FLOWFIELD ISSUES RELATED TO TILTROTORS

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ABSTRACT

This paper discusses results on several issues related to future tiltrotor craft. Experiments show that wing trailing edge flap deflection causes a lateral shift of the wake impingement region. Steady surface blowing to redirect the wake produces a 20% improvement in the effect of the flaps, essentially eliminating download at a low forward speed. Flow visualization and large area velocimetry have been shown in large-scale experiments, efficiently enough to enable flow control experiments. Measurement distances have reached the values needed for measurements around full-scale vehicles. Instantaneous velocity field data suggest that cyclic pitch adjustments might enable a further reduction in download.

INTRODUCTION

In this paper we present results obtained from experiments related to tiltrotor aerodynamics. Three issues are discussed. The first is the effect of flap deflection and upper surface blowing on download in low speed forward flight in the helicopter mode. The second is the use of flowfield measurements in large-scale development testing for rapid exploration of ideas. The experiments described here demonstrate both basic test cases of rotor wake/ lifting surface interaction and scale-model tests of tiltrotor craft, where various phenomena are visualized, isolated, quantified, and modified.

DOWNLOAD REDUCTION

The experiments described here were done in low-speed forward flight, at advance ratios of 0.075 to 0.1, because they were conducted in a wind tunnel where hover experiments could not be done. Extrapolation of the results to hover is left to the reader. Current tiltrotors generally have download-to-thrust ratios of around 10 percent[1], which is a substantial fraction of the hover payload. Using Newton's 2nd law of motion, it can be argued that download comes from the momentum change of the flow as it interacts with the wing, turning first inboard along the wing and then up in the fountain effect region. The upper bound on the payoff from redirecting the spanwise flow to prevent the fountain effect is thus roughly 50% of the download. In hover, the flap on current tiltrotor aircraft is deflected 60 to 75 degrees, partly to reduce the area of the wing normal to the wake. Also, some of the flow over the wing goes forward and spills over the leading edge. Both of these features hinder transition to lifting forward flight, or reduce lift/drag ratio. In a forward flight condition, even at a low advance ratio of 0.075 used here, a much lower flap setting, perhaps around 20 degrees, appears to be optimal. Experiments show that tangential blowing can substantially improve the flap effectiveness, and redirect the spanwise flow rearward.

McVeigh et al[1] have compared the performance of several devices in alleviating hover download on tiltrotor aircraft. Geometric devices to minimize spanwise flow, and to promote chordwise flow were investigated. Significant improvements in hover power required and lift were seen with the “Butterfly” device which deflects the spanwise flow into two separate streams, one forwards of the aircraft, and one backwards.

In small-scale experiments at the Georgia Tech 7’ x 9’ wind tunnel, some of the fluid dynamic mechanisms of these devices have been studied, for the phase of low-speed forward flight in transition from hover to forward flight. The correspondence of the flight vehicle geometry and the test geometry, a basic full-span wing-rotor configuration is shown in Figure 1. The retreating blade side on the wing surface is analogous to the wing of the tiltrotor. Figure 2 shows the actual experimental set-up.

The effect of circulation control via surface blowing has been studied for tiltrotors in hover. Lee[2] studied the effect of tangential blowing on the upper surface, simulated by separation point displacement. A small displacement of the separation point on the airfoil was found to completely change the entire flow field over the wing. Download was significantly reduced, primarily due to the

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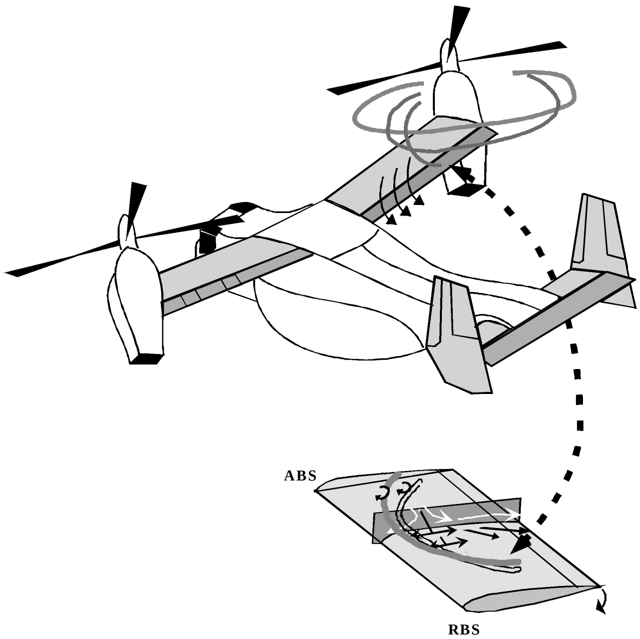


Figure 1: Correspondence of tiltrotor wing/rotor geometry during transition, to the geometry of the experimental configuration studied in the Georgia Tech John J. Harper 7' x 9' wind tunnel.

reduced pressure on the upper surface. Felker et al[3], in a small-scale experiment, studied the effect of boundary layer control blowing on download of a wing in the wake of a hovering rotor. Such blowing caused significant reductions in download, between 25 and 55%.

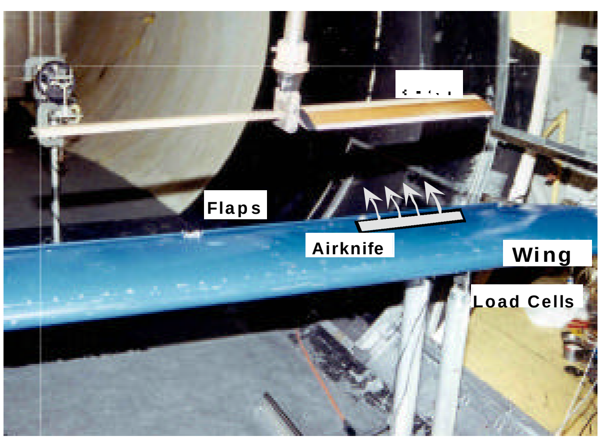


Figure 2: Photograph of experimental setup in Georgia Tech John J. Harper windtunnel

Investigations of the effect of both trailing edge blowing and flap deflection on download were carried out at Georgia Tech. A schematic of the rotor-wing set-up in the John Harper wind tunnel at Georgia Tech is shown in Fig. 3. A full-span NACA0021 wing with 0.4 m chord is placed at zero degree angle of attack with respect to the tunnel freestream. A 0.914 m diameter, two-bladed constant-chord, untwisted NACA0015 teetering rotor with 8.57 cm chord is mounted from the tunnel roof upstream of the wing leading edge and centered at mid-span. Pressure distributions were determined using an array of 189 pressure taps on the wing's upper and lower surfaces. The majority of these pressure taps were concentrated on the upper surface of the wing, beneath the center and retreating blade side (RBS) of the rotor.

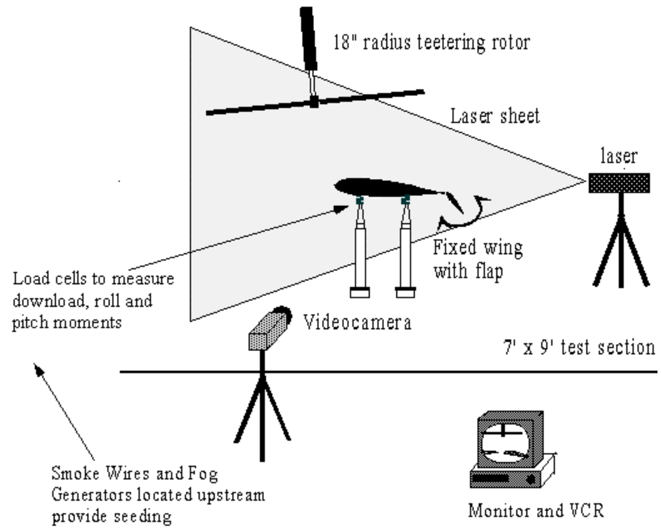


Figure 3: Schematic of experimental setup in Georgia Tech windtunnel.

A segmented wing trailing edge flap system was used, consisting of 4 computer controlled NACA0012 flap segments with a 0.127 m chord. The flaps could be independently deflected over a range of –15 to 45°. For flow visualization, the rotor was run at 1050 RPM and an advance ratio of 0.075 was maintained by keeping the tunnel freestream steady at 3.77 m/s. Force measurements were conducted at the same advance ratio, but with the rotor rpm at 2100. Four S-type compression/tension load cells were used to record download on the wing with an uncertainty of 0.04%, (< 0.02lbs). The load cells formed the top part of the stand on which the wing was situated. Previous work at this tunnel has shown the correspondence of velocity fields and vortex trajectories between these two test conditions, scaling with advance ratio in this range. The static pressure distribution over the surface had previously been measured, with the rotor running at 2100 RPM and maintaining the same advance ratio of 0.075.

Slotted blowing was provided using an "Airknife" blowing device constructed of aluminum. Pressurized air is supplied to the Airknife, which uses the Coanda effect to turn the airflow 90° so that it is directed tangential to the upper surface of the device. The slot is 0.1524m long and has an amplification ratio (entrained air to compressed air) of 30:1. It is mounted inside the wing so that the airflow from the jet is tangential to the wing surface. The Airknife was located on the retreating blade side (RBS), 0.274 m from the rotor hub in the spanwise direction, and 0.286m from the leading edge of the wing. This places it near the trailing edge of the wing, under the tip of the rotor. Compressed air at 40 PSI was supplied to the Airknife.

Flap-Induced Lateral Shift of Wing Pressure Distribution

It is widely known that large flap deflections are an effective means of download reduction in hover. The primary reason for download reduction in the hover case is the reduced planform area of the wing. Less surface area is exposed to the downwash of the rotor, resulting in a lower download on the craft. However, in forward flight conditions, such as during transition, large flap deflections also result in large drag. The effect of smaller flap deflections was investigated.

Contours of the pressure coefficient on the wing surface on the RBS, referenced to freestream dynamic pressure, are plotted in Figure 4. The rotor wake impinging on the wing causes a large region of positive pressure, with pressure coefficients about 2.0. The undeflected case is shown in Figure 4(a). A shift in the rotor wake impingement on the wing is seen in Figure 4(b), with the portions of the segmented flap system deflected 30°. The contours with the full span flaps deflected show a decrease of mean pressures throughout the measurement area, as expected. The pressure reduction due to flap deflection corresponds to a maximum ΔCp of 1.4. The contours indicate a shift in the high-pressure regions towards the ABS. Two other flap deflection configurations were performed as well. Deflecting only the two inboard flaps (equivalent to outboard flaps on the V-22) produced a shift in the pressure contours similar to that from the full span deflection. Deflecting only the two outboard flaps, however, showed little effect on the pressure contours. SCV measurements in the mid-span location suggested a skewing of the rotor wake towards the ABS, reinforcing the observation from Fig. 4.

Four compression/tension load cells were used to measure the steady-state loads on the wing. Loads were time averaged over 30 seconds for each setting. Figure 5 demonstrates download reduction on the wing with increasing deflection of all four flap segments. Data for 30° inboard and outboard flap deflection are also shown. Flap effectiveness in download reduction is seen to linearly increase up to 30 deg. of deflection. Beyond 30 degrees, increasing flap angle does not significantly change the download on the wing, but does produce a large drag increase. Deflecting the outboard flaps alone was mildly effective, while inboard flaps were shown to be nearly as effective as full span deflection. At an advance ratio of 0.075, full span flap deflection beyond 15 deg. changed the net wing force to lift.

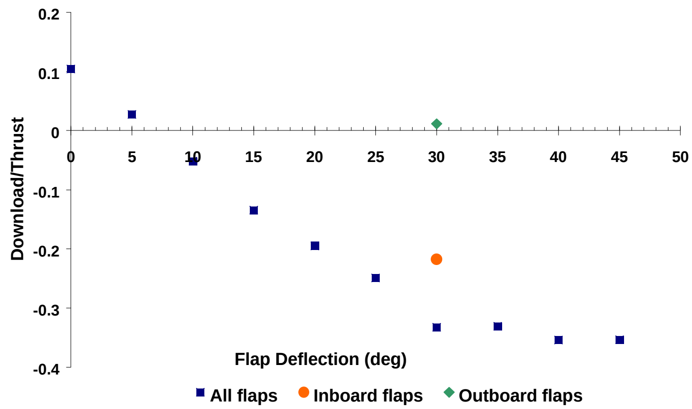


Figure 5: Variation on download on wing with flap deflection

Effect of Blowing on Download

The effect of surface blowing from the RBS of the wing on the flowfield and download was examined. The effects of the jet alone, and then in addition to flap deflection were studied. The effectiveness of trailing edge flap deflection has been previously reported[8], and was discussed in the previous section. The jet allows us to study the effects on the flowfield through systematic steps, from no modification, to flap deflection, to no flap deflection and jet on, to flap and jet blowing, and eventually to unsteady blowing. However, the power requirement for a blowing jet must be weighed against the cruise drag penalty, or weight of deployment, of fixed mechanical devices. Since the full span flap deflection and inboard flap deflections proved most effective, only these flap deflection cases were examined in conjunction with the surface blowing.

Table 1 shows the progression of geometries. At 2100 rpm, in hover conditions, the rotor imposes a load on the wing of 29.4% of rotor thrust. In low-speed forward flight at an advance ratio of 0.075, the baseline download due to the rotor wake is determined by subtracting the load cell readings from wind-only conditions. Flap deflection and blowing cases are all at 2100 rpm, 0.075 advance ratio. All blowing cases are using a steady 40 psi air supply. The effect of blowing on the wing loading in still conditions (no rotor or wind) was negligible. However, blowing during hover had a significant effect, causing a 13 percent reduction in download on the wing. Due to the extremely low advance ratio, the download on the wing in forward flight was virtually the same as in hover.

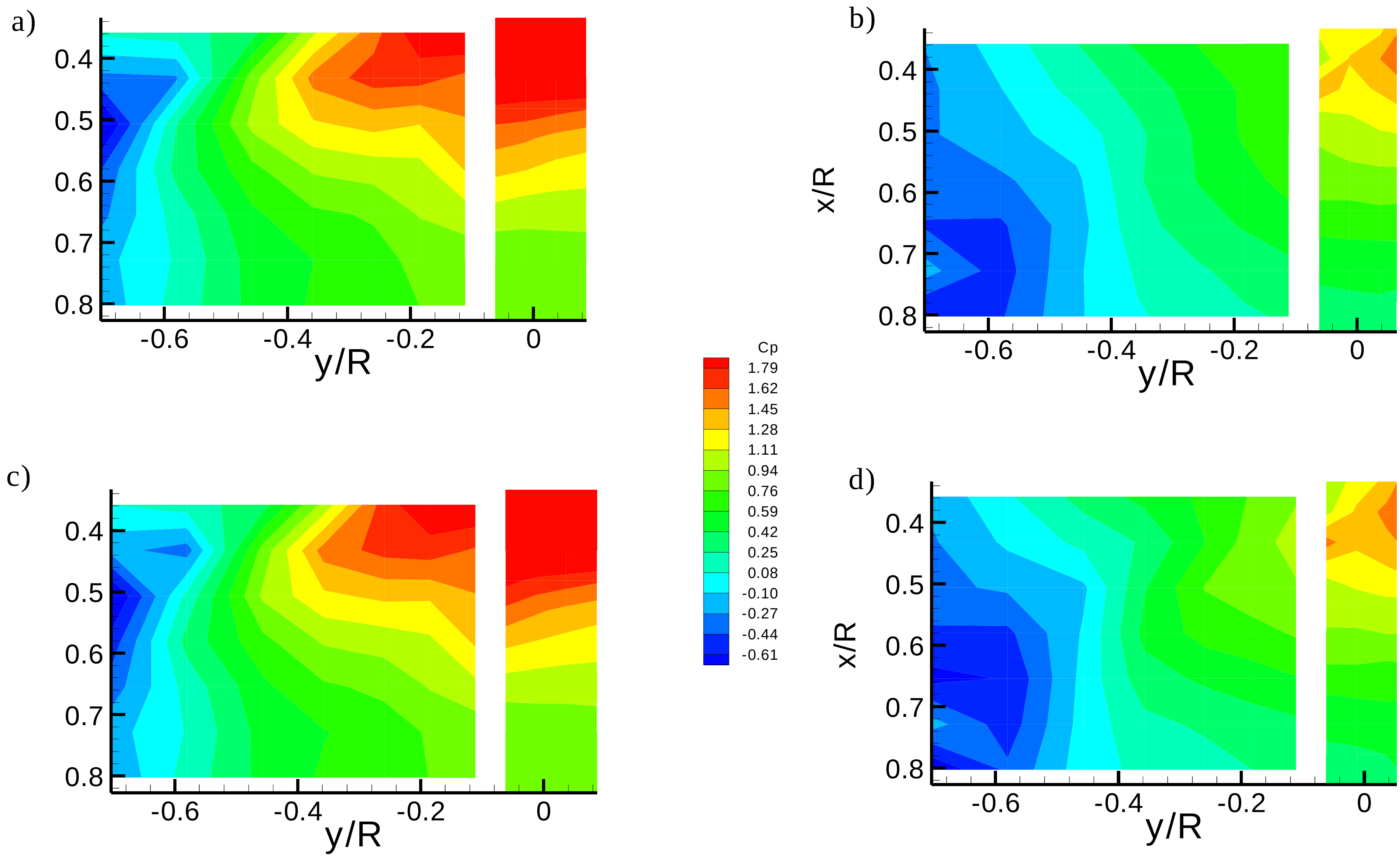


Figure 4: Static Pressure contours over the wing upper surface with segmented flap system at a) 0° b) 30° c) Outboard only flaps at 30° d) Inboard only flaps at 30°

Blowing had varying effects on download reduction in conjunction with flap deflection. With no flap deflection, the Airknife's effect on download was negligible. It did cause some degree of reduction in download for all flap deflection angles tested. It improved the effectiveness of inboard flap deflection to a greater extent than full span deflection. Smaller angle flap deflections showed a greater percentage change in download reduction with the blowing on than large flap deflections. This is perhaps due to increased flow separation at the leading edge of the flap at higher angles. A 20 percent increase in download reduction was seen with the addition of the Airknife with 20° deflection of the inboard flaps. An 11.5 percent improvement over the flaps alone was seen for blowing with 20° full span flap deflection. An approximate 6 percent improvement in download reduction was seen with the addition of the Airknife to 30° flap deflections.

Configuration	**Download/ Thrust**	**Reduction in D/T**
Rotor only, Hover	0.294	-
Rotor only, Hover+Airknife	0.258	0.036
Rotor in Forward flight	0.304	-
Full Span Flaps 30°	-0.081	0.385
Inboard flaps 30°	0.003	0.300
Airknife only	0.301	0.003
Airknife + full 30° flaps	-0.106	0.41
Airknife + inside 30 ° flaps	-0.016	0.32

Table 1: Change in Download on Wing for Various Geometries

The effect of lower stagnation pressures of the blowing on download was also studied. The pressure was varied between 20 and 40psi in 5psi increments. For hover, blowing stagnation pressures below 35psi had little effect. A stagnation pressure of 35psi resulted in a 11% reduction in download, whereas a 40psi stagnation pressure caused a 13% reduction. Higher stagnation pressures were not studied in this experiment, though they should be considered for future tests.

Preliminary results from varying stagnation pressure of blowing in conjunction with flap deflection indicate that a pressure of 30 psi may generate optimal reduction in downloads for this experiment. Table 2 shows percent improvement in lift generated/download reduction with the addition of blowing over flap deflection alone.

At 30 PSI, the Airknife consumes 1.65 standard cubic feet of air per minute per inch. For the 0.1524m slot, this translates to a blowing mass flow rate of 0.057 kg/s for the full Airknife. This device might easily scale to application on full-scale rotorcraft. Based on a V-22 half span length of 7.01 meters and assuming that the slot height remains constant, a blowing slot would scale to a length of 0.95m. This length would result in a required blowing mass flow rate of 4.33×10^{-2} kg/s if the same air pressure were used. For an engine mass flow rate of 50 kg/s, this means that a bleed-off of approximately 0.086% of the engine mass flow will be needed for surface blowing. Based on the table above, the addition surface blowing to flap deflection increased download reduction by 6 to 20 percent, depending on the geometry.

Stag. Pressure (psi)	20° full flaps	20° inboard flaps	30° full flaps	30° inboard flaps
20	11	5	5	na
25	12	15	6	13
30	19	15.3	19	24
35	13	13.2	7	13
40	12	20	6	6

Table 2: Percent improvement in lift due to addition of blowing

FLOW-DIAGNOSTICS AND FLOW-CONTROL EXPERIMENTS IN LARGE FACILITIES

The second major issue discussed in the paper is that of using advanced flow measurement capabilities such as light sheet imaging and planar / volume velocimetry under the constraints of full-scale development testing conditions. Associated with the development of VTOL vehicles such as tiltrotors is the complexity of the resulting flowfield. Most of this flowfield is in the incompressible regime with concentrated regions of high velocity associated with the tip vortices and vortex sheets. Work done jointly by Georgia Tech with Bell on a 1/6-scale tiltrotor half-model is discussed. Similar techniques were also used in the Boeing VTOL tunnel on a 15% full model of the 609 Civil Tiltrotor[1]. The measurement distances used have achieved the values needed for measurements around full-scale vehicles.

A portable Spatial Correlation Velocimetry (SCV) system was developed. Rotor-synchronized visualization SCV were conducted in the hover flowfield around a 15%-scale half model of the V-22 at Bell Helicopter's Whirl Cage facility (Figure 6). Rotor RPM was 2760 for all runs.

The daunting measurement challenges of quantifying the velocity field, as a function of rotor azimuth at several spanwise locations, are approached using the planar

Spatial Correlation Velocimetry technique. This technique determines planar velocity fields from the spatial cross-correlation between time-separated images. SCV has been applied to quasi-steady and unsteady, 2-D flows with laser illumination[4,5] and 3-D unsteady rotorcraft flows with white light sheets at full-scale tip Mach number and measurement distance[6]. The different aspects of the technique have been validated using solid surface displacement and addition of random measurement noise[4], and point velocity measurements[7]. SCV has previously been used in quantifying the effects of flap deflection on a wing-rotor configuration at Georgia Tech.[8] The velocity measurements were made using pulsed white light sheets, theatrical fog generators, and a pair of intensified commercial-grade CCD video cameras with time-lagged shutters. The dual-camera system is aligned to the same object field and recorded the seeded flowfield section, illuminated by the pulsed white-light sheets. Time-separated images of the seeded flow pattern are captured, digitized and broken down into small area arrays for cross-correlation. The shift of the cross-correlation peaks from (0,0) gives the displacement vector. Since the time delay between images is known, velocity can then be obtained.

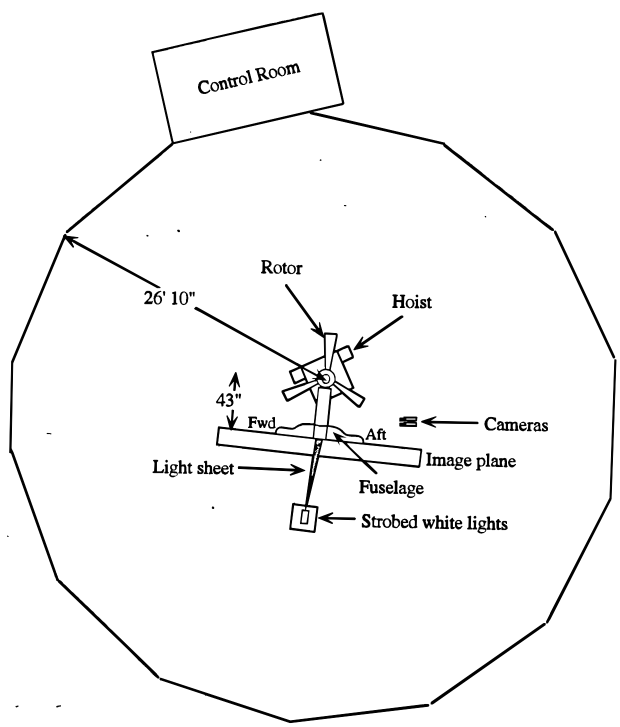
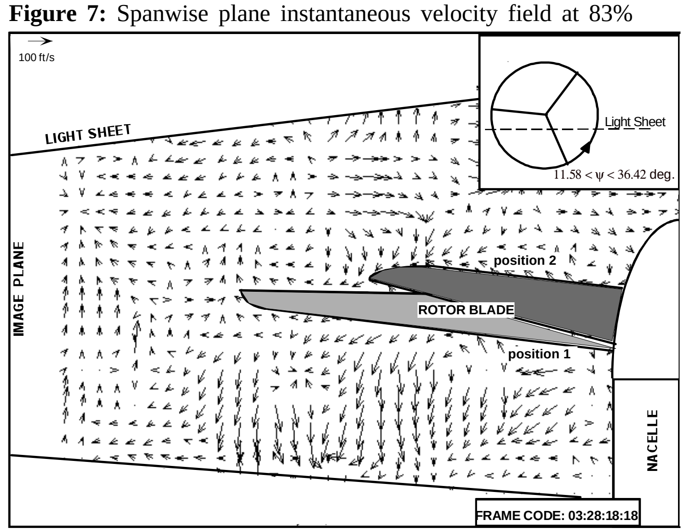


Figure 6: Typical measurement configuration for tiltrotor flows in a wind tunnel. Camera and light source distances to the measuring plane exceeded 5 meters. Facility borders are not to scale.

A schematic of the experimental setup is shown in Figure 6. The light-to-measurement plane and camera-to-measurement plane distances exceeded 5 meters. The size of the measurement areas surpassed 1m x 0.67m, but could also be zoomed in to view more detail.

The objective of the tests was to measure the velocity field in selected planes, including the download generation region and fountain flow. Data were acquired in 6 spanwise planes, each vertical and parallel to the leading edge of the model wing, and 6 chordwise planes. In the spanwise vertical plane at 83% chord, the flow was predominantly downward, including instantaneous velocities reaching up to 46 m/s, as seen in Figure 7. At 55% chord, seen in Figure 8, strong spanwise flow and upflow along the symmetry plane were observed. The implications of this upflow are discussed in more detail in the next section. Closer to the leading edge, at 33% chord, the spanwise flow was seen to be less than at 55% chord, agreeing with Third Velocity Component Reconstruction of the velocity field over the wing-rotor setup at Georgia Tech.[9] This flowfield is shown in Figure 9.

Figure 7: Spanwise plane instantaneous velocity field at 83%



chord location

The "fountain effect" is clearly visible in the instantaneous velocity field at 55% spanwise plane. It is seen to a lesser extent in the 83% field and not at all in the 33% instantaneous velocity field. This variation in upflow in the different planes is more likely due to difference in the choice of image pair and rotor azimuth than any changes in upflow along the chord. This is borne out by the time-averaged flow fields, which clearly show the upflow of the fountain effect at all three spanwise planes. Figure 10 shows an example time-averaged velocity field at the 33% spanwise plane. Similar indications of the fountain effect were seen in both the 55% and 83% spanwise plane time averaged velocity fields.

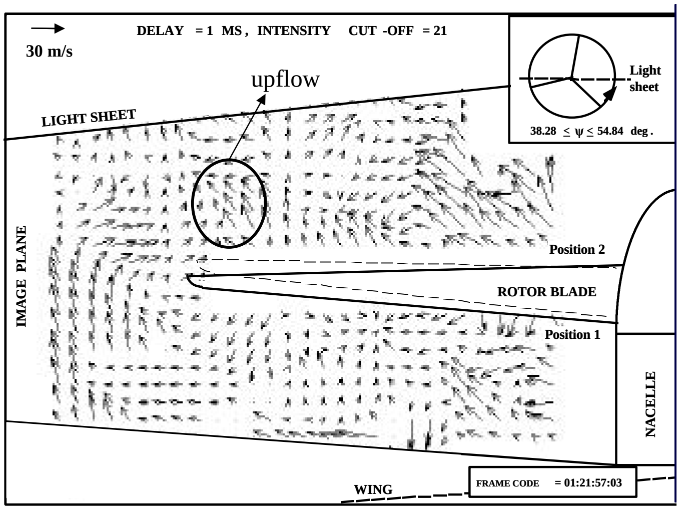


Figure 8: Spanwise Plane Instantaneous Velocity Field at 55% Chord Location

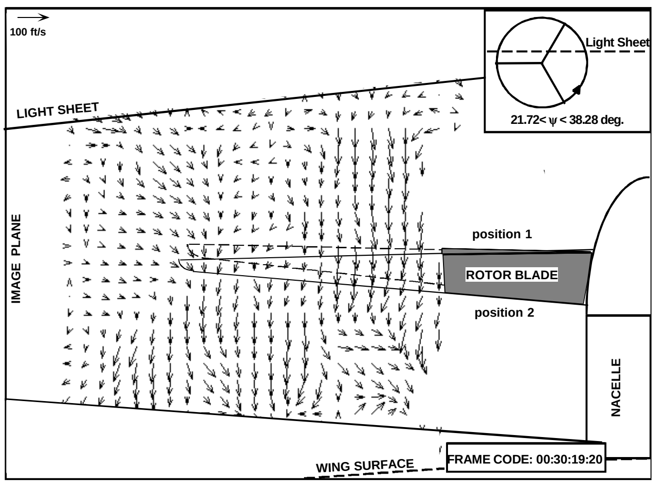


Figure 9: Spanwise Plane Instantaneous Velocity Field at 33% Chord Location

Ensemble averaged velocity fields were obtained by grabbing a ten second movie of the flow visualization yielding 300 velocity fields. With a constant video framing rate of 30Hz and a rotor RPM of 2670, the rotor azimuth change between successive frames is 192°. Thus, the velocity fields fall into 15 different azimuth bins. Velocity fields were averaged for each separate azimuth. Ensemble averaged fields show velocity magnitudes about half of the instantaneous fields analyzed, as seen in Figure 11. This is attributed to smearing due to varying rpm and low-frequency unsteadiness in the facility (the wake exhaust doors had to be closed to keep light out).

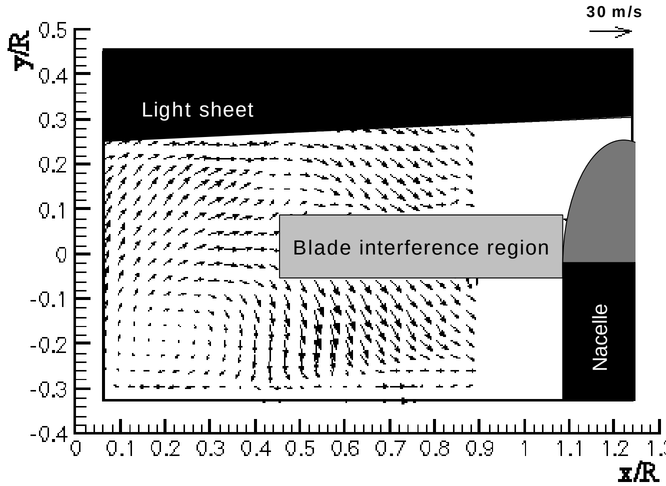


Figure 10: Time averaged velocity field for spanwise plane at 33% chord location

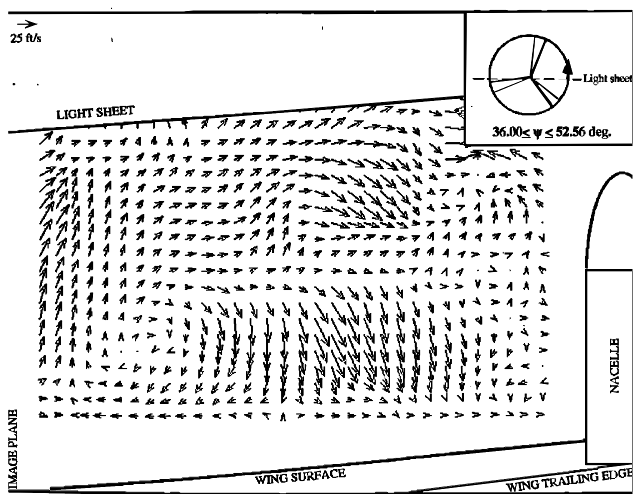


Figure 11: Ensembled-averaged velocity field at 55% spanwise plan for rotor azimuths between 36° and 52.56°

ROTOR/FLOWFIELD PHASING

Another issue in download alleviation is the occurrence of high pressures on the upper surface of the wing due to the passage of the rotor blade over it. This issue is complicated by the fact that the rotor tip Mach number may be as high as 0.7. At such Mach numbers, there is a substantial phase lag between the passage of the blade, and the occurrence of the pressure field on the wing, as shown in Figure 12. In addition, there is a phase lag in the propagation of any reflected pressure and velocity fields at the rotor plane, as observed in tests conducted on a 15% scale tiltrotor with full-scale tip Mach number. The issue is the possibility of tailoring the cyclic pitch program of the rotor, to alleviate the download without losses in rotor performance.

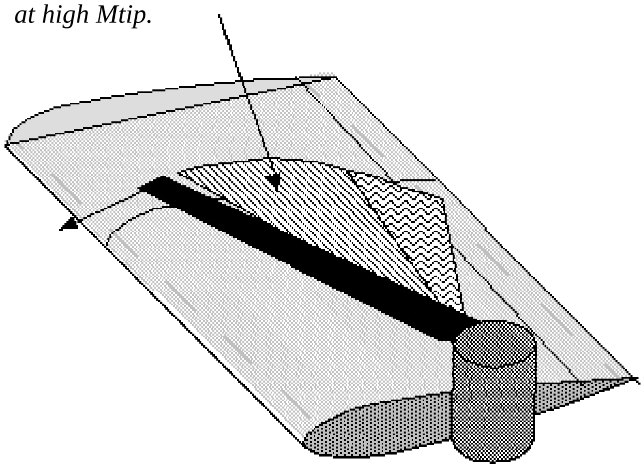


Figure 12: Schematic illustration of the phase lag between blade passage and pressure signature of the blade on the wing surface, when the rotor tip speed is in the compressible range.

At the 55% chord plane of the Bell tests (Figure 7), there is a very strong upflow, on the order of 36m/s, seen above the rotor disk, extending considerably inboard of the tip immediately after blade passage. This is attributed partly to the "blade passage effect", where a large unsteady pressure increase is observed on nearby surfaces as the blade passes by. Where the flowfield below the rotor is unobstructed, this pressure translates into strong downward flow. However, with the wing surface so near, the pressure wave must reflect off the surface.

The upflow observed is consistent with relief of the blade passage pressure pulse. This upflow also occurs with a substantial phase lag, 30 to 90° after blade passage, consistent with the sound propagation time to and from the wing surface. This was observed with multiple image pairs from the same rotor azimuth, negating the possibility of simple noise or "stray" smoke patterns. At later rotor azimuths, far removed from the passage of the rotor blade, the upflow is diminished significantly, as expected.

This suggests Opposed Lateral Cyclic, or "detuning" the two rotors, as a possible technique for future tiltrotor craft to achieve flowfields substantially different from the traditional expectation of a symmetric "fountain", alleviating the download and fountain problems. By tailoring the cyclic pitch program, reducing blade pitch as the blade passes over the wing, the pressure pulse and fountain flow can be greatly reduced. If the net download reduction exceeds the thrust reduction due to cyclic pitch, this may prove a viable way to reduce hover download.

TECHNIQUES FOR HIGH DESCENT RATES

Recently there has been some attention to the possibility of high rolling moments being encountered in high-speed descent due to one rotor entering some form of the "Vortex Ring State" (VRS). The traditional knowledge base on VRS indicates that the highest hub loads, indicating occurrence of VRS, are associated with descent coupled with forward flight, not pure hover. Some of what is discussed above may be relevant to the design of devices to counter such situations. An example is the possibility of combining fast-acting flaperon deflection and upper-surface tangential blowing on the stalled (downward-moving) wing with the opening of slots in the other (upward-moving) wing. Combined with the lateral shift of the wake impingement region observed in the GT experiments, these might provide the additional rolling moment to enable recovery.

CONCLUSIONS

Methods for modification of download due to the impact of the rotor wake on the wing were examined. The development of spanwise flow along the wing is a well-known phenomenon, and methods of modifying this flow through trailing edge flap deflection and surface blowing were studied. Flap deflection, both full span and inboard only configurations, are effective at reducing download and shifting the rotor wake on the wing. At small flap deflections, the download forces generated by the rotor in this experiment are eliminated, while slightly larger deflections begin to create lift. Slotted blowing showed promise in hover, where it reduced download on the experiment by 13 percent. Blowing did improve the effectiveness of flap deflection at reducing download. The effect of smaller flap deflection angles, which incur a smaller drag penalty, had a larger improvement in effectiveness with the addition of blowing. Slotted blowing in conjunction with flap deflection thus works as a lift enhancement device, working to increase lift generated by small flap deflections, without the increase in drag that is caused at large flap angles. Blowing also works to eliminate or reduce the fountain effect y adding energy to the flow, working to direct the rotor wake off the wing.

Blowing in conjunction with smaller angle flap deflections may prove to be a viable method for download reduction and spanwise flow modification on full-scale tiltrotors. Further investigation on the effect of varying slot air velocity, location and well as unsteady blowing, in tandem with flap deflection, should be carried out. The feasibility of high frequency pulsed blowing, synchronized to the rotor azimuth, is being investigated.

Scale-model tests at Bell Helicopter and the Boeing VTOL tunnel have demonstrated the viability of SCV as a reliable technique for testing of large-scale flows. The measurement distances used in these tests, with measurement areas of over 1m x 0.6 m, have achieved the values needed for measurements around full-scale vehicles. The flexibility of this system makes is relatively easy to capture different parts of the flowfield, and determine the effectiveness of flow modification devices. The upflow at the image plane, or "fountain flow", was reliably captured using the SCV technique. Both instantaneous and time-averaged velocity fields showed a curious upflow feature above the rotor disk at 55% chord, well inboard of the rotor tip. Further investigation of this feature is warranted, to determine the feasibility of Opposed Lateral Cyclic as one possible method of further reducing download in hover conditions.

More work is needed to fully understand the complex coupling between the rotor and flowfield. Fully understanding this relationship can lead to new methods of flow control and download reduction, such as mentioned in this paper. The on-site testing techniques outlined in this paper are valuable tools in exploring this flowfield and examining the effectiveness of flow control devices. On-the-fly modifications are easily compensated for with this diagnostic technique.

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