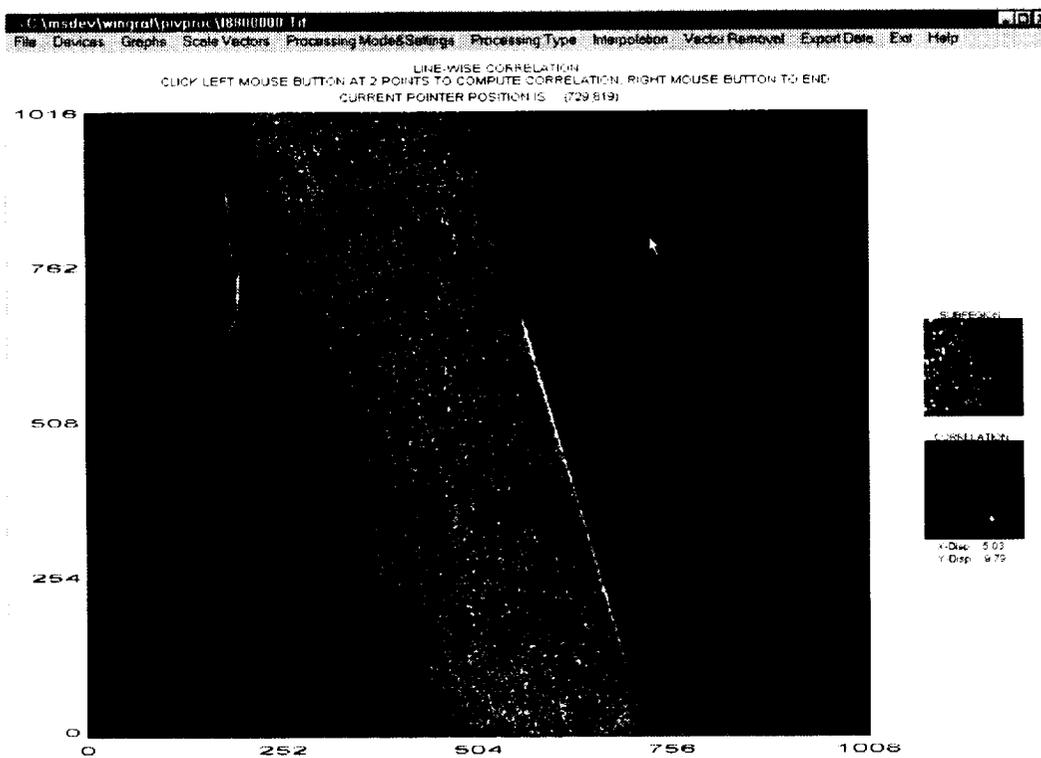

Figure 8: Line Processing mode showing the line of computed velocity vectors overlaid on the raw image file.
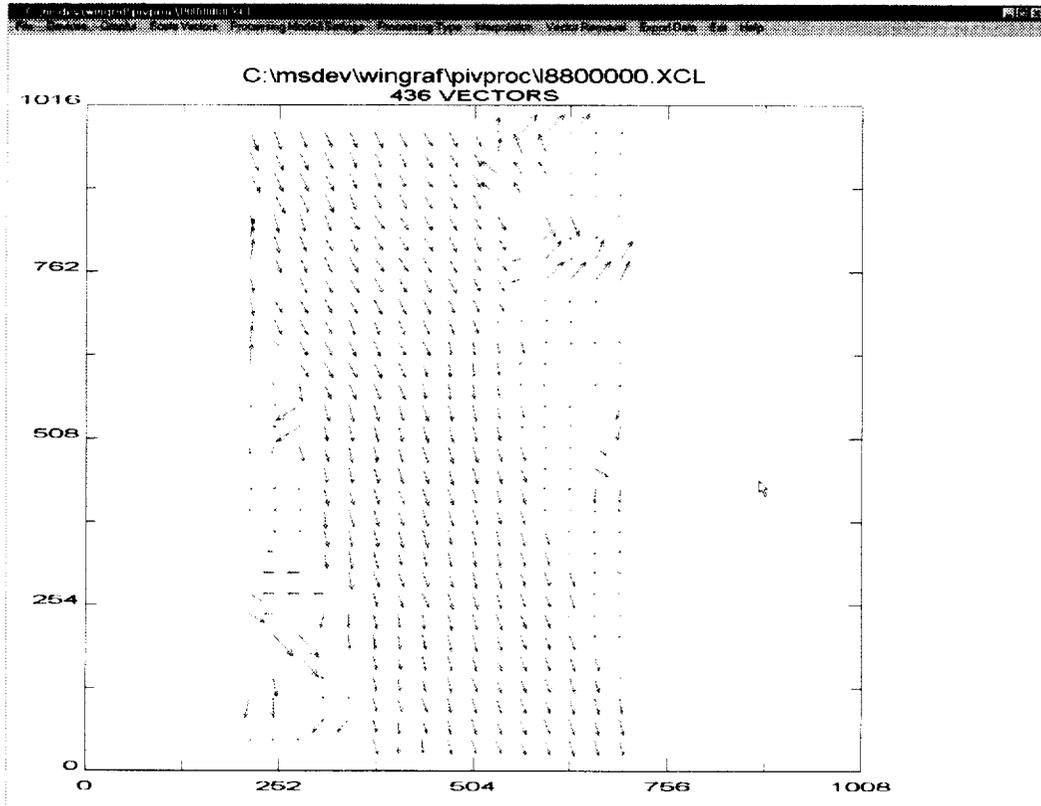
Figure 9: Region of Interest correlation processing result. Approximately 300 good vectors have been detected. Spurious vectors occur outside of the light sheet.
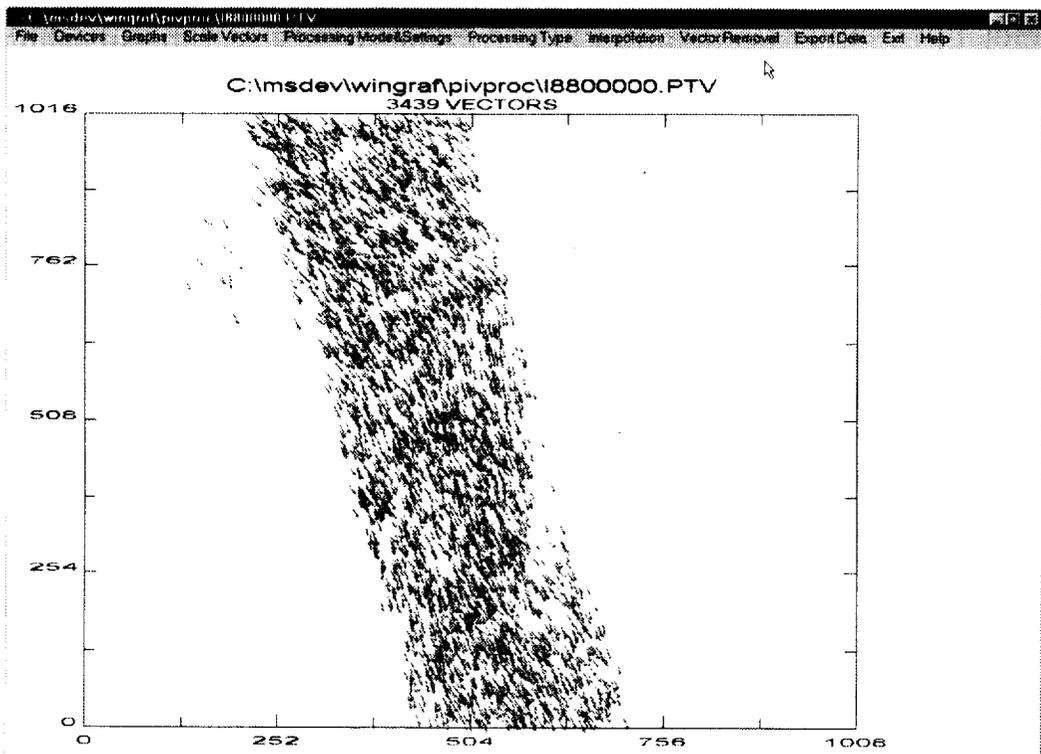

Figure 10: Particle tracking result using correlation processing vector map from figure 9 above. Over 3400 vectors have been detected.

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13. ABSTRACT (Maximum 200 words)

Digital Particle Image Velocimetry (DPIV) is an instantaneous, planar velocity measurement technique that is ideally suited for studying transient flow phenomena in high speed turbomachinery. DPIV is being actively used at the NASA Glenn Research Center to study both stable and unstable operating conditions in a high speed centrifugal compressor. Commercial PIV systems are readily available which provide near real time feedback of the PIV image data quality. These commercial systems are well designed to facilitate the expedient acquisition of PIV image data. However, as with any general purpose system, these commercial PIV systems do not meet all of the data processing needs required for PIV image data reduction in our compressor research program. An in-house PIV PROCessing (PIVPROC) code has been developed for reducing PIV data. The PIVPROC software incorporates fuzzy logic data validation for maximum information recovery from PIV image data. PIVPROC enables combined cross-correlation/ particle tracking wherein the highest possible spatial resolution velocity measurements are obtained.

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