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Technical Support Package

Digital PIV Measurements of Flow in a Centrifugal Compressor

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for

DIGITAL PIV MEASUREMENTS OF FLOW IN A CENTRIFUGAL COMPRESSOR

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DIGITAL PIV MEASUREMENTS IN THE DIFFUSER OF A HIGH SPEED CENTRIFUGAL COMPRESSOR

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ABSTRACT

Particle Imaging Velocimetry (PIV) is a powerful measurement technique which can be used as an alternative or complementary approach to Laser Doppler Velocimetry (LDV) in a wide range of research applications. PIV data are measured simultaneously at multiple points in space, which enables the investigation of the non-stationary spatial structures typically encountered in turbomachinery. Obtaining ample optical access, sufficiently high seed particle concentrations and accurate synchronization of image acquisition relative to impeller position are the most formidable tasks in the successful implementation of PIV in turbomachinery. Preliminary results from the successful application of the standard 2-D digital PIV technique in the diffuser of a high speed centrifugal compressor are presented. Instantaneous flow measurements were also obtained during compressor surge.

A. 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 wherein a pulsed laser light sheet is used 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 Nd:YAG 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.[1] While each technique has some inherent benefits, the appropriate choice depends on the characteristics of the flow and recorded image constraints. For a general overview of the various implementations of the PIV technique see Reference 2.

Turbomachines are used in a wide variety of engineering applications for power generation, pumping and aeropropulsion. The need to reduce acquisition and operating costs of aeropropulsion systems drives the effort to improve propulsion system performance. Improving the efficiency in turbomachines requires understanding the flow phenomena occurring within rotating machinery. Enhanced operability can be obtained by operating turbomachinery at off-design conditions. However, in order to maintain stable operation over a wider range of flow conditions, active stall control or constant blowing must be used.[3] Detailed investigation of flow fields within rotating machinery have been performed using Laser Doppler Velocimetry (LDV) for the last 25 years. LDV measurements are time and ensemble averaged over all of the blade passages in a rotating machine.[4] The small height blade passages in turbomachinery prove very difficult for obtaining LDV measurements close to the hub surface. Since the light sheet propagation direction can be made parallel to the hub surface in turbomachinery, PIV offers the potential to obtain measurements closer to surfaces than those obtained using LDV. A series of instantaneous spatial velocity measurements obtained using PIV can be averaged together to compute the time-mean flow field. In addition, the instantaneous flow field capture capability of PIV can be optimally utilized such as in the study of stall cell propagation in compressors.

Numerous researchers have employed various PIV techniques to study the unsteady flows in rotating machines. PIV has been used to make blade-to-blade plane velocity measurements in a centrifugal compressor.[5] Although not a rotating machine application, photographic PIV measurements have been obtained in a transonic turbine cascade rig.[6] The light sheet illumination was introduced via an 8.0 mm diameter hollow turbulence generating bar which was already part of the experimental rig. Digital PIV has been used to study the flow in a radial pump.[7] Low seed particle concentrations were identified as not suitable for rotating machine studies, where high spatial resolution measurements are required. Another Digital PIV setup was used to investigate the flow field in the impeller and volute of a centrifugal pump.[8] The lab scale facility used water as the working fluid and a transparent impeller. More recently, high speed PIV measurements were obtained in the stator trailing edge region in a transonic axial compressor blowdown facility.[9] Successful PIV measurements have been obtained in the rotor blade passage of a transonic axial compressor, where both instantaneous and time-averaged cross-correlation processed vector maps were obtained.[10]

The application of PIV to turbomachinery at NASA Lewis Research Center (LeRC) is a three stage program wherein 2-D PIV is initially applied to resolve issues regarding optical access, light sheet delivery and flow seeding. The 2-D PIV measurements will be used to augment previous surveys obtained using Laser Doppler Velocimetry (LDV). PIV measurements will be obtained closer to the diffuser hub in a centrifugal compressor than was possible using LDV. The second phase of the program involves the use of PIV to study the onset of compressor stall. A series of fast response pressure transducers will be inserted around the perimeter of the centrifugal compressor casing to detect the onset of stall. Knowledge of the stall cell development will be used to trigger the PIV system to capture these stall cells as they exit the diffuser. In the third phase of the program, a stereo viewing optical system employing tilted CCD sensor planes which satisfy the Scheimpflug condition will be used to acquire planar, 3-component velocity measurements. The stereo viewing planar, 3-component PIV technique utilizing Fuzzy inference for maximized data recovery has been previously demonstrated in a supersonic nozzle flow at LeRC.[11] The ability to measure instantaneous 3-component velocity vector fields is critical to enhancing the knowledge base of performance limiting tip clearance flows in turbomachinery.

In this work we discuss the successful application of digital 2-D 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 LeRC. A special optical periscope probe was used to generate and introduce the light sheet into the flow. Measurements were obtained at 12, 25, 50, and 88 percent span with the impeller running at the design speed of 21,789 rpm and 4.54 kg/s mass flow. A brief description of the optical setup and some preliminary results are presented. Techniques for generating time-averaged velocity vector maps from vector maps containing spurious vectors are also presented and discussed. The averaged measurements illustrate that PIV yields high accuracy velocity vector maps in much less time than traditional LDV techniques. Previous measurements using LDV could not get closer than 50 percent span to the hub surface in the small height passages (17 mm) in the diffuser. PIV measurements were obtained at 12 and 25 percent span, much closer than previously possible. Initial results from attempts to capture unsteady flow during surge are also presented. PIV data were collected when the compressor had actually entered surge, capturing a near zero flow condition from the exit of the impeller while operating at design speed.

B. Compressor Facility, Optical Access and Light Sheet Delivery

The centrifugal compressor is an Allison Engine Company design that was scaled up to a flow size of 4.54 kg/s from the original size of 1.66 kg/s. The impeller and vaned diffuser were designed to produce a pressure ratio of 4:1 at the design mass flow. The standard day corrected speed for the design flow condition is 21,789 rpm with an exit tip speed of 492 m/s. The impeller contains 15 main blades with 15 splitter blades and has 50° of backsweep from radial at the discharge. The splitter blade leading edge, located at 30 percent of the main blade chord, is offset slightly toward the main blade suction surface to provide an even flow split. The inlet tip diameter is 210 mm and the inlet blade height is 64 mm. The exit diameter is 431 mm and the exit blade height is 17 mm. The vane diffuser consists of 24 two-dimensional wedge vanes with the leading edge located at a radius ratio of 108 percent relative to the impeller exit. The diffuser has an overall area ratio of 2.75 with a total divergence angle of 7.8°. The diffuser exit radius is 363 mm and dumps directly into a 90° annular bend.

A test-rig cross section showing the flow path through the impeller and diffuser can be seen in Figure 1. The rig casing is designed to accept 4 separate window frame inserts; each containing a different set of windows with interspersed locations to provide access all along the flow path from the impeller entrance to the diffuser. A large, window port (70 × 7 0 mm) has been designed to enable optical access over the impeller exit/diffuser section of the compressor, as is shown in Figure 1. This window port was not available for the current measurement program. Instead, a smaller window insert with a clear aperture measuring 30 × 70 mm was used for the measurements presented here. The smaller window opening is centered in the frame insert, providing about half of the stream-wise optical access of the window port shown in Figure 1. There is not sufficient space near the compressor rig for the PIV CCD camera to view the illuminated flow passage directly; therefore, a mirror mounted at 45° to the illumination plane is used to provide the CCD recording camera with a view of the illuminated flow passages. The left-right image reversal caused by viewing through the 45° mirror was compensated for in the data processing.

A very compact light sheet delivery system was constructed using a periscope type configuration.[10] The pulsed Nd:YAG beam is directed down the bore of the tube which contains light sheet forming optics and a 90° turning mirror. The periscope probe has an outside diameter of 12.7 mm and utilizes 8 mm diameter optics (256 mm focal length spherical and –102 mm focal length cylindrical lenses) to form the Nd:YAG laser beam into a laser sheet of approximately 13 × 1 mm at a distance of 240 mm. An articulated light arm with mirror joints was used to couple the beam from the Nd:YAG laser down the bore of the probe. Use of the light arm simplifies the coupling of the Nd:YAG beam to the periscope and also adds an increased level of safety to the installation since the beam is entirely enclosed when outside of the compressor casing. There is a tendency for the laser beam path to wander depending on the orientation of the light arm. Some care must be taken to ensure that the laser beam travels down the center of the light arm to properly couple light into the probe. The light sheet delivery probe has been successfully used to deliver 125 mJ pulsed illumination into the compressor facility. The light sheet exits the probe through a window which keeps the optics inside the probe protected from contamination by seed material.

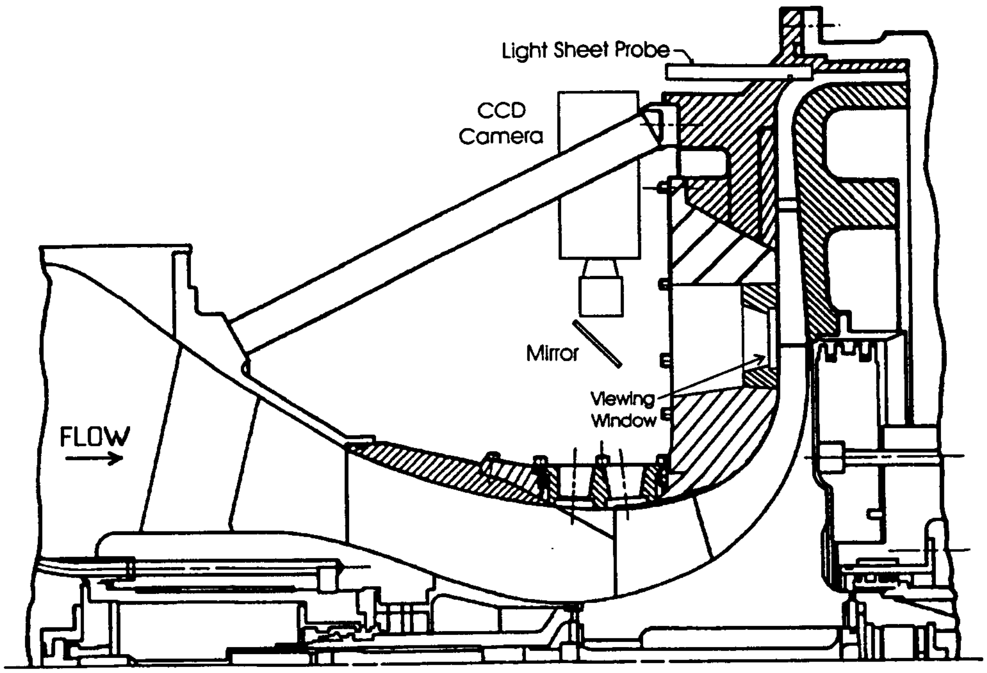

Figure 1

Schematic cross-section of centrifugal compressor facility. Optical access port and CCD camera mounting configuration are shown. Light sheet insertion and recession into compressor casing is also illustrated.

The small diameter periscope probe is inserted through the compressor casing downstream of the diffuser vanes at the 90° bend in the flow passage, as shown in Figure 1. Five insertion holes where machined into the rig casing to permit illumination of four different diffuser vane passages. The four illuminated diffuser vane passages are successively higher in the optical viewport window, providing access to both the pressure and suction surfaces of the diffuser vanes and the space between the exit of the impeller and the diffuser, see Figure 2. The smaller optical viewing port is shown in Figure 2, which is the one used in this work. Moving the probe in and out through the casing changes the spanwise location of the illumination plane. The insertion holes were machined so that approximately half of the probe diameter was recessed in the casing wall. These insertion locations ensure that the light sheet probe does not disturb the flow at the actual measurement location, nor does it choke the flow through the diffuser vanes.

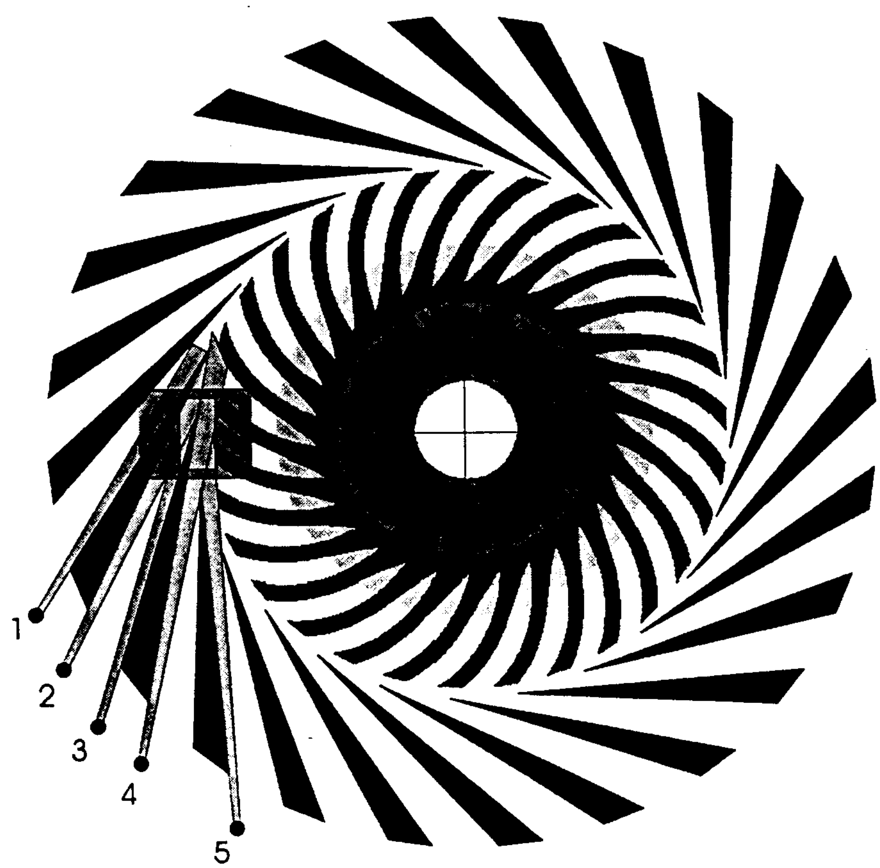

Figure 2

Schematic drawing of vaned diffuser and impeller. Light sheet probe insertion locations and light sheet extents are indicated in the figure. The optical viewing port is also shown.

C. SEEDING

Seeding the high temperature and high speed flow encountered in the diffuser is a challenging task. In a previous LDV velocity mapping program conducted in this centrifugal compressor facility, a seeding system was specifically designed to enable measurements in the high temperature flows encountered in the diffuser region. Attempts to use PSL seeding failed due to the seed material collecting and then melting on the optical access ports. Instead a technique employing pH stabilized dispersions of alumina in ethanol was used. The dispersions of alumina were injected into the facility via two commercial spray nozzles mounted in the plenum tank, approximately 10 meters upstream of the impeller. The alumina powder had a mean particle size of 0.7 ± 0.2 μm. The concentration of alumina powder used in the dispersions was approximately 25 grams/liter. The resulting mass loading of seed material in the compressor flow field at the measurement location was approximately 0.4 percent. A side benefit of the alumina seeding is that it does not have a tendency to adhere to the optical access ports, permitting long rig run times without contamination of the view ports. Previous experience in applying PIV to a transonic compressor required localized seed injection[10], rather than global seeding as described above. However, the lower mass flow and higher compression ratio of the centrifugal compressor relative to the transonic axial compressor yielded sufficiently high seed particle concentrations to support correlation data reduction.

D. Image Acquisition And Data – Processing

Electronic image acquisition has been demonstrated to provide adequate spatial resolution velocity measurements in the narrow flow passages encountered in turbomachinery. Another advantage of electronic image acquisition is the near real-time feedback of the experimental parameters such as: laser pulse energy; seed particle concentration; assessment of flare light from blade surfaces and camera inter-exposure time. Use of a $1{,}008 \times 1{,}016$ pixel, “frame- straddling” CCD camera enables cross-correlation data reduction. Cross-correlation data reduction is the optimal data reduction technique for PIV since it offers directionally resolved velocity vectors, no self correlation peak and hence no restriction on the minimum particle displacement between exposures.

A digital delay generator triggered from a once-per-rev signal on the impeller drive shaft was used to trigger image acquisition and laser firing, permitting PIV data to be recorded from a selected blade passage on the impeller. Increasing or decreasing the trigger delay time enabled collecting velocity vector maps at different impeller phasing positions relative to the diffuser vanes. Delay time increments of 1/180 of the revolution time were used to provide uniform circumferential sampling (or phase stepping) of the 15 main impeller blades relative to the 24 diffuser vanes. Using this time increment, a series of 12 successive phase steps resulted in one impeller main blade and one splitter blade passing by the diffuser vane under study. The camera image acquisition and laser firing were all software controlled via a commercial synchronizer. The PIV control and data acquisition computer was located next to the compressor rig. Remote operation was accomplished using a remote PC interface, which enabled a monitor, keyboard and mouse located in the facility control room to operate the PIV computer located up to 150 m away inside the compressor facility.

The image acquisition software used in the PIV system enables acquisition of a single image frame pair or alternatively, a sequence of image frames. Efficient data acquisition was achieved by acquiring 32 frame sequences and saving them directly to the hard disk. The acquired image sequences were used to compute time-averaged velocity vector maps. Correlation processing of the images was performed off-line after the experiment was completed. The image acquisition rate was 10 frame pairs/sec (limited by the Nd:YAG laser repetition rate) and the time to store each image to disk was approximately 1 second. This data acquisition mode minimized the rig run time and offered maximum flexibility in the selection of the appropriate post processing of the acquired images.

The commercial PIV system used to collect the data offers on-line data visualization capabilities that are extremely useful for optimizing the experiment parameters. However, the commercial system lacked some features necessary to expedite processing the large volumes (gigabytes) of data acquired in this measurement program. A custom Windows 95/NT application interface based cross-correlation data processing program was written to process the large volumes of data in batch mode, automating many steps that would otherwise have to be done manually. The FORTRAN based data reduction software incorporated left/right image reversal correction, image gain scaling, region of interest processing, fuzzy logic data validation and on-line graphical display of the velocity vector maps as they are processed.

Averaging the sequence of velocity fields together creates a more complete velocity vector map. If all of the PIV images were uniformly seeded and of good quality this would be a straight forward process. However, while the seed density is generally reasonably uniform, some image frames are acquired with sparse or non-uniform seeding; which when processed yield velocity vector maps that are incomplete or have spurious vectors where the seed density is inadequate for proper correlation processing. These spurious vectors have a detrimental effect on the computed mean flow properties, and therefore a procedure for judiciously removing them which employs hard velocity limits and the application of Chauvenet's Criteria to produce high quality time-averaged velocity vector maps is required[10].

Submicron particles are required to faithfully follow the flow in transonic turbomachinery. Although the geometric image of the seed particles is much smaller than the 9 µm CCD pixel size, diffraction effects of the optical system may produce effective particle images which are on the order of the CCD sensor pixel size[12]. For example: a PIV image recording system using a f/5.6 camera lens operating at a magnification of 0.16 and using an illumination wavelength of 0.532 µm yields a 9 µm diameter point spread function on the CCD sensor. Hence, the optical system cannot discern particles below 9 µm in diameter. The 0.7 µm diameter seed particles end up being imaged to objects on the order of the CCD pixel size and hence will result in a minimal correlation peak centroid estimation error.[13]

Flare light reaching the CCD camera can cause significant amounts of blooming, leaving large areas of the imaged field useless and even damaging the CCD sensor. Sheet forming optics were selected to produce a light sheet width that matched the diffuser throat opening of 13 mm. The light sheet probe mounting holes were positioned circumferentially around the compressor casing to ensure that the light sheet could be directed along the diffuser vane without actually intersecting the diffuser vane. Aligning the light sheet along the diffuser vane stagger angle minimizes the intersection area of the light sheet with the vane surface, hence, significantly reducing the amount of surface flare light. Painting the diffuser hub black also significantly improves the signal to noise ratio in the recorded images. Some flare light from the impeller blades and diffuser vane surfaces is desirable for referencing since it marks the position of these surfaces in the recorded images.

E. RESULTS AND DISCUSSION

1. LIGHT SHEET PROBE AND FLOW SEEDING

The light sheet probe worked very well for providing the requisite 13 × 1 mm light sheet with minimal scattering from the diffuser vanes and impeller. A sample single exposure PIV image illustrating the high concentration of seeding obtained is shown in Figure 3. The diffuser vane suction surface and impeller are observed in the figure. After the initial trial PIV run, the light sheet probe was covered in seed material, except for the exit window glass, which remained clean. The alumina powder does not appear to adhere to glass surfaces, as was observed by the lack of seed material buildup on the optical access port window. After the initial run, the light sheet probe was disassembled and cleaned. In subsequent runs, the exterior surface of the probe exit window remained clean, but now seed material was getting inside the probe. Seed material was getting in through some small adjustment screw holes in the side of the probe. Sealing these holes before the next test program will prevent seed material from entering the probe and extend the data acquisition operating time of the PIV system.

The optical access port and probe exit window only remained clean if the seeder was turned on at the compressor's design operating condition. At design conditions the tip clearance gap is closed down very tightly (0.4 mm) and the compressor casing temperature near the diffuser reaches 175° centigrade. If the seeder was turned on at less than design conditions then the optical access ports became coated with seed material in a matter of seconds. Hence, the seeder was only operated after the compressor had reached design conditions.

Figure 3
Sample single exposure PIV image obtained from the centrifugal compressor rig. The outline of the diffuser vane is observed on the left and the impeller is on the right.

2. SYNCHRONIZATION

Image synchronization was based on the assumption of the impeller maintaining constant rotational speed. There was some noticeable fluctuation in the observed impeller position in the image sequence data acquired. The uncertainty in synchronization is caused by the variation in impeller speed over time. The standard deviation in rotational speed as measured by the impeller blade tip position in the acquired images corresponded to approximately ± 2.6 mm at the impeller exit, or 0.2 percent of a rotation. This fluctuation is roughly ± 40 rpm out of 21,750 rpm. Since the data are averaged on the scale of the rotor passage, the 2.6 mm fluctuation amounts to a 6 percent variation across a blade passage. The fluctuation in the recorded position of the impeller adversely impacts the fidelity of the time-averaged velocity vector maps generated from the data.

Velocity gradients and flow structures are smeared out. The synchronization error could be corrected by manually determining the rotor position in each PIV image pair and interpolating the data onto a regular grid before performing the averaging process; however, this was not done, therefore the time-averaged velocity data presented in this paper suffers from this poor synchronization.

The electronic delay used is a fixed time delay based on the average rotor speed. The next measurement campaign will employ an electronic shaft angle encoder[14], which generates an updated time delay based on the last rotation of the impeller. Use of this adaptive time delay should significantly reduce the timing error.

3. VELOCITY DATA

The compressor was operated at the design condition of 4.54 kg/s mass flow and 21,750 rpm. Due to the small optical access port available for these measurements, data were obtained only for light sheet insertion ports #3, #4 and #5. Only data from illumination ports #4 and #5 are presented here. The camera field of view for the PIV measurements was approximately 48 × 48 mm, yielding a spatial resolution of 48 μm/pixel. The CCD camera was operated in “frame-straddling” cross-correlation mode with a time delay $\Delta T = 1.72$ μs between image acquisitions. The data were processed using 64 × 64 pixel sub-regions with approximately 60 percent overlap.

Velocity measurements were obtained at 12, 25, 50 and 80 percent span (0 percent span is at the hub, while 100 percent span at the blade tip). The blade tip speed at the exit of the impeller is 490 m/s. In the following figures, the x-direction corresponds primarily to the compressor radial coordinate, while the y-direction corresponds to the circumferential compressor coordinate.

Figure 4 shows an instantaneous PIV velocity vector map obtained from illumination port #5 at 25 percent span. The diffuser vane and impeller orientation are shown in the figure. The velocity vector magnitudes are coded by vector length and also coded by gray scale. The impeller rotation is counter clockwise and the light sheet propagates in the upward direction. No interpolation or data filling have been applied. Some features of note in the figure are the high velocity packet of fluid at the top right. This fluid has both radial and circumferential velocity components. Just below this high velocity packet is a "low momentum" fluid packet, with velocity vectors pointing straight down. The "low momentum" fluid only has circumferential velocity from the impeller, no through flow velocity. The velocity is less than the wheel speed due to the 50° backsweep of the impeller blades at the exit. The circumferential velocity component is actually equal to the rotor tip speed multiplied by the sine of the backsweep angle ($V_{tip} \cdot \sin[50°]$), which is approximately 370 m/s. Previous LDV and CFD computations have failed to predict the occurrence of "low momentum" fluid this close to the hub.

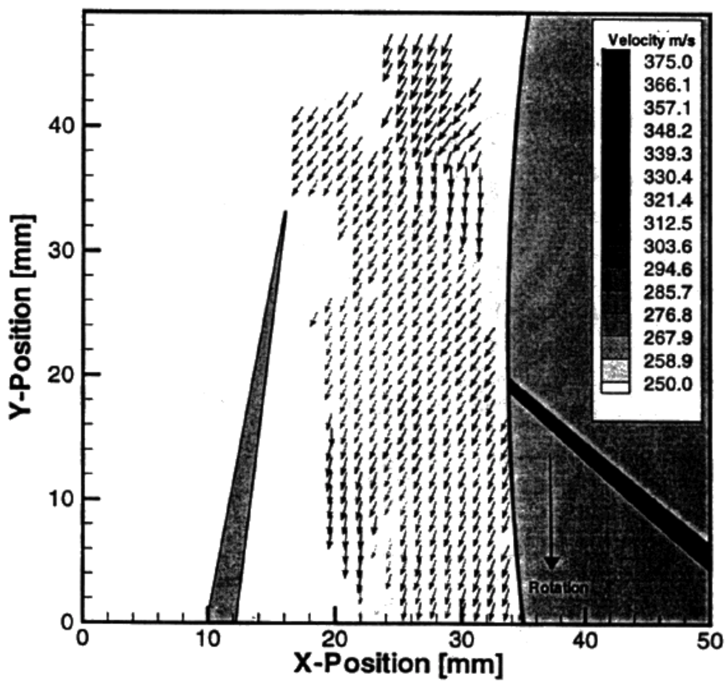

Figure 4

Instantaneous velocity vector map at 25 percent span. The diffuser vane and impeller blade tip are shown. The velocity vectors are encoded by length and gray scale. High momentum fluid is shown at the top of the figure by the dark velocity vectors. Below this fluid packet is observed a low momentum fluid packet with only a circumferential velocity component. Some flow angle turning is observed below the diffuser vane.

The next data sets were obtained from light sheet insertion port #4 with the compressor again operating at design conditions. The once-per-rev signal from the impeller shaft was used to synchronize the image acquisition with the impeller orientation, so that phase stepped images of the impeller relative to the diffuser vane could be obtained. Image sequences of 48 image pairs in length were obtained at each of 12 phase steps. The data in the series were processed and used to generate 12 time-averaged velocity vector maps. The details of the time-averaging and outlier removal procedure were discussed above. The 12 phase stepped images permit the easy creation of animated flows, which unfortunately cannot be presented here. Instead, just two of the images obtained from the series are presented.

Figures 5 and 6 show the time-averaged flow field at two phase steps of the impeller at 88 percent span. Figure 5 shows a high circumferential, low radial velocity fluid packet that is a typical artifact of tip clearance flows. This fluid packet has just emerged from the impeller and is tightly concentrated. Some moderate flow turning is observed around the diffuser vane. Figure 6 shows the rotor at a later phase stepped position (61 μs after Figure 5) where now the fluid packet from the top of Figure 5 is observed to have convected further out into the diffuser vane passage and is starting to mix with the low velocity surrounding fluid. Although the synchronization error discussed above is significant, the velocity vector maps in Figures 5 and 6 still show well defined regions in the flow.

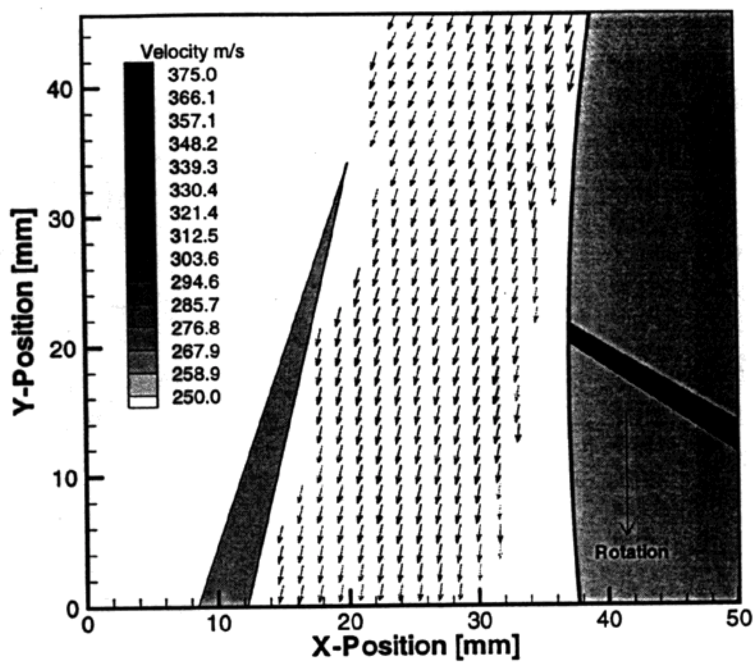

Figure 5

Time-averaged velocity vector map suing 48 frame sequence. High velocity fluid packet is observed at the top of the figure.

4. COMPRESSOR SURGE

The next stage of the research program will investigate the onset of stall in compressors as discussed above. Although pressure transducers had not yet been installed in the casing, an effort was made to assess the potential for capturing stall cells by forcing the compressor into surge. Surge occurs after the compressor has already stalled and is achieved by reducing the mass flow into the compressor using the facility throttle valve. The compressor surged relatively quickly as the flow was reduced to 4.4 kg/s. The PIV image sequence acquisition was initiated before the

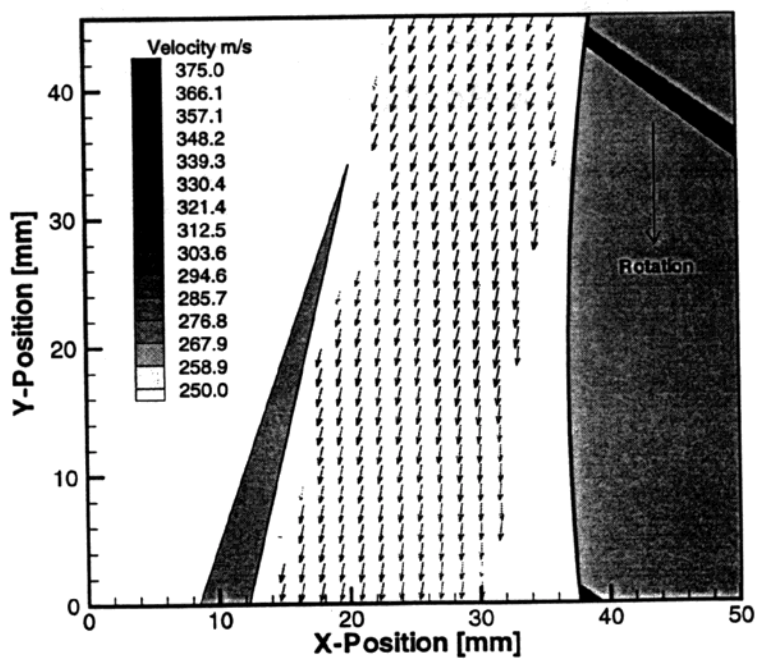

Figure 6

Time-averaged vector field from 48 frame image sequence taken 61 μs after the data in Figure 5. The high velocity fluid packet has now moved down into the diffuser and is starting to mix out.

compressor went into surge and captured images while the flow was surging. No rotor synchronization was used during these measurements. During surging a distinctive noise signature is heard from the compressor. Correlated with the noise signature were PIV image acquisitions depicting very high seed particle concentrations. Only one seed nozzle was used to keep the particle concentration down to a usable level. The high seed particle concentrations were believed to come from particles being knocked loose from the impeller and/or from a buildup of seed material in the flow due to the surging. Prior to surge, the observed velocity vector field would be similar to those in Figures 5 and 6, fairly uniform at roughly 310 m/s with some flow angle turning below the diffuser vane. The surge images were randomly acquired, no mechanism was in place to correlate the image acquisition with the surge process. The light sheet probe was inserted into hole #4 at approximately 30 percent span. A sample velocity vector plot while the compressor was in surge is shown in Figure 7. The features of interest are the two recirculation zones, or areas of almost net zero velocity observed near the top and bottom of the flow field and the apparent flow turning around the diffuser vane. The range of flow velocities has dropped significantly from the steady state flow case. Above and in between these recirculation zones the flow field is somewhat reestablished, but still of much lower velocity magnitude than the steady state condition. This instantaneous snapshot appears to have captured the compressor flow at the peak of the back-flowing surge, where now the flow is just starting to reestablish in the exit if the impeller. This data confirms that PIV will provide valuable information for the investigation of the onset of compressor stall.

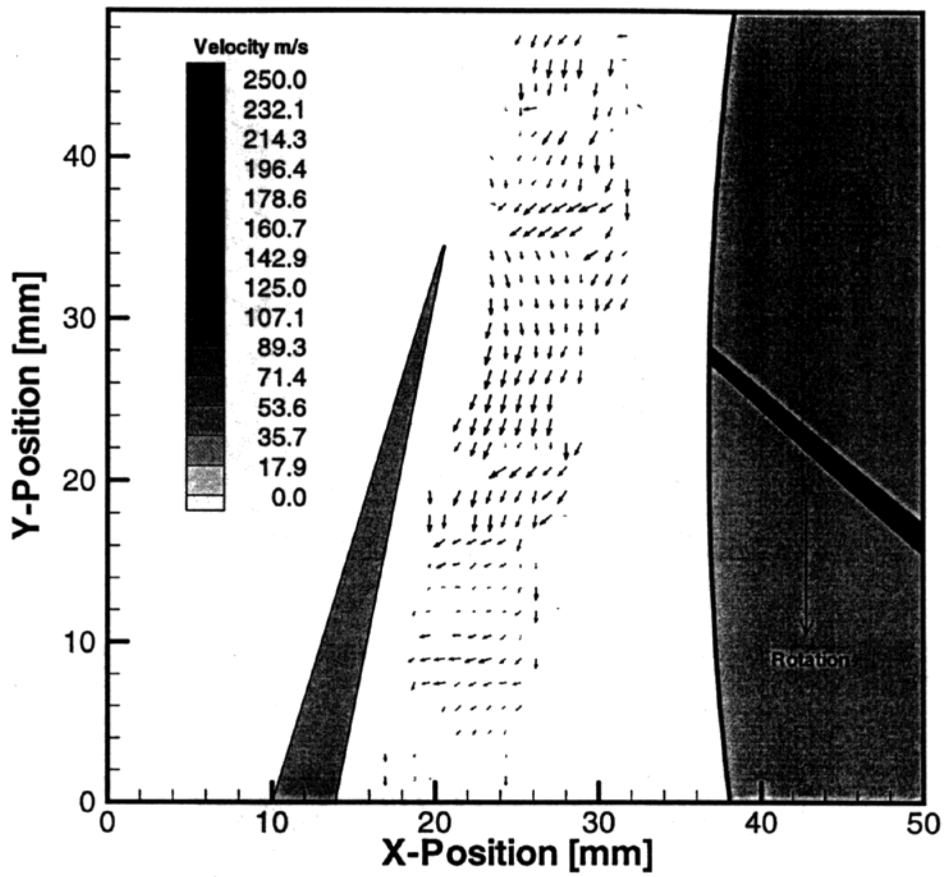

Figure 7

Instantaneous velocity vector map obtained during compressor surge. Note the two near zero velocity fluid packets at the top and bottom of the figure. The velocity magnitude has dropped significantly compared to the data in Figures 5 and 6.

5. MEASUREMENT UNCERTAINTY

The time-averaged vector fields enable the computation of the relative standard deviations in the measurements. The computed relative standard deviations contain the effects of flow turbulence, the measurement errors of the PIV technique, the errors in the once-per-rev trigger signal and any particle seeding variations or particle lag effects. The relative standard deviations for the data shown in Figure 5 and 6 is approximately 8.5 percent on average across the measurement region. The expected measurement errors from the PIV technique are believed to be on the order of a few percent for the instantaneous PIV images, and on the order of 1 percent for the 48 frame averages shown here. Since the expected flow turbulence is on the order of 6 percent, the relative standard deviations shown here are believed to result mostly from the flow turbulence. The contribution to the measured relative standard deviations arising from errors in the once-per-rev signal timing are expected to be on the order of 1 percent, and only really pronounced in regions where the velocity changes rapidly. The remaining particle lag errors arising from non-uniform particle seeding or particle lag are also assumed to be less than 1 percent. Accounting for the contribution of all of these error sources agrees with the observed relative standard deviations.

F. CONCLUSIONS

Successful PIV measurements have been obtained in a high speed centrifugal compressor yielding both instantaneous snapshots and time averaged velocity vector maps of the complex turbomachinery flow. Light sheet illumination was obtained by inserting a light sheet generation probe through the compressor casing downstream of the measurement location. Global seeding of the flow with alumina yielded sufficiently high seed particle concentrations to support correlation data reduction. Seed material contamination of the optical access port and light sheet generating probe was not significant. Techniques were demonstrated for phase stepping the rotor relative to the diffuser and for computing time-averaged velocity vector maps using data containing spurious vectors resulting from varying amounts of particulate seeding in the captured images. The average velocity vector maps obtained here in just a matter of minutes have previously taken a factor of 13 longer to obtain via LDV in similar facilities. PIV measurements were obtained closer to the diffuser hub (12 and 25 percent span) than previously obtainable using a normal incidence LDV system.

Synchronization errors resulted in fluctuations in the rotor position in the computed time-average velocity maps. An electronic shaft angle encoder will be used in the future to eliminate this synchronization error. Also the impeller blade passages will be inscribed to permit easy identification of rotor and splitter blade passages. Despite the synchronization errors, the time-averaged PIV results show clear evidence of the velocity fluid packets emerging from the impeller and the flow turning around the diffuser vanes. The PIV measurement errors have been shown to be less than variations caused by the flow turbulence. The nominal relative standard deviation in the PIV measurements were computed to be 8.5 percent, most of which results from the flow turbulence.

PIV has been shown to be a viable technique for capturing instantaneous flow field phenomena such as compressor surge. Coupling the PIV system to high response pressure transducers should enable the study of stall precursors and help in the understanding of the onset of compressor stall.

G. ACKNOWLEDGMENTS

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