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# Whole-Field Velocity Measurement for Rotorcraft Aerodynamic Interactions*

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## ABSTRACT

Measurements of instantaneous velocity fields in rotorcraft flows are reported. The Spatial Correlation Velocimetry (SCV) technique is used to study two configurations - the first is an isolated rotor, and the other is a wing-rotor combination. Previous results are shown to indicate the expected accuracy and application to various problems. Both configurations are tested in low speed forward flight in a wind tunnel. In the wing-rotor flowfield, data acquired with a pulsed laser sheet are used, along with a continuity equation solver, to extract all three components of the periodic velocity field within a large volume. The isolated rotor experiments are made with pulsed white light sources, identical to those used in testing at large rotorcraft facilities. Preliminary comparisons are made with point-wise velocity data acquired using laser velocimetry.

## INTRODUCTION

During takeoff, landing and transition, the wake of the rotors of a tiltrotor aircraft interact with the wings, causing download and unsteady flow phenomena. To quantify such a problem and understand it various elements, 3-component, periodic velocity data as well as surface pressures and vortex trajectories are required, for several test conditions with several flap settings. This poses an immense challenge to traditional measurement techniques. While pointwise laser velocimetry can be, and has been, used to define phenomena and vorticity distributions in a few specified planes, use of LV to quantify the whole flowfield is prohibitive.

Conventional Particle Image Velocimetry (PIV) can be used in wind tunnel flows to quantify small sections of the flowfield at a time. Typical dimensions of flowfield areas used in PIV are on the order of 0.3m x 0.3m at most, even when large-array cameras (2K x 2K arrays) are used, combined with laser pulse energies of over 200 milli-Joules. Current pulse repetition rates (i.e., velocity fields per second) are restricted to about 15 per second when the laser has such pulse energy. These figures are optimistic: there has not been any published demonstration of PIV measurement in a rotor wake as yet. The performance of conventional PIV in the presence of strong out-of-plane flow, in large-scale air flows (velocities more than a few mm per second), remains to be examined.

In practice there are other mundane, but show-stopping, problems. The foremost is that a laser with such pulse energies is a Class IV laser, which requires stringent safety precautions, and costs a large amount. Setting up, aligning and operating such lasers in the hectic environment of a rotorcraft wind tunnel test is not a trivial task, either to certify or implement. When the flowfield of interest is in a large wind tunnel (distance to measuring volume > 3 meters), and the areas of interest are on the order of 2m x 2m, conventional PIV remains beyond the present budgets of most facilities.

Gorton et al [1] have demonstrated the use of Doppler Global Velocimetry in the tailrotor flowfield of a helicopter model, in the 14’ x 22’ Subsonic tunnel at Langley Research Center. This technique is an excellent choice where the flow velocity is high. However, current limitations on resolution appear to limit the accuracy to about 1 to 2 m/s, making it difficult to apply in low-speed flows. DGV also requires a powerful laser (monochromatic source), as well as several cameras. While Samimy et al [2] have demonstrated the use of a single camera for each velocity component (down from 2 per component) in supersonic flows, this has not been shown in flows containing reversal, as in the case of rotorcraft flows.

Work at Georgia Tech has aimed to obtain velocity fields from large-area smoke images, at video rates, from the large distances typical of rotorcraft facilities. The Spatial Correlation Velocimetry technique [3 - 9] has been applied to increasingly complex flowfields - steady and unsteady water flows [3], dominantly-2-D, quasi-steady and unsteady wind tunnel flows with laser illumination [4 - 5] turbulent wind tunnel exit flow using steady white light sheets [7], and finally to 3D unsteady rotorcraft flows [6]. The different aspects of the technique have been validated using solid surface displacement [4], addition of random measurement noise [4] and comparison with point velocity measurements [7].

In this paper, the following issues are addressed. First, a technique is described for measuring all 3 components of velocity over a large volume in a rotor wake. This is applied to the rotor wake/wing interaction flowfield, in the 2.7m x 2.1m tunnel at Georgia Tech. Next, the requirements for performing SCV measurements in large facilities are discussed, with reference to 3 such tests performed to-date. Next, the accuracy of velocity measurements performed over large areas using an inexpensive white light sheet system is addressed using a wind-tunnel exit flowfield which is primarily one-dimensional. Finally, an isolated rotor flowfield is used to set up a challenging test case containing the complexities of rotorcraft wakes. Preliminary comparisons are made between results obtained with the pulsed white light sheet system used in large facilities, and point-wise laser velocimeter data.

## THIRD VELOCITY COMPONENT SOLVER

Since our primary interest is in low-speed air flows, we use a method for the computation of the third velocity component based on satisfying the incompressible continuity equation. Several parallel planes of SCV data are taken throughout the flowfield of interest. The solver steps across the flow, starting from two boundary planes where the component of velocity normal to the plane is known (usually zero or constant), so that all components and their gradients can be specified in these planes. In the wind tunnel this is done simply by going away from the rotor wake region and, where necessary, going near the tunnel walls. This second order Third Velocity Component (TVC) solver yields the out-of-plane component at all the parallel planes.

A test case of rotating flow interacting with ground was chosen to validate the TVC algorithm. Details of the flow and implementation are described in [8]. The Navier-Stokes equations in cylindrical coordinates are used to analyze this problem. The solution was used to generate 27 slices of 2D velocity data (a 41 x 31 grid of radial and azimuthal velocity components) parallel to the ground. When the two boundary planes are chosen in the farfield, there is a very good match with the exact solution except for a small region near the ground where the gradient in the axial velocity profile is steep. The radial and tangential velocities reconstructed from 2D data planes of the other two components also compared well to the known solution.

Further numerical experiments verified the robustness of the code in the presence of upto 25% random noise, added to simulate experimental uncertainties. The computation of the third component involves computing velocity gradients from velocity values at surrounding grid points. Therefore, interpolation is required in-plane and between planes to compensate for missing data points and also to increase the resolution of the 2D velocity data where required. Second order polynomial interpolation was chosen as the most suitable.

## ROTOR-WING TEST

The experimental set-up in the 2.7 m x 2.5 m test section of the John J. Harper wind tunnel at Georgia Tech. is shown in Fig. 1. It consists of a ceiling mounted rotor system, a floor mounted wing system and the image acquisition systems comprising of smoke generators, video cameras and pulsed laser light. The wing spans the full width of the wind tunnel, eliminating wing tip effects in the rotor wake interaction region. A full-span NACA0021 wing with 40 cm chord at a 0° angle of attack to the freestream direction is used. A cambered flap with a 12.5 cm chord is attached to the trailing edge of the wing. The two-bladed, teetering, 91.4 cm diameter rotor is mounted on the tunnel roof with its hub at 12.7 cm upstream of the wing leading edge and centered at mid-span. The rotor hub is at a height of 36.83 cm above the wing centerline.

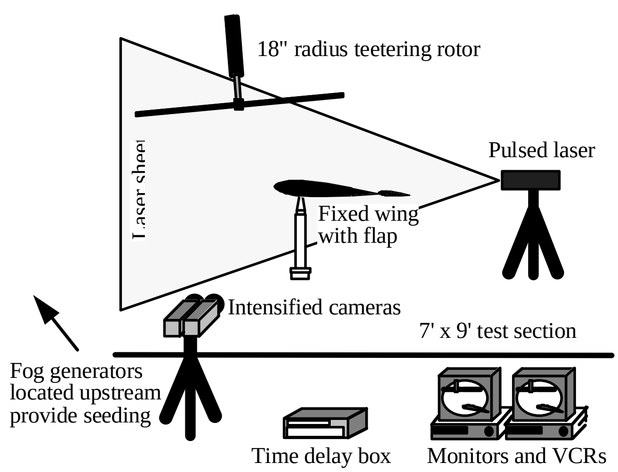



Fig. 1: Experimental set-up for wing-rotor

The rotor was run at 1050 RPM and an advance ratio of 0.075 was maintained by keeping the tunnel freestream steady at 3.77m/s. A dual-camera system is setup on a traverse outside the test section, with the shutter of one camera delayed by a specified interval with respect to the shutter of the other. A third camera is used to keep track of the rotor azimuth by focusing on an azimuth disk attached to the rotor shaft. With a 30 Watt pulsed copper vapor laser source operating at 5994 pulses/sec, test parameters are adjusted to give one laser pulse per image. The laser beam is collimated into an optical fiber used to transport the light into the test section. This fiber is connected to laser sheet generating optics mounted on a traverse located 2.54m downstream of the rotor hub. Theatrical fog generators used to seed the flow are located 2.54m upstream of the rotor hub.

## PROCEDURE

The measurement area is about 65 cm x 50 cm between the rotor and the wing extending from the rotor hub to beyond the flap hinge at the wing trailing edge. A 55 cm X 40 cm gridboard is placed vertically in this plane covering much of the image area of interest during the camera calibration. The two cameras are aligned to view the exact same measurement area within 1 pixel error. At the test condition of 1050 RPM rotor speed and 3.77m/s tunnel speed, the smoke is turned on and flow visualization recorded. This is repeated for 3 different delays between the camera shutters to capture a wider range of flow speeds. In the current experiment delays chosen are 3.34, 4.34 and 6.67 ms. These are chosen to be multiples of the laser pulse width, to ensure a flash of light when the delayed camera is triggered. The light sheet is stepped normal to itself in steps of 5.08 cm covering the entire rotor wake and extending to the tunnel wall on the retreating blade side. Several images are captured at each location for phase averaging (2 - 3 minutes of continuous video recording).

### Run times

These experiments were completed in a total tunnel occupancy time of less than 4 weeks. The SCV data acquisition itself was completed in 6 days. This gave 2D velocity data in 27 chordwise planes throughout the rotor wake region upto the tunnel walls on the RBS. Each vector field is generated in approximately one minute using a 175 MHz SGI-O2 workstation with an R10000 chip.

### Data Reduction

The recordings from the two cameras are digitized as Quicktime movies of about 10 sec. duration, and analyzed, one image pair at a time. The rotor azimuth is determined from the display of the azimuth disk that is mixed in with one of the video signals. Images are sorted according to azimuth and all vector fields at the same azimuth are averaged to get the phase averaged results. A total of 600 vector fields were obtained at each chordwise station in the flow. These were then averaged into 24 azimuth bins, so that 25 vector fields were ensemble averaged in each bin. The vector fields thus obtained are not strictly instantaneous, but are associated with the middle azimuth location of the delay between the two shutters.

## RESULTS

Fig. 2 shows ensemble-averaged velocity fields in the azimuth interval centered at 324°. in 4 chordwise planes, 10.2 cm apart, under the Retreating Blade Side of the rotor, with the flap at 0°. The phenomena due to the tip vortex at different phases of its interaction with the wing can be seen. Two regions of tip vortex interaction with the wing - one near the leading edge and one further back and the absence of a 2-per-revolution variation in flow features indicate a separation of vortex trajectories from the two rotor blades [9].

**[Figure 2 attached as pdf]**

Velocity traces along the wing chord were extracted from the 2D planar velocity fields. These traces are plotted for two heights above the wing centerline and at four spanwise stations on RBS in Fig. 3. The solid line trace is at z/R = 0.14 (6.4 cm above wing centerline) and the dotted one is at z/R = 0.46 (21 cm above wing centerline). The wing centerline is at z/R = 0 and the rotor tip path plane at z/R = 0.81. Square and round symbols are used to denote the streamwise and vertical components respectively. These sample traces have been extracted from the data set at a fixed rotor azimuth of 324°. Close to the wing surface the streamwise component is considerably less than freestream and reaches near freestream values at the z/R=0.46 station. While these magnitudes are reasonable detailed comparisons with LV measurements (where available) is required to reinforce these findings.

**[ Figure 3 attached as pdf]**

Figure 4 shows the spanwise-vertical velocity field above the wing at X/R = 0.467, extracted from 17 chordwise-vertical planes of 2-D velocity data under the Retreating Blade Side of the rotor. The flowfield shows the development of an outward-flowing spanwise wall-jet profile, conforming to expectations. The rotation due to the rotor wake induces the right-to-left velocities seen nearer the rotor. Further work on refining and validating the flow measurement is in progress.

[Figure 4 attached as pdf ]

## APPLICATION TO LARGE-SCALE ROTORCRAFT TESTING

The SCV technique is especially suited to large-scale facilities where flows with reversal have to be measured. In such facilities, the following conditions generally hold true:
1. Set-up and alignment times are of the order of hours, not months as in the case of laser-based techniques. Thus the instrumentation must be amenable to quick transportation, installation and alignment.
2. The use of Class IV lasers involves extreme safety precautions, which conflict with the safety requirement of having visual access to the test configuration.
3. Optical paths are of the order of 10 to 20 meters.
4. Run-time is at a premium, generally costing on the order of $5000 per hour.
5. Rotor runs must be completed in a few minutes for each setting.
6. Preliminary confirmation of data quality must be available within minutes following each run, so that schedule adjustments can be made quickly.
7. Each test run will involve numerous control, operation and data acquisition objectives, so that the velocity measurement cannot dictate the run schedule.
8. The complexity of the set-up usually results in serious delays before the first data acquisition run is performed, so that one is always in a hurry.

In 1996, the SCV technique was applied to rotorcraft flowfields in the NASA Ames Axial Flight Facility, the Bell Helicopter Textron hover facility, and the Boeing VTOL tunnel, within a space of 6 months. In each case the entire measurement system was packed up and shipped Federal Express to the facility in question, from Atlanta. The total time from unpacking to repacking was 1 week in each case. Typical distances and flow area dimensions are given in Table 1

**Table 1: Measurement Parameters in Large Facilities**.

| Parameter | Value |
|---|---|
| Source-to-flow distance, m | 10 |
| Camera-object distance, m | 10 |
| Flow area imaged, m x m | 2m x 1.4m |
| In-plane Velocity m/s | $-30 < u < +50$ |
| Out-of-plane speed, m/s | 5 m/s |

To enable such measurements, several modifications were made to the SCV technique. These include:
1. The use of white light sources, rather than lasers, to minimize the eye-damage danger inherent in coherent illumination.
2. The use of pulsed light sources to obtain suitable image intensity with a system that could be plugged into a standard 15-amp, 110 volt AC outlet.
3. The use of a seeding system which is used in most facilities for smoke visualization, rather than the specialized Laser Velocimeter seeding systems. This enabled the seeders to be rented locally from theatrical supply companies, and eliminated the need for special precautions which would have been required with toxic seeding systems. This also broke through the difficulties of seeding a very large flow facility with sufficient particle density to allow visualization.
4. The reduction of the analysis code to a version which could run on an Intel486 PC, which in turn could be transported and set up, independent of the host facility's computer systems. This eliminated the hassles of getting secure access to proprietary data systems.

The tests conducted in 1996 produced flowfields which are generally agreed to be qualitatively correct. Quantitative validation is, however, a difficult problem in such flows: at best there may be hot-wire data at some locations, but these too are subject to uncertainty when there are large changes in flow direction. It is nearly impossible to find validation data acquired under the same conditions as the SCV data, simply because of the practical problems (see features F4 and F7 above). Below we list some of the requirements for validation:

V1: The validation technique must be believable, and its accuracy known.
V2: The validation technique must have the same spatial resolution as the SCV technique.
V3: The validation technique must have the same temporal resolution as the SCV technique.
V4: The validation must be performed under the same conditions as the SCV measurements.

### Steady White Light SCV Validation

The accuracy of the velocity measurements using the white light system is demonstrated over the speed range from 0 to 19 m/s by comparing instantaneous velocity vectors to the time-averaged velocity measured by a TSI Velocicalc™ probe placed downstream of the exit of a 1.07 m x 1.07 m wind tunnel. The light sources used here were four 400-

watt outdoor halogen lamps, with optics added to generate a continuous sheet of light, whose thickness increased from roughly 6mm at the generators to about 25mm at 3 meters away. The light sheet was oriented in a plane which was along the flow direction, but cut across the exit section at 45°. The camera was placed 9.14 meters from this plane, normal to it.

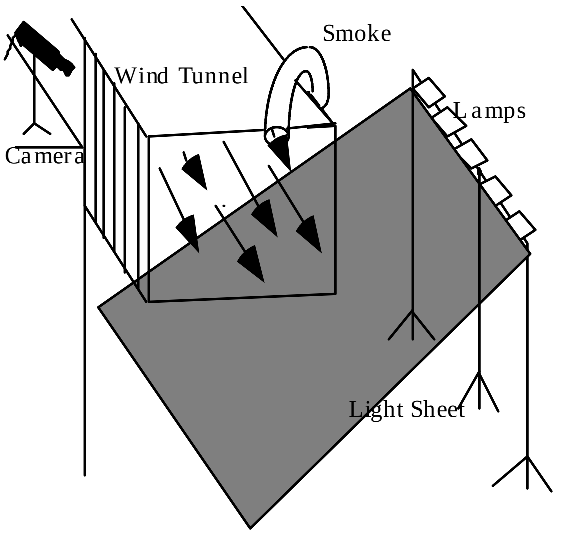



Figure 5: SCV set-up at the exit of a 1.07 m X 1.07 m wind tunnel. From Ref. [7].

Even though the flow velocity here is high, very small time delays are not required due to the large image area. This enabled the use of a single video camera where consecutive frames separated by 33.33 ms are correlated to obtain the velocity field. Also, the gradients in this flow region are sufficiently small so that high spatial resolution is not needed. Instantaneous velocity from SCV matched the point velocimeter reading with no bias error over the entire range of velocities tested. The figure below shows the comparison with different camera and lens settings.

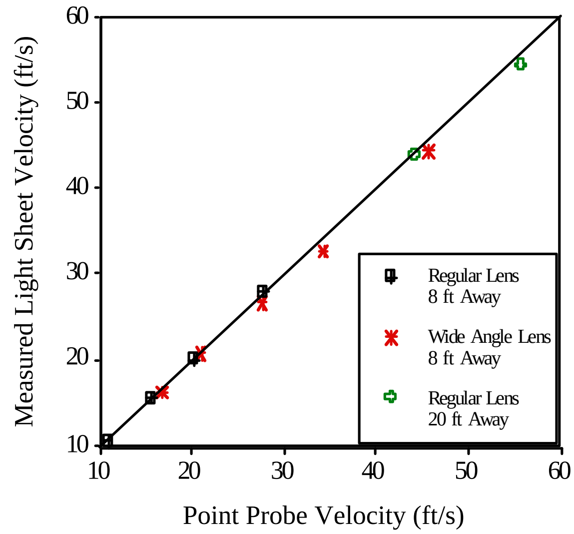



Figure 6: Calibration against TSI Velocicalc point velocity sensor. From Griffin, Funk & Komerath [7].

## ISOLATED ROTOR TEST CASE

Description of set-up

A two bladed teetering rotor with a 10° fixed pitch and a NACA0015 airfoil section was tested. The blade has an untwisted planform with a radius of 0.914m and chord length of 8.57 cm. The rotor shaft is inclined at 6° to simulate forward flight. Test conditions were held constant at 1050 RPM (accurate to within 1 RPM) and advance ratio of 0.1. The freestream velocity at these test conditions is 5.03 m/s. These settings were chosen for comparison with previously acquired LDV data on the same configuration.

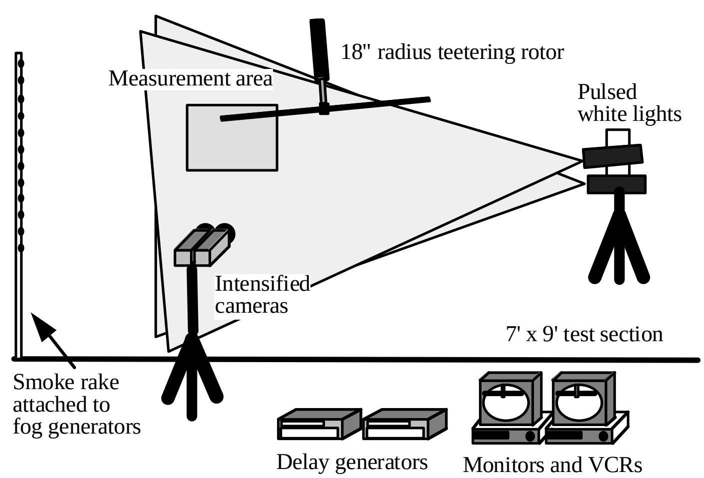



Figure 7: Experimental set-up for isolated rotor test in Harper Tunnel

The flow was illuminated using a pair of EG&G 40 Watt strobed white lights which were pulsed at 29.97 Hz so as to synchronize with the video cameras. Each light was synchronized with one camera. The two lights are aligned such that both illuminate the same section of the flow as shown in the figure above. Two Stanford delay generators were used to set the time delay between one light/camera pair and the other. Fog generators were used to seed the flow. The smoke from the fog generator is fed into a vertical rake mounted on a traverse in the test section (far upstream of the rotor). This allows seeding over an area in the plane of the light sheet. Both light sheet and smoke position are remotely controlled via computer. The SCV measurement area is on the upstream part of the wake is shown. The measurement area is 0.36 m X 0.28 m (14" X 11") upto 0.23 m (9") inboard of the blade tip. For a normal 640 X 480 CCD array this translates to 42 pixels/inch.

**RESULTS**

The SCV measurements shown in this paper are marked by the rectangular region upstream of the rotor hub in Fig. 7. A series of flow visualization images are shown in Fig. 8 from rotor azimuth of 210° to 360° (or 0°) in steps of 30°. Tip vortices are identified as small regions of no seeding surrounded by swirling smoke patterns. At about 210° the tip vortex is just formed and is barely visible near the blade tip in Fig. 8(a). With each 30° increment in the rotor azimuth the downstream convection of the tip vortex is clearly seen. The reflection of the blade edge in the light sheet is seen for the 0° image (f). Such a region of bright pixel intensity not related to the flowfield is a source of error in SCV measurements. Therefore some spurious vectors due to motion of the rotor blade between images at the 0° and 180° azimuths are expected.

The velocity fields obtained using these images (and the corresponding ones from the second camera) and shown in the same sequence in Fig. 9. The azimuths shown here are the central azimuths in a bin which is 12.6° wide. This is essentially the angular displacement of the rotor blade in the time interval between the two images correlated. The images shown in Fig. 8 are from the second delayed camera and therefore these azimuths are 6.3° later than the corresponding centered azimuths in Fig. 9. The images from camera would be 6.3° ahead of the centered azimuth. The time resolution of the velocity field shown is therefore 12.6° or 2 ms (this is the delay set between the two cameras).

The rotor blade tip is located at the origin of the co-ordinate system used. The x-axis is downstream distance in inches and y-axis is the vertical distance below the blade tip. The part of the image used up by the video frame code is marked. This frame code is used to match images from the two cameras. The downflow region in the wake is clearly convecting downstream. The rotation of the vectors in Figures 9(d), (e) and (f) is consistent with the direction of the tip vortex rotation. Vorticity contours shown indicate regions of high vorticity and these correlate well with the position of the tip vortices in the flow visualization images in Fig. 8. At the near zero azimuth location i.e. Fig. 9(f) where reflection of the rotor blade is visible in the images some upward vectors are seen near the tip path plane (seen to a lesser extent in (a) and (e)). This is because the blade reflection moves upward from image 1 to image 2 and the correlation captures this motion. These vectors are therefore not indicative of any flow feature.

[Figure 9 attached as pdf]

Figure 10 attached as pdf ]

<u>Comparison with LDV</u>

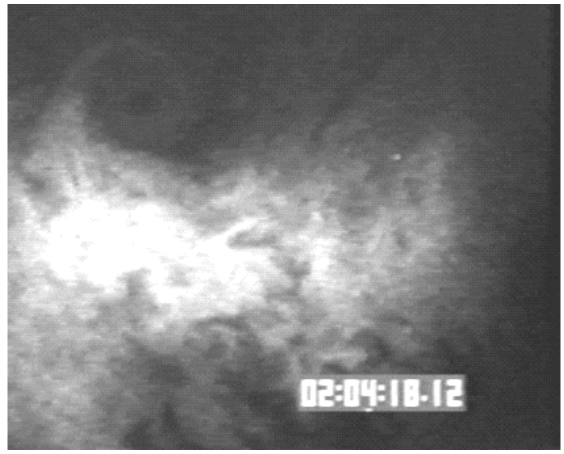
In Figure 10, preliminary comparisons are made between the SCV results and single-point measurements made using a Laser Doppler Velocimeter (LV). For this comparison, the LV data are averaged to a resolution (temporal and spatial) similar to that of the SCV, so that many sharp features are lost. LV data points within a square window of 4 cm side are averaged. This corresponds to the 64 X 64 pixel correlation window in SCV. The line traces in Fig. 10 show the radial variation of the streamwise velocity component inboard of the blade tip. Four azimuths are shown with a 180° phase difference between (a) and (c) and also (b) and (d).

The LV measurements were performed before the SCV measurements were made, and as such did not include the effects of the complex and somewhat intrusive smoke seeding system which was placed upstream for the SCV measurements. The challenge in this comparison is that the flowfield involves high out-of-plane velocities on the order of 10m/s, which reaches 3 times the freestream component. Thus seed particles are not expected to stay in the measurement plane beyond a very short time interval. Despite this, the comparison shown in Fig. 10, for the azimuth-resolved velocities along a radial line below the rotor tip path plane, are fair.

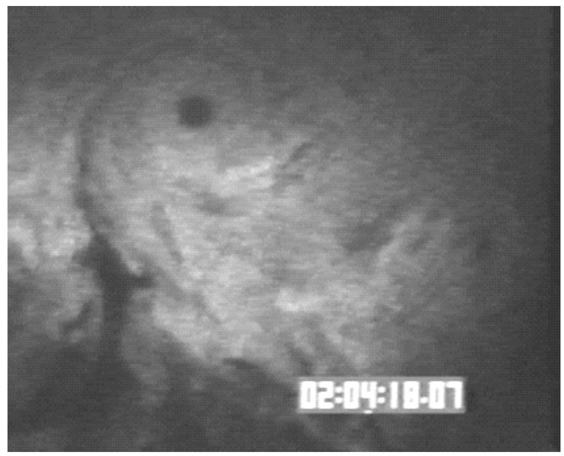
## CONCLUSIONS

The instantaneous 3D phase-resolved velocity field of a rotor wake/wing interaction flowfield has been captured.
The extension of the planar SCV technique to 3D using several closely spaced parallel planes of 2D velocity data and a second order finite difference solver has been successfully implemented in this flow.
Vorticity contours computed from planar velocity data show a separation of vortex trajectories as they interact with the wing and the related flowfield effects.
Initial third velocity component results show the development of the spanwise wall jet above the wing, due to wake interaction.
White-light SCV has been developed to the extent where fair agreement with LV velocities were obtained in the wake of an isolated rotor.
The spatial and temporal resolution of the SCV measurements are being improved using a Lagrangian iterative process, which allows the use of data obtained at short time intervals and smaller correlation windows.


(a) rotor azimuth = 210 deg.




(b) rotor azimuth = 240 deg.




(c) rotor azimuth = 270 deg.


(d) rotor azimuth = 300 deg.


(e) rotor azimuth = 330 deg.


(f) rotor azimuth = 0 deg.

Figure 8 : Sequence of flow visualization images used for SCV in the isolated rotor test

## ACKNOWLEDGMENTS

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## REFERENCES

1. Gorton, S.A., Meyers, J.F., Berry, J.D., "Velocity Measurements Near the Empennage of a Small-Scale Helicopter Model", AHS 52nd Annual Forum, Washington, D.C., June 1996.

2. Clancy, P.S. and Samimy, M., "Multiple-Component Velocimetry in High Speed Flows Using Planar Doppler Velocimetry", 35th Aerospace Sciences Meeting & Exhibit, Reno, NV, Jan. 1997, AIAA 97-0497.

3. Komerath, N.M., Fawcett, P.A., "Spatial Cross-Correlation Velocimeter", United States Patent No. 5,249,238, Sept. 1993.

4. Fawcett, P., Komerath, N.M., "Spatial Correlation Velocimetry in Unsteady Flows", AIAA 91-0271, Jan. 91.

5. Fawcett, P.A., Funk, R.B., Komerath, N.M., "Quantification of Canard and Wing Interactions Using Spatial Correlation Velocimetry", AIAA 92-2687, 10th Applied Aerodynamics Conference, Palo Alto, CA, June 1992.

6. Funk, R.B., Fawcett, P.A., Komerath, N.M., "SCV Measurements in the Wake of a Rotor in Hover and Forward Flight", AIAA paper 93-3080, 24th Fluid Dynamics Conference, Orlando, FL, July 1993.

7. Griffin, M.H., Funk, R.B., Komerath, N.M., "Wind Turbulence Measurement Over Large Areas Using Spatial Correlation Velocimetry". Proceedings of the Silver Symposium of the Flight Test Engineers Society, Patuxent River, MD. V-4-12, August 1994.

8. Reddy, U.C., Matos, C.A., Mahalingam, R., Komerath, N.M., "Whole-field velocity measurement in unsteady periodic flows', AIAA 97-2325, June 1997.

9. Reddy, U.C., Matos, C.A., Mahalingam, R., Funk, R.B., Komerath, N.M., "Velocity Measurements in a Rotor Wake Interacting With a Fixed Wing". AIAA Paper 98-1033, 36th Aerospace Sciences Meeting, Reno, NV, January 1998.