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14. ABSTRACT

If the velocity and density fields can be captured and resolved accurately in space and time, the aerodynamics of vehicles with complex interactions can be calculated with certainty. With new vehicles using large co-axial rotors and small quad rotors, flow field interactions are critical to understand at all size scales. The suite of equipment acquired here is to exploit recent breakthroughs in understanding flows relevant to high-speed rotorcraft and UAV problems, and generally to the science of vortical and rotating flows. It consists of three subsystems. The first is a

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Report Title

Final Report: Equipment for Rapid Whole-Field Velocity and Density Capture in Rotor Flows

ABSTRACT

If the velocity and density fields can be captured and resolved accurately in space and time, the aerodynamics of vehicles with complex interactions can be calculated with certainty. With new vehicles using large co-axial rotors and small quad rotors, flow field interactions are critical to understand at all size scales. The suite of equipment acquired here is to exploit recent breakthroughs in understanding flows relevant to high-speed rotorcraft and UAV problems, and generally to the science of vortical and rotating flows. It consists of three subsystems. The first is a high-rate laser and fast, high-resolution camera for stereoscopic Particle Image Velocimetry in thin sheets. This has adequate spatial and temporal resolution for a foray into turbulence. The second is a cost-efficient set of Plenoptic cameras to explore the capture of whole-field density and multidimensional velocity fields, combining essential features from Particle Tracing Velocimetry, Photogrammetry, and Tomography. The third is a Millimeter Wave Interferometer to enable measurements across density gradients. A pair of computers equipped with parallel processing using advanced graphics modules has also been acquired, to cope with the immense data throughflow from these systems. With these we believe that we can demonstrate whole-field velocity, pressure (from laws-of-physics numerical solution) and density capture in periodic but turbulent, vortical flows of relevant Reynolds and Mach numbers. Plenoptic cameras combine high depth of field with high-resolution post-processing of individual planes. The context set by the state of the art in flow measurements, and the educational benefits permitted by our strong and continuing record of graduate and undergraduate research team participation and publication, are also explained.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

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TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Nandeesh Hiremath	0.00	
Dhwanil Shukla	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Narayanan M. Komerath	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Joseph Robinson	0.00	Aerospace Engineering
Thomas Kim	0.00	
FTE Equivalent:	**0.00**	
Total Number:	**2**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

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Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

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Summary

If the velocity and density fields can be captured and resolved accurately in space and time, the aerodynamics of vehicles with complex interactions can be calculated with certainty. With new vehicles using large co-axial rotors and small quad rotors, flow field interactions are critical to understand at all size scales. The suite of equipment acquired here is to exploit recent breakthroughs in understanding flows relevant to high-speed rotorcraft and UAV problems, and generally to the science of vortical and rotating flows. It consists of three subsystems. The first is a high-rate laser and fast, high-resolution camera for stereoscopic Particle Image Velocimetry in thin sheets. This has adequate spatial and temporal resolution for a foray into turbulence. The second is a cost-efficient set of Plenoptic cameras to explore the capture of whole-field density and multidimensional velocity fields, combining essential features from Particle Tracing Velocimetry, Photogrammetry, and Tomography. Plenoptic cameras combine high depth of field with high-resolution post-processing of individual planes. The third is a Millimeter Wave Interferometer to enable measurements across density gradients. A pair of computers equipped with parallel processing using advanced graphics modules will help to cope with the immense data throughflow from these systems. With these we believe that we can demonstrate whole-field velocity, pressure (from laws-of-physics numerical solution) and density capture in periodic but turbulent, vortical flows of relevant Reynolds and Mach numbers. The context set by the state of the art in flow measurements, and the educational benefits permitted by our strong and continuing record of graduate and undergraduate research team participation and publication, are also summarized.

1. Problem Statement

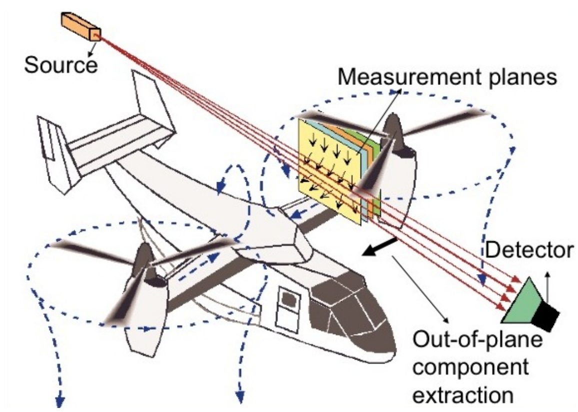

Fig. 1.1: **Goal: Whole field extraction of all flow properties in rotorcraft problems**

The package that was requested consisted of the equipment needed to obtain temporally and spatially resolved velocity and density-gradient fields in vortical flows. The high-rate dual laser would allow flash rates up to 10KHz. The high-resolution PIV camera would allow velocimetry at up to 400 velocity fields per second, and lower spatial resolution videography at up to 10,000 FPS. In addition, we requested two Light Field (Plenoptic) cameras, to attempt an innovative combination of techniques and capture both velocity and density-gradient fields. When combined with the capabilities of the high-rate laser, this camera pair would open several avenues. Features from Particle Tracing Velocimetry, Photogrammetry, and Tomography could be combined.

1.1 Why: Impact on Current and Planned Research

If the velocity and density fields can be captured and resolved accurately in space and time, the aerodynamics of vehicles with complex flow field interactions can be calculated with certainty. With new vehicles using large co-axial rotors, tilt rotors and small quad rotors, flow field interactions are critical to understand at all size scales. An early representation of what would be needed, is shown in Figure 1.1 from [1] from Urmila Reddy's PhD Thesis at our lab, circa 1998. With the above package, we believe that we can demonstrate whole-field velocity, pressure (from laws-of-physics numerical solution) and density capture in periodic but turbulent, vortical flows of relevant Reynolds and Mach numbers. These will enable us to answer pressing questions on the fundamental aspects of flows with strong radial acceleration, encountered in all rotary wing aerodynamics applications. We have come as far as possible with 14FPS PIV and stereo PIV systems. The requested equipment is necessary to move ahead. At the same time, we see an opportunity to make a large leap forward towards the grand goal of being able to quantify whole-field velocity, density and pressure in periodic, unsteady and turbulent flows. Below, the relevance to current and planned research is first presented, before going into detail on the proposed methods.

1.2 Related Projects

1. ARO Project W911NF1010398: Flowfield Characteristics on a Retreating Rotor Blade. This project developed a high-advance ratio rotor rig at the John Harper wind tunnel (see Figure 1.2). It produced the first capture of quasi-periodic structures that limited the growth of radial flow on rotor blades. Vrishank Raghav's PhD thesis produced the first full 3-component velocity fields in rotor dynamic stall. A 1-year extension explored a hypothesis on the nature of the flow under a retreating rotor blade at advance ratios high enough for reverse flow. We have now shown that the aerodynamics in this regime, including the critical pitching moment behavior that determines stability of the rotor, can be related to vortex flow aerodynamics, extended from knowledge on swept and delta wings at angle of attack. The flow field involves the development, bursting, detachment and convection of strongly 3-dimensional vortices, as well as the effects of rotation on these. Preliminary estimates of the pressure field have been obtained from our velocity measurements. Nandeesh Hiremath is completing his PhD Thesis on this topic. The requested equipment would greatly enhance the resolution and accuracy of velocity and pressure fields in this case. The density field reconstruction experiments would allow us to develop techniques to be transferred and used in large-scale wind tunnels where rotorcraft development such as for the JMR vehicles is undertaken.

2. NRTC VLRCOE Project number W911W6-11-R-0005 BAA - Georgia Tech, Task 16. Oct. 2011 - December 2016. This task with a parallel sub-grant to

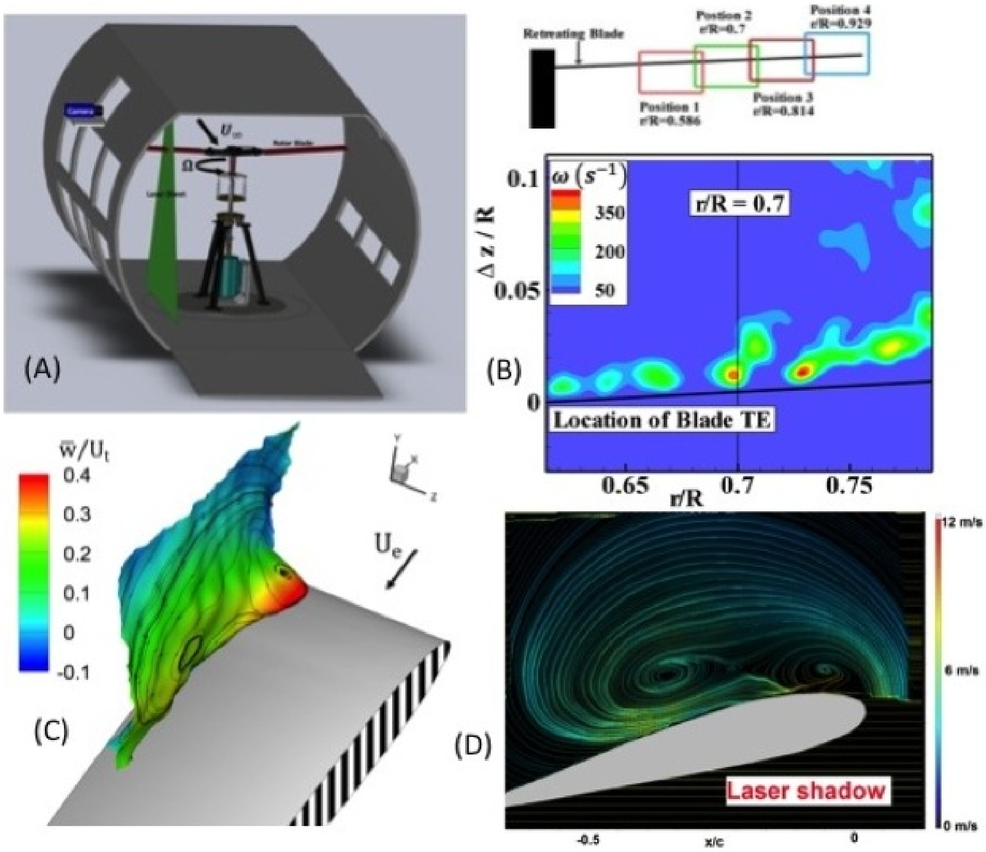

Fig. 1.2: **Dynamic Stall Velocity Field With Radial Velocity. (a) 2.7m x 2.5m tunnel test section with 2-bladed rotor. (b) Discrete structures in the radial jet shear layer, captured with PIV at the trailing edge of the retreating rotor blade. (c) 3D representation of the velocity field of the dynamic stall vortex just before it detaches. (d) streamline contours of the dynamic tall vortex showing development of a secondary vortex as the primary detaches. From our recent ARO-sponsored work.**

Ohio State University (Prof. J. Gregory), seeks to advance diagnostic techniques for transient rotorcaft flow problems, including pressure sensitive paint (OSU) and particle image velocimetry. The target is to be able to modify the pitching moment during dynamic stall, through diagnostic knowledge of the dynamic stall velocity and pressure fields, developed systematically. This has synergy with the ARO project above. Efforts to conduct Pressure Sensitive Paint measurements have not succeeded to date, but will be resumed with better estimates of the pressure field from the velocity measurements done under the ARO project.

We had reached a stage where we could acquire 3D instantaneous velocity vector fields in a plane using stereo PIV over moderately sized (roughly 150mm x 150 mm) thin measurement planes, at 14 velocity fields per second. We can also acquire volume velocity fields over small volumes (25 mm x 25mm 25mm) at the same rate using Tomographic PIV. Load measurement can be conducted with 6-DOF load cells with roughly 10 Hz frequency response. To go beyond, we needed the requested system. Some specific areas of interest that defined the requirements for the present system were listed in the proposal.

1.3 Velocity, Pressure and Density Field Capture in Compressible Flows

Our latest efforts in extracting static pressure fields from measured velocity fields, are shown in [2]. The method is to capture closely-spaced velocity fields using stereo PIV, satisfy the continuity equation, and feedthe interpolated data set as input to a Navier-Stokes calculation of pressure. This will benefit greatly from the high-speed PIV system as it will allow turbulence information to be included rigorously.

Efforts to capture whole-field density from interferometry and schlieren techniques promise breakthroughs. The keys here are (a) whole-field illumination, (b) suitable backgrounds, (c) existence of density gradients refracting light and (d) capture of the density gradient field with sufficient depth of field, sensitivity and resolution and (e) reconstruction through solution of an integral equation. The last item benefits from having multiple perspectives in order to enhance the uniqueness of solutions. As outlined in the proposal, the acquired system will be used to explore this.

Plenoptic or Light Field cameras enable images to be captured and stored over an entire volume, with data in specified planes extracted *a posteriori*. We concluded after surveying the market and technical field, that:

- The Plenoptic camera has the potential to eventually replace stereo PIV with whole-field PTV.
- Present scientific-grade plenoptic cameras available commercially, are not a good investment for exploratory method development as they do not offer adequate temporal resolution,

- On the other hand, we felt that the Lytra ILLUM mass-market camera could be used to capture density fields. The depth of field variability in post-processing can be used in a number of ways to compensate for spreading of the light source and facility constraints, even if it turns out to be impossible to directly translate into an ability to interrogate specific planes.
- With two cameras as used by MetroLaser Inc. to capture density gradients around supersonic aircraft in flight in sunlight illumination, we should be able to implement schlieren in the wind tunnel or in our 9-foot rotor facility.
- With two ILLUM cameras positioned orthogonally, we should also be able to use photogammetry techniques to capture and reconstruct the entire density field with suitable light sources.
- On the other hand, when combined with a high-rate laser, the still camera feature of the ILLUM is adequate to capture several planes of velocity data. This can be done with traditional PIV by capturing multiple images by sweeping the light sheet as the blade goes through the field of view.
- The ILLUM camera can also be used for PTV with the traces of particles appearing due to multiple, closely-spaced flashes from the laser being recorded in the light field camera.

Thus, a pair of ILLUM cameras will enable us to both capture density fields, and explore capture of high-rate velocity fields to perform mass-conserved interpolation of 2D velocity data for pressure field reconstruction. In addition, PTV using the high rate laser may provide volume velocity fields as well.

1.4 Research-related education

The Experimental Aerodynamics Group at the School of Aerospace Engineering operates the John J. Harper 2.13m x 2.7m wind tunnel and the 2.7m Rotor Diagnostics Facility. Both of these are run by student teams led by graduate students pursuing degrees in experimental aerodynamics, with a strong tradition of undergraduate participation in the research teams. We have seen over 200 undergraduates on our teams, several of whom have stayed on for MS and PhD degrees. Importantly, our large facilities are operated primarily on PhD-generating research projects. with a strong tradition of undertaking diagnostics that require long setup and iteration times.

The results are seen in the quality of the 18 PhDs who have graduated in the past 20 years, 4 of them winning the Georgia Tech Sigma Xi Outstanding PhD Thesis award (top 1% of theses in a given year) and 5 more being finalists for the same. Each of the thesis awards, curiously, has been in direct causal sequence from one of the DURIP awards preceding this one. Three of our PhDs are working in US DoD organizations, 5 in US academia/research, 8 in the US aerospace / strategic industry, and the other two are respectively in senior positions in academia in Taiwan and rotorcraft R&D in Republic of Korea. Our 75+ M.S. graduates are distributed between NASA, DoD, academia and other industry/ professional careers.

A summary of our group's progress in the diagnostics field follows. This project is a logical next step in a progression towards understanding and using vortical flows for rotorcraft applications.

1. Starting from the 1980s, we used laser velocimetry to capture the detailed core structure including secondary features in the core of a tip vortex in hover and the flowfield around a rotor tip, the flow over a double-swept tip at high pitch angles , and the flow between a rotor and airframe in forward flight. These were very time-consuming measurements, but by ensuring near-perfect periodicity in the flow, it was possible to synthesize 3-D flows from single point, single-component, azimuth-resolved measurements.

2. In the mid-80s quantitative laser sheet imaging captured blade flowfields, vortex dynamics and core size evolution [3]. Initially this was done using a continuous-wattage argon ion laser with synchronized motors, a chopper wheel and still photography [4] and then with a Bragg Cell electronic chopper and videography [5, 6]. A DURIP-funded pulsed copper vapor laser advanced the image clarity and temporal resolution by orders of magnitude, allowing single-shot images to capture wake/airframe interaction, vortex-surface collisions [7] and wake/lifting surface interactions with transient stall. Robert Funk generated an animation of the transient vortex-induced separation on a lifting surface [8], Jaimoo Kim did an animation of the interaction between the tip vortex vorticity field and the shear layer from a backward-facing step [9] . Mahalingam [10] and Wong captured [11] of the vortex velocity field from a blade tip in forward flight, defined the capabilities of extensive and accurate periodic velocity field measurements.

3. The copper vapor laser enabled development of the Spatial Correlation Ve-

locimetry concept [12], demonstrating use of separate video images (initially it was the odd and even line-scans that composed an interlaced video image) of a flowfield, with the 2D FFT- conjugate multiply - inverse FFT technique to get cross-correlations for the 2-D velocity field without resolving particle images, and in the presence of substantial noise. We took this towards quantifying velocity over large areas , and then developed a white-light system using machine-vision strobes, that could be scaled up to perform Velocimetry in larger scale facilities such as the BHTC Hover Stand , the Ames 30ftx 30ft settling chamber of the 7ft x 10ft wind tunnel, and the Boeing VTOL tunnel (60ft diameter chamber), with light source and camera distances of over 30 feet. The results from the Ames experiment led to a breakthrough in proving that under clean test conditions with no feedback from downstream obstructions, the transition from the near wake to the far wake occurs through a deterministic rollup process of the tip vortices, which stay strong and well-organized for much longer ages than previously shown, at realistic Reynolds numbers [13].

4. Balakrishnan Ganesh validated PIV in cross-flow against LDV in the near wake of rotor blades in forward flight to compare the shear layer rollup and tip vortex formation process over different tip shapes [14]. He performed the first PIV studies of the formation of the ground vortex in low-speed IGE forward flight. Limited camera resolution required stitching flow regions together to make a larger composite.

5. Our team [15, 16], used PIV to capture the quasi-periodic structures breaking up the radial jet over a rotor blade in dynamic stall.

6. Goal [17] and Barbely [18] captured the high-frequency acoustic field in a resonator, separating fluid motion from the motion of large solid particles using Particle Tracing Velocimetry (PTV). Stereo PIV has recently been used as shown above, to capture the detailed dynamic stall flowfield, completing what can be done with 14 FPS PIV. Our 14PPS Tomographic PIV system allows capture of the entire volume flowfield, but only over small volumes at close range.

7. High-frequency PIV is a new development. With 800 Hz repetition rates, and high-resolution cameras, phenomena occurring over the same blade can be captured in a temporal sequence. This allows us to capture the evolution of features that are not periodic. The whole-field density measurement follows up

on a concept explored in Urmila Reddy's PhD thesis in 1997. She assembled phase-resolved, ensemble-averaged 2-D velocity fields taken at several chordwise-vertical planes along the span of a wing with a rotor wake impinging on it, and solved the continuity equation to obtain the third component (span wise). Now with stereo PIV we can do much better, since we have 3D velocity data in each plane.

The new additions to our diagnostic systems are providing excellent opportunities for student training and innovative explorations.

2. Summary of Results

2.1 Acquired Equipment Package

2.1.1 Stereoscopic high-speed, high-resolution PIV system

The high speed PIV system comprises of two high speed cameras, laser system, and the computer for analysis. By optimizing the camera resolution and laser pulse energy to our needs with assistance from the vendors, we were able to accommodate a stereoscopic PIV system with 2.56K x 1.6K resolution, two cameras, and the capability to obtain up to 800 velocity fields per second at full-field resolution, and substantially larger temporal rates with lower resolution. Sufficient on-board memory was acquired on the cameras to permit acquisition of up to 6 seconds of continuous data. This allows extaction of turbulence features in many fields of interest in rotorcraft flows such as rotor wakes. This acquired equipment will enable us to capture non-periodic velocity fields to enable tracking of structures within one passage of a rotor blade operating in a wind tunnel.

2.1.2 Laser system

Laser system comprises of a high speed dual laser head capable of emitting 527nm wavelength light with a 2 x 30 mJ per pulse. This high speed laser system with a maximum repetition rate of 1kHz is in conjunction with the high speed imaging systems. The old Litron laser has maximum of 200 mJ/pulses but we are confident that 30mJ pulses are sufficient with the camera sensitivity now available, as seen in the velocity fields acquired and shown with the new system at the end of this chapter. The laser system also incorporates power supply/controller unit, and the chiller unit. Also, a PTU-X HS is used for the high frame rate cameras and high repetition rate laser systems, supporting time based and cycle based image recording. The specifications are listed below.

- Nd:YLF Dual Cavity Diode Pumped Solid State, High Repetition Rate Laser
- 2 x 30 mJ/pulse (@527 nm) at 1 kHz repetition rate, up to 10 kHz repetition rate from each head
- Includes beam combination optics, laser heads, power supply, and chiller

Fig. 2.1: **Dual Cavity ND:YLF Laser System (Laser Head, Controller, Chiller)**

2.1.3 High Speed Camera

Two Phantom v341 cameras are being used in experiments involving understanding of multiaxial rotor wake interaction. The cameras have a spatial resolution of 2560 x 1600 pixels using a CMOS sensor and can operate from 10 to 800 fps at full resolution and upto 10,000 frames per second in reduced resolution, in contrast to our pre-existing Pro X cameras with a capability of 14 fps. At full resolution, the cameras have a 12 bit digital output with a 16 GB RAM. The data are transmitted to the computer through a Gigabit Ethernet interface. The cameras came with Nikon 50mm lenses. In addition, two Sigma macro lenses with 17-70mm, and two telescopic Sigma lenses with 18-300mm were acquired. The telescopic lenses help studying particular phenomena inside the tunnel while keeping the camera outside the 7ft x 9ft test section. By optimizing resolution and speed, we were able to afford significant memory storage on each of two high-speed PIV cameras rather than the one proposed. This permits stereo PIV at rates high enough to capture turbulence, which is by nature 3-dimensional. Each camera's onboard RAM can store upto 16GB of data, and is transferred to the computer through a gigabit ethernet cable. All the PIV processing over several image pairs is done on a dedicated computer. With these specifications, we expect to be able to capture a continuous stream of upto 8 seconds worth of velocity field data at full framing rate and resolution. This will enable both temporally-resolved imaging of 3-D velocity fields, and capture of turbulence statistics going down close to the Kolmogorov scales in the flows of interest here.

2.1.4 Programmable Timing Unit (PTU - X)

The programmable timing unit is the brain of the PIV system. It consists of the following:

1. 16 fast sequencer controlled output lines,
2. 16 software controlled I/O lines,
3. 2 input channels (cyclic trigger and image recording sequence start),
4. 2 output analogue lines (0 - 10 V),
5. 10 ns time resolution,
6. Jitter less than 50 psec, variable trigger delay for phase-resolved measurements, trigger delays based on time OR phase angle (for rotating machinery),
7. USB-2 device.

8. PTU-X HS Upgrade: for all high frame rate camera and high repetition rate laser systems, supports time-based and cycle-based image recording

The PYU-X with the high speed upgrade is shown in Figure 2.2.

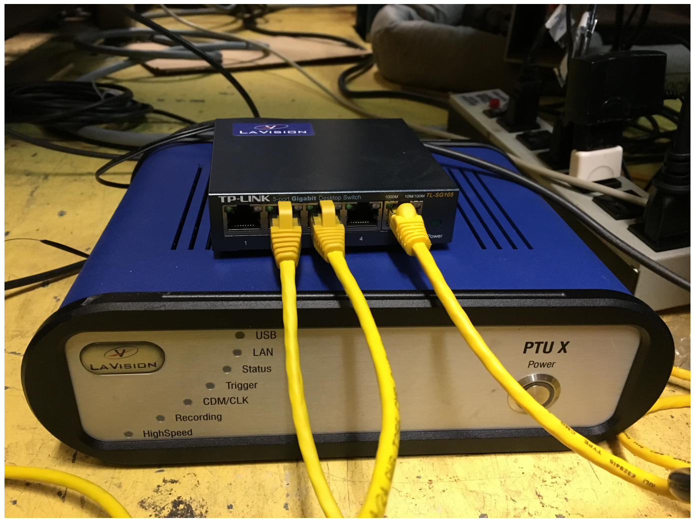

Fig. 2.2: **PTU-X with HS Upgrade**

2.1.5 Data Analysis and Processing Systems

At full resolution, each image is about 6.7 MB in size. Each 2D PIV result frame requires two such images, and stereo PIV requires 4 images. The PIV system can capture 400 Stereo PIV fields per second, which is 1600 images per second or 10720 MB (10.72 GB) per second. This is a huge amount of data that has to go through image processing. In processing, the image is split into interrogation windows typically of size 32 X 32 pixels with an overlap of 50 percent. This results in total of 160 X 100 interrogation windows per image pair per camera. I.e 16000 interrogation windows per image pair or 32000 interrogation windows per Stereo PIV frame. This processing is done in three to four passes to ensure noise free results. In each interrogation window, processing includes 2D FFT and inverse FFT computations. The basic SPIV data acquisition computer has the following specifications, and it is shown in Figure 2.3.

Specifications

- Dual processor tower PC
- 2 x six-core XEON processors
- 32 GB RAM, 256 GB SSD boot drive
- 3 TB SATA data drive
- PCI-e slots only, read/write DVD
- 700 W power supply
- 1 x GPU compatible
- 22" flat screen monitor, keyboard, mouse, Windows 7 Professional (64-bit)
- DaVis 8 software installation and testing

2.1.6 Pair of Lytra ILLUM Light Field Cameras and Miscellaneous Optics

A pair of Lytra ILLUM light field cameras have focal lengths of 9.5 - 77.8 mm (30 - 250 mm equivalent), with 8x optical zoom, constant aperture of 2.0. The CMOS light field sensor has 40 MegaRay light field resolution. The sensor active areas is 10.82 x 7.52mm. The ISO range is from 80 to 3200. The camera uses the Qualcomm Snapdragon 800 processor. The image format is light field RAW, with an aspect ratio of 3:2, and 2D export resolution of 2450 x 1634. File storage is by SDXC/SDHC memory cards, which must be bought separately. The focal plane shutter speed can be varied from 32 seconds to 1/4000 second, with a flash sync speed of 1/250 second. A self timer is provided, as well as a continuous drive speed of 3 frames per second. Region autofocus is provided. A touchscreen is provided with a 4-inch backlit LCD and dual hinges tilting, with articulate angles of -10 to + 90 degrees. A light field refocus function is provided. The camera uses the Lytro Light Field Sensor and Lytro Light Field Engine 2.0, with the Lytro Desktop software for picture management, editing and sharing, compatible with the Ma OS or Windows 7/8 64-bit. Wireless WiFi 802.11a/b/g/n/ac is provided. Output can use Micro USB 3.0. The camera is powered by a removable 3.7V, 3760 mAH Lithion ion battery.

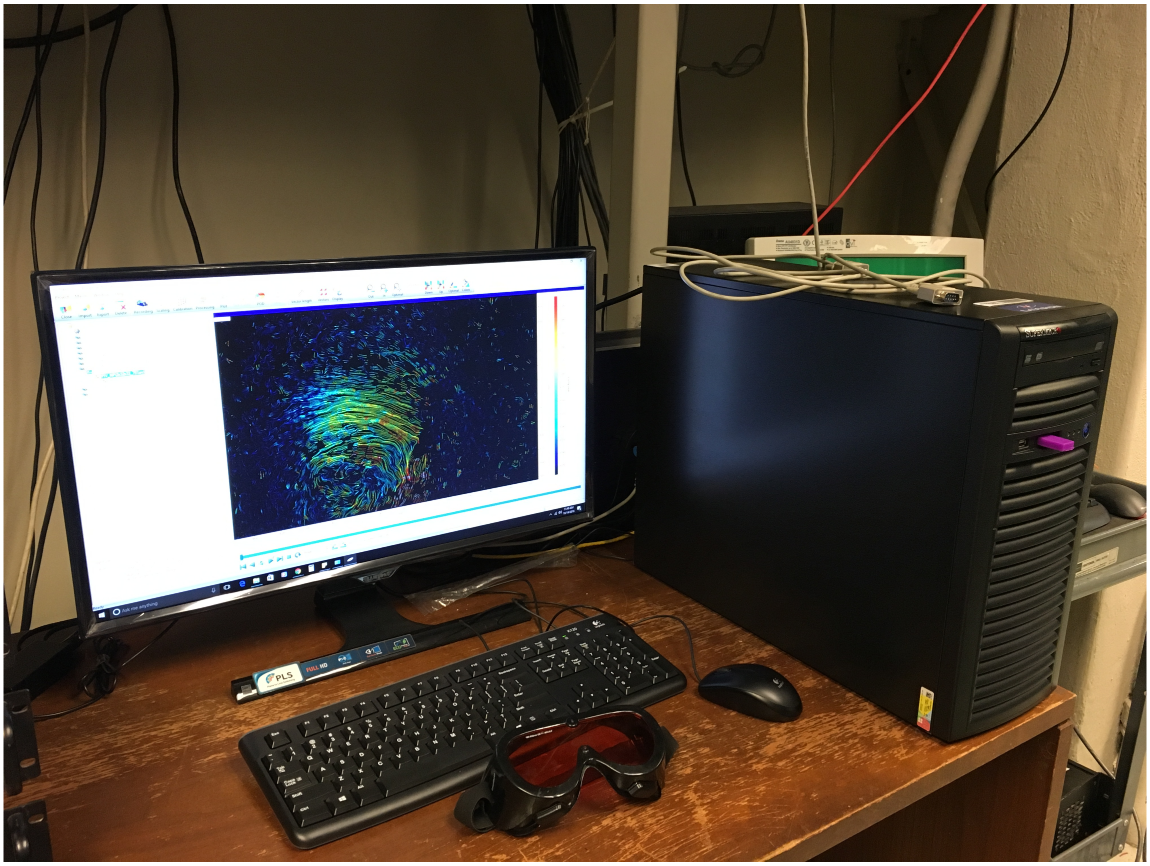

Fig. 2.3: **PIV Data acquisition Computer**

2.2 Millimeter Wave Interferometer

A target of opportunity in this project was the acquisition of a millimeter wave interferometer system. This provides a complementary diagnostic to laser and ultrasonic diagnostic systems, in enabling capture of turbulent density fields as well as, in the longer term, flows with droplets. The system acquired is a Quinstar 94 GHz Interferometer, configured so that it can be used in backscatter mode or direct inline mode. The system consists of 94 GHz sources, an amplifier, and a I-Q mixer. The I-Q mixer generates a signal with the bandwidth of the phenomenon being studied (turbulence or periodic rotor wakes) comprised of an amplitude fluctuation and a phase signal.

The I-Q mixer was consuming too much power, and hence the system is at present back at the manufacturer's facility for improvement to the mixer, At this writing the improvements have been accomplished with design refinements and the renewed system is being completed at the vendor's manufacturing facility. We plan to use this system along with the density field imager, in order to obtain quantitative calibrations, before going on to diagnostic applications unique to millimeter waves

2.3 Data Processing Computers

The massive post-processing involved in high speed stereo PIV and Plenoptic cameras and millimeter wave interferometry is to be done by two high performance computers shown in figure 2.4. These are Lenovo workstations equipped with high-performance graphics processors. The computers are both ThinkStation Model P900, Dual CPU E5-2660 v3, 128.0GB RAM, 1x1TB SATA SSD. We purchased three Nvidia Geforce 1080 GTX. This allows both high-speed image processing and correlation with professional-level CFD codes such as the ROTCFD family of Navier Stokes solvers, as well as the Stanford HiFiLES Large Eddy Simulation solver, for low-Reynolds number rotor flows.

Fig. 2.4: **The two high performance computers for data processing**

2.4 Initial Setup: CoAxial Rotor Experiment

Figure 2.5 shows a small co-axial rotor experiment installed in the John Harper Wind Tunnel, along with one of the new high speed cameras, set up for laser sheet visualization and PIV. Figure 2.6, shows the vortex interaction of the two blades of a co-axial counter rotating setup, during the blade crossing. Figure 2.7 is an instantaneous 2D PIV result taken through the High Speed PIV system. Getting results in this flow field is challenging due to the plane of interest being perpendicular to the primary flow direction, causing seeding particles to leave the illuminated laser plane before the second image.

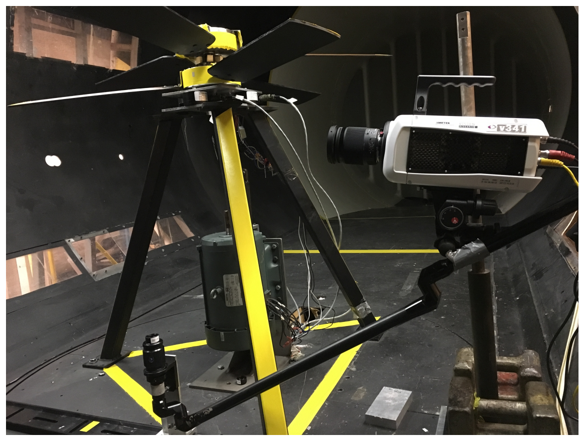

Fig. 2.5: **Phantom v341 High Speed Camera setup for studying coaxial rotor wake**

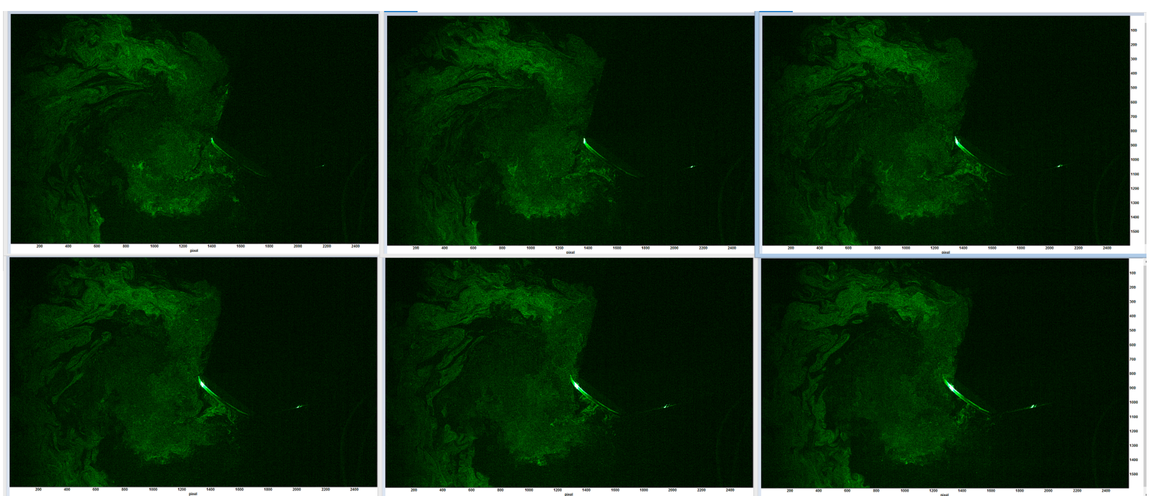

Fig. 2.6: **High Speed Camera Images of a vortex interacting with blade (800 Hz)**

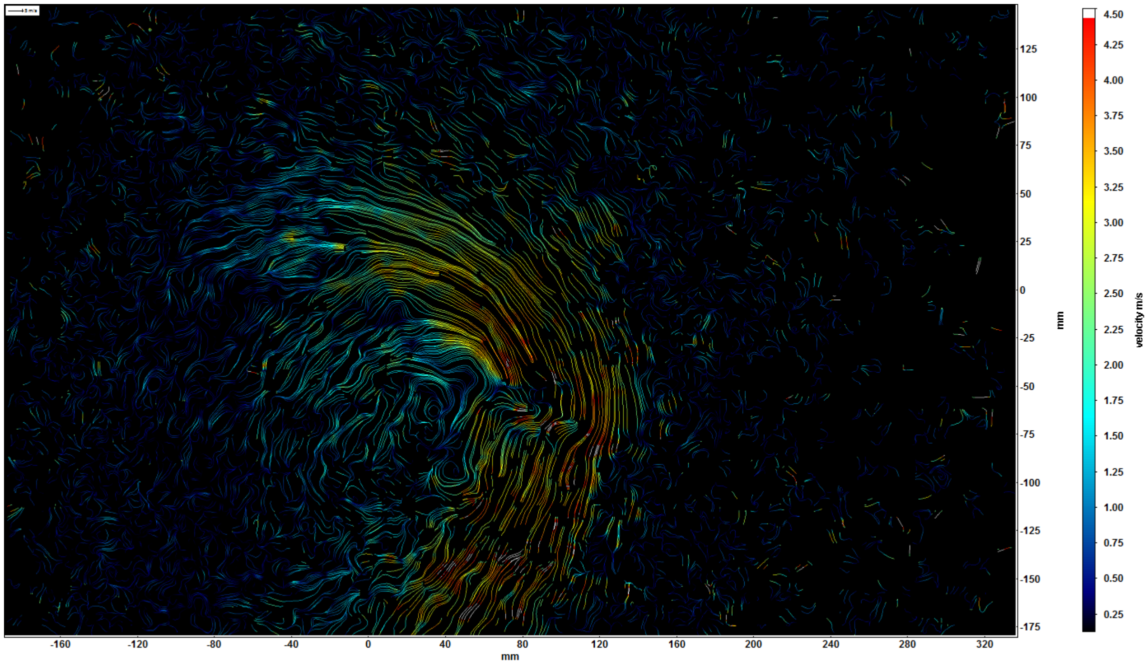

Fig. 2.7: **Instantaneous PIV result obtained for coaxial rotor wake using the high speed PIV system**

2.5 Concluding Remarks

The system acquired has substantially broader and deeper capabilities than what we proposed. By optimizing laser power and camera specifications we were able to acquire a system that is performing high-speed stereoscopic particle image velocimetry in the wake of a rotor in the large test section of our wind tunnel. Onboard memory on the cameras permits acquring upto 6 seconds of continuous 3-component velocity field data at 800 velocity fields per second with sufficient resolution to capture 3-dimensional turbulent flow quantitative information. The two high-performance parallel-processing graphics card-equipped computers provide the resources to exploit this dense data stream. The pair of plenoptic cameras provides a good avenue to capture depth resolution in density field reconstruction. The millimeter wave interferometer provides a completely new capability in density fields with and without particulate matter. Initial results from the wake of a co-axial, counter-rotating rotor system promise a good chance of capturing the elusive vortex collisions that are postulated to be a fundamental feature of such wakes, with significant implications for the understanding of high-speed rotorcraft aerodynamics.

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