Download Modification using Surface Blowing

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ABSTRACT

Results are reported on the modification of the wing download due to a rotor wake interaction, using surface blowing. Previously, the wake/wing interaction flowfield has been studied qualitatively and quantitatively using surface pressure fields and off-surface velocity fields. The development of spanwise flows had been shown, along with the effects on surface pressure and download and when a trailing edge flap was deflected. New results on the redirection of the wake, using surface blowing, show a 20% improvement in the effect of the flaps in reducing the download.

INTRODUCTION

All rotorcraft experience aerodynamic interactions between the rotor wake and the fuselage and tail sections of the craft.. In hover and low speed flight, the rotor wakes of tiltrotor craft interact with the wing, causing download. This interaction causes download on the wing. Alleviation of the download offers the potential of a significant increase in tiltrotor payload.

During hover and transition to forward flight, wake-induced download on the wings of a tiltrotor aircraft is mitigated, and lift is enhanced, by deflecting wing trailing edge flaps. The experiment described here examines the effect of surface blowing, both separately, and in conjunction with trailing edge flap deflections. Figure 1 shows the relation between the tiltrotor case, and the basic full-span wing-rotor configuration used in the wind tunnel. The retreating blade side on the wing surface is analogous to the wing of the tiltrotor.

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BACKGROUND

The flowfield in the rotor wake/wing interaction region is dominated by interacting tip vortices and vortex sheets, with large-amplitude, periodic variations in each component. Two well-known features from previous work, using scale-model and full-scale tests[1], are:

a. The wake interaction with the wings produces a strong spanwise flow, directed inboard along the wing upper surface. In the case of the full tiltorotor aircraft configuration, the spanwise flows from the two rotors interact, and develop into a "fountain effect" which has been suspected as one cause of rotor noise.

b. Flap deflection alleviates the download on the wings.

Upper bounds on the download can be estimated as follows: At hover / vertical takeoff, the tiltrotor thrust is roughly equal to the takeoff weight of the craft. Part of the rotor wake encounters the wing: this can be roughly estimated by considering the portion of the wing projected onto the rotor disk. This part of the rotor wake is turned along the wing. Some of the flow goes spanwise along the wing surface. In the region near the fuselage, this flow turns upward to form the well known "fountain effect", further increasing the download. The downward component of the reaction to the rate of change of momentum involved in these turns, explains most of the download. There may also be strong transient contributions due to the pressure field of the rotor passing over the wing. This may be balanced by the improvement in rotor performance due to wing proximity.

In hover, the wake impinging on the wing causes high pressures on the upper surface. The flow spreads out, with part of it going over the trailing edge, and part over the leading edge. As transition to forward flight occurs, it is important to reduce the upper surface pressure early, so as to establish a lifting flowfield over the wing. Thus, the tendency of the impinging flow to spread out over the leading edge must be curtailed, without aggravating the high pressure on the upper surface.

Current tiltrotors generally have download-to-thrust ratios of around 10 percent[2], which is a substantial fraction of the hover payload. The upper bound on the payoff from redirecting the spanwise flow to (a) prevent the fountain effect and (b) prevent flow over the leading edge, is roughly 50% of the download, as argued above. A large part of this is already achieved using trailing edge flap deflection. In hover, the flap is deflected up to 60 degrees; 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.

Liu et al[2] have tested various download reduction devices for tiltrotor craft in hover. 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.

Such devices, which turn this spanwise flow both forwards and backwards, are suitable for hover conditions, but less suited for forward flight transition conditions. A short take-off run can also put the rotorcraft into a condition similar to the conditions of the experiment described here. Use of such a fountain flow abatement device during forward flight transition would delay establishment of attached flow on the wings and delay attainment of aerodynamic lift. *Thus we seek devices which will deflect the spanwise flow rearwards with minimum drag and power penalty, while helping to establish a lifting flow on the upper surface.*

The effect of circulation control via surface blowing has been studied for tiltrotors in hover. Lee[3] 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 reduced pressure on the upper surface. Felker et al[4], 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 was seen to caused significant reductions in download, between 25 and 55%.

The experiment described in this paper studies the rearward deflection of the spanwise wall jet, using chordwise slot blowing, from a jet. It is reasoned that such a jet would (a) reduce the pressure over the wing upper surface, (b) alleviate the spanwise flow, promoting establishment of the chordwise flow necessary for aerodynamic lift, (c) entrain air that would otherwise go over the leading edge and redirect it rearwards, (d) increase rearward momentum of the flow, providing a small thrust increase, and (e) encourage the early development of aerodynamic lift on the wings. Such a jet can be turned off in forward flight, so that it entails no drag penalty. The effect of chordwise slot blowing on the effectiveness of trailing edge flap deflection on download reduction is also examined: some lift augmentation by the Coanda effect is postulated, for a future optimized flap/knee geometry.

The effect of the trailing edge flaps on download reduction and the spanwise flow had been previously examined in earlier phases of the present experiment.[5] As mentioned before, the finding was that a flap deflection on the order of 20 percent produced the best lift/drag ratio. If the hover download-alleviation scheme could be optimized to produce the best download alleviation at this condition, the takeoff payload of tiltrotor craft could be increased substantially.

EXPERIMENTAL DETAILS

The rotor-wing set-up in the John Harper wind tunnel at Georgia Tech is shown in Fig. 2. A full-span NACA0021 wing with 0.4 m chord is placed at 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 with its hub at 0.127 m upstream of the wing leading edge and centered at mid-span. The rotor hub is at a height of 0.4191 m above the wing centerline.

A segmented wing trailing edge flap system was used, consisting of 4 computer controlled NACA0012 flap segments with a 0.127 m chord. Computer control of the flaps allowed

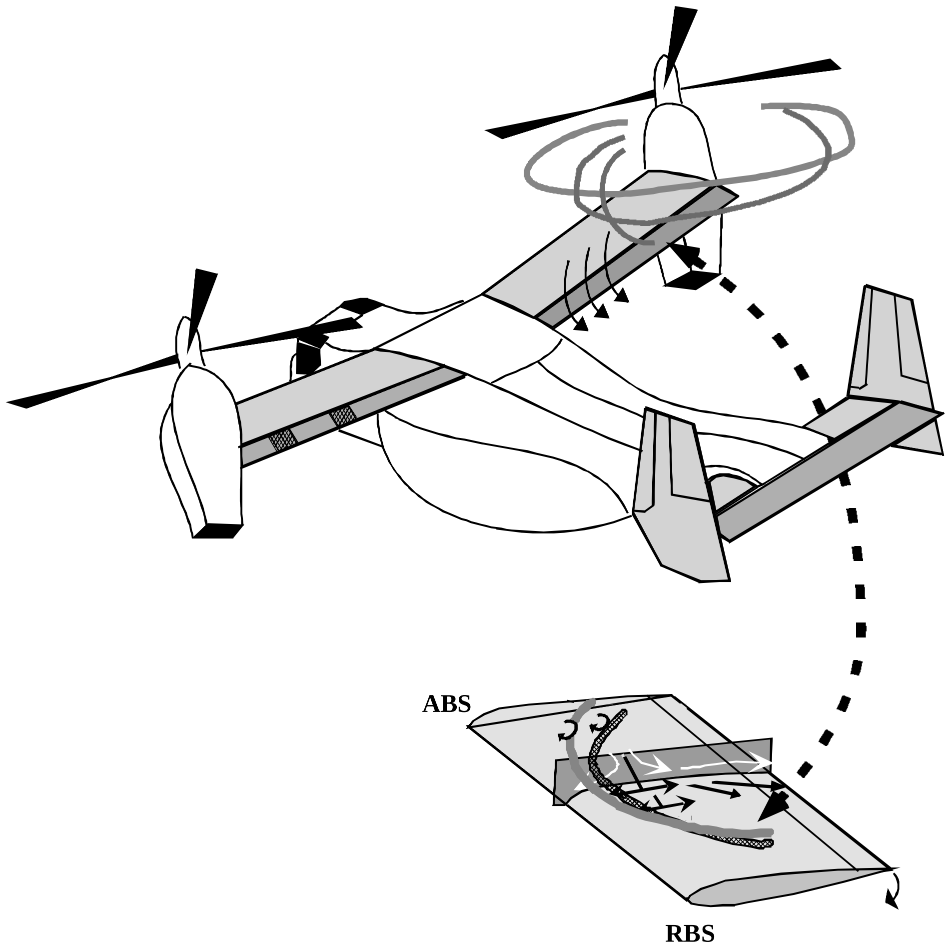

Figure 1: Relationship between tiltrotor case and full-span wing-rotor experiment

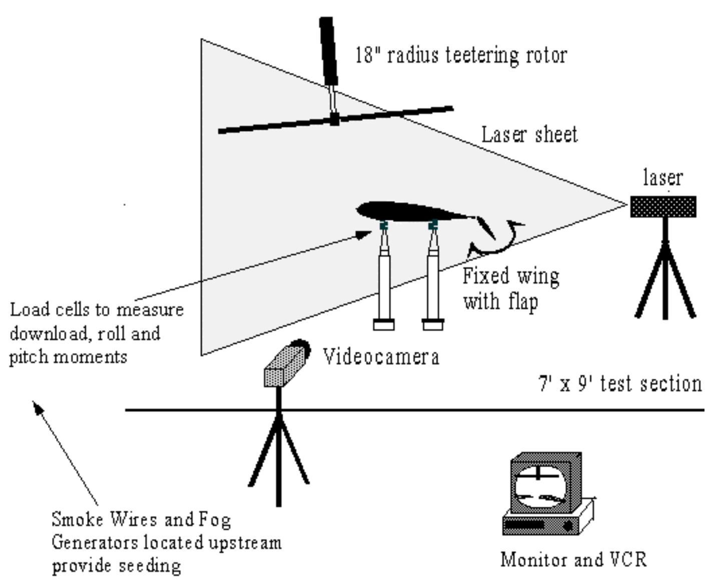

Figure 2: Experimental Setup

them to be independently deflected to various angles from outside the windtunnel. 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. 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 split flap system was attached to the trailing edge of the wing, and deflected using push-pull rods. Each flap could be independently controlled, and cover a minimum deflection range of -15 to 45 degrees. 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. Load cells were located 0.178 m apart in the chordwise direction, and 1.232 m apart in the spanwise direction. 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. Figure 3 shows the installed geometry of the Airknife in the wing. Compressed air at 40 PSI was supplied to the Airknife. The effect of varying stagnation pressure of the air supplied to the Airknife was also investigated.

Figure 4 shows contours of the velocity profile of the Airknife jet alone, at 50mm and 150mm downstream of the slot. This velocity profile was obtained by traversing a TSI VelociCalc probe over a grid with half-inch spacing in the horizontal direction and quarter inch spacing along the vertical direction at several planes downstream of the Airknife. At 50mm downstream from the Airknife, the jet is less than 25mm thick, and at 150mm downstream, it is 63mm thick. The velocity profile across the jet is quite uniform, with sharp falloff at the edges of the jet.

RESULTS

1. Spanwise Jet on Lifting Surface

In previous work without the blowing, the spanwise jet across the Retreating Blade Side (RBS) wing surface was reconstructed using a Third Velocity Component Solver[6] and chordwise two-dimensional velocity fields obtained using Spatial Correlation Velocimetry (SCV). Figure 5 shows three spanwise cross sections of the flow at 24° rotor azimuth at x/R locations of 0.29, 0.47 and 0.89 are shown. Here, R is the rotor radius and x is measured from the rotor hub in the downstream direction.

The flowfield shows the development of a spanwise jet across the wing surface. The jet is seen to develop immediately on the wing, at the leading edge, and grows stronger further downstream. Both the velocity and physical dimensions of the jet increase. Although there are fluctuations in velocity magnitude, this flow behavior is seen at other rotor azimuths as well.

2. Modification of the Rotor Wake Due to Flap Deflection

There exists a region of high pressure, with pressure coefficients above 2.0, on the lifting surface under the rotor, due to the rotor wake impinging on the wing. This area of high pressure can be modified through deflection of the trailing edge flaps. Contours of the pressure coefficient on the wing surface on the RBS, referenced to freestream dynamic pressure, are shown in Fig. 6. Several flap combinations are shown here. The contours with the flap deflected show a decrease of mean pressures throughout the measurement area, as expected. The pressure reduction due to flap deflection corresponds to a ΔC_p of 1.4 at y/R=0.03. The contours indicate a shift in the high pressure regions towards the advancing blade side (ABS).

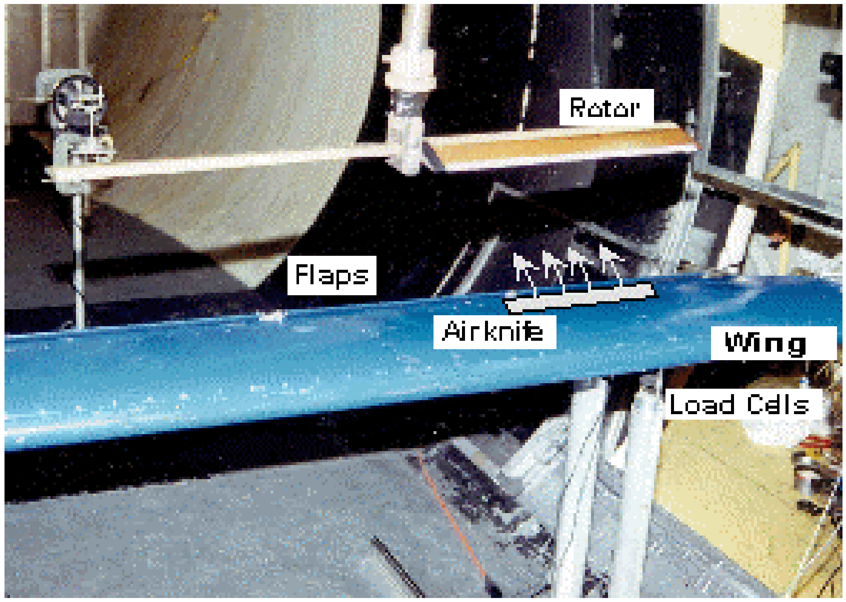

Figure 3a: Airknife Experimental Setup

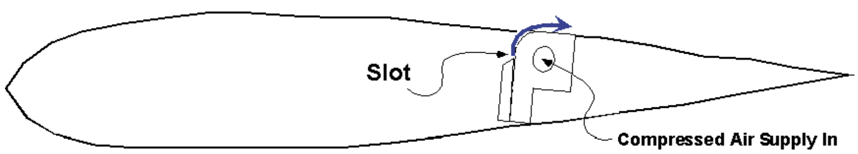

Figure 3b: Schematic of Airknife inside wing body

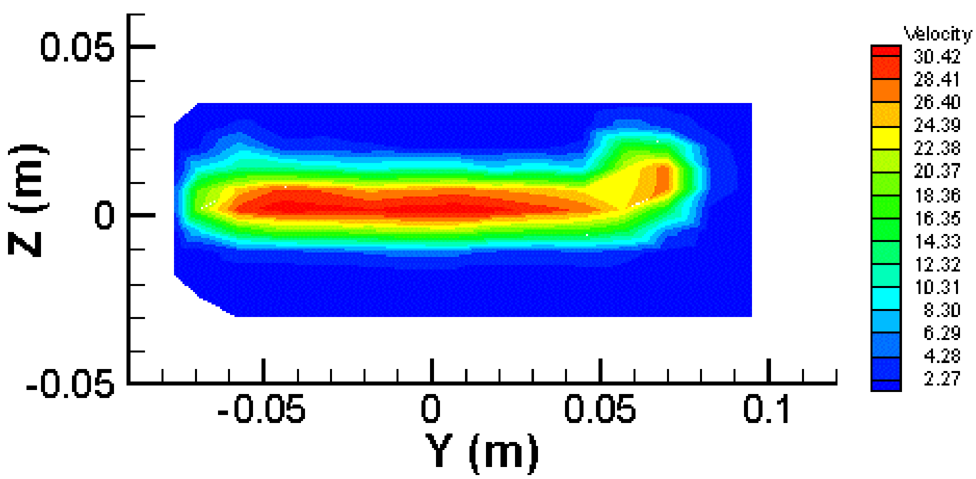

Figure 4: Airknife Velocity Profile (m/s)

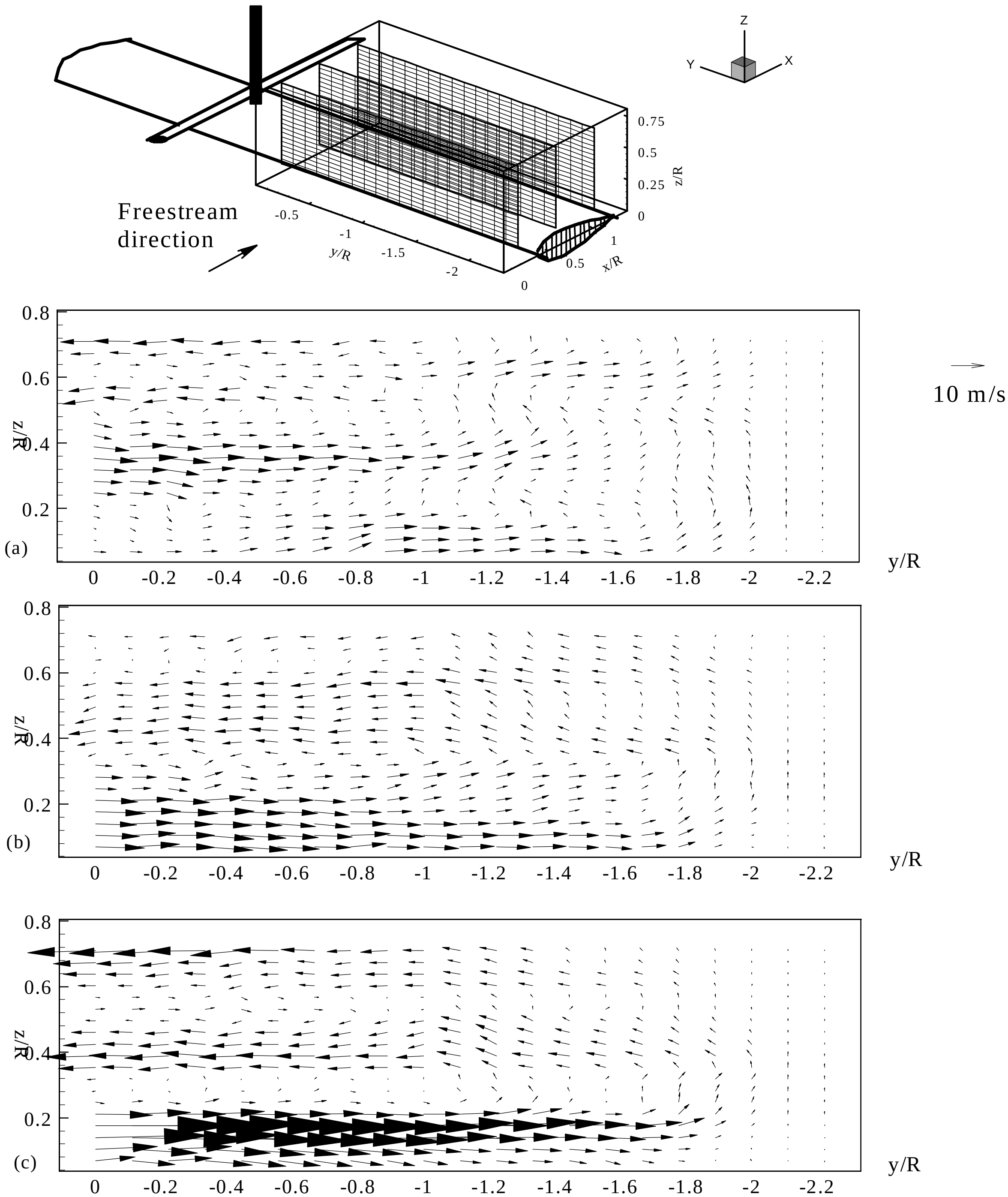

Figure 5: Spanwise Velocity Fields over the wing upper surface from Third Velocity Component results. Spanwise velocity profiles at 24° azimuth for a) x/R=0.29 b) x/R= 0.47 c) x/R=0.89

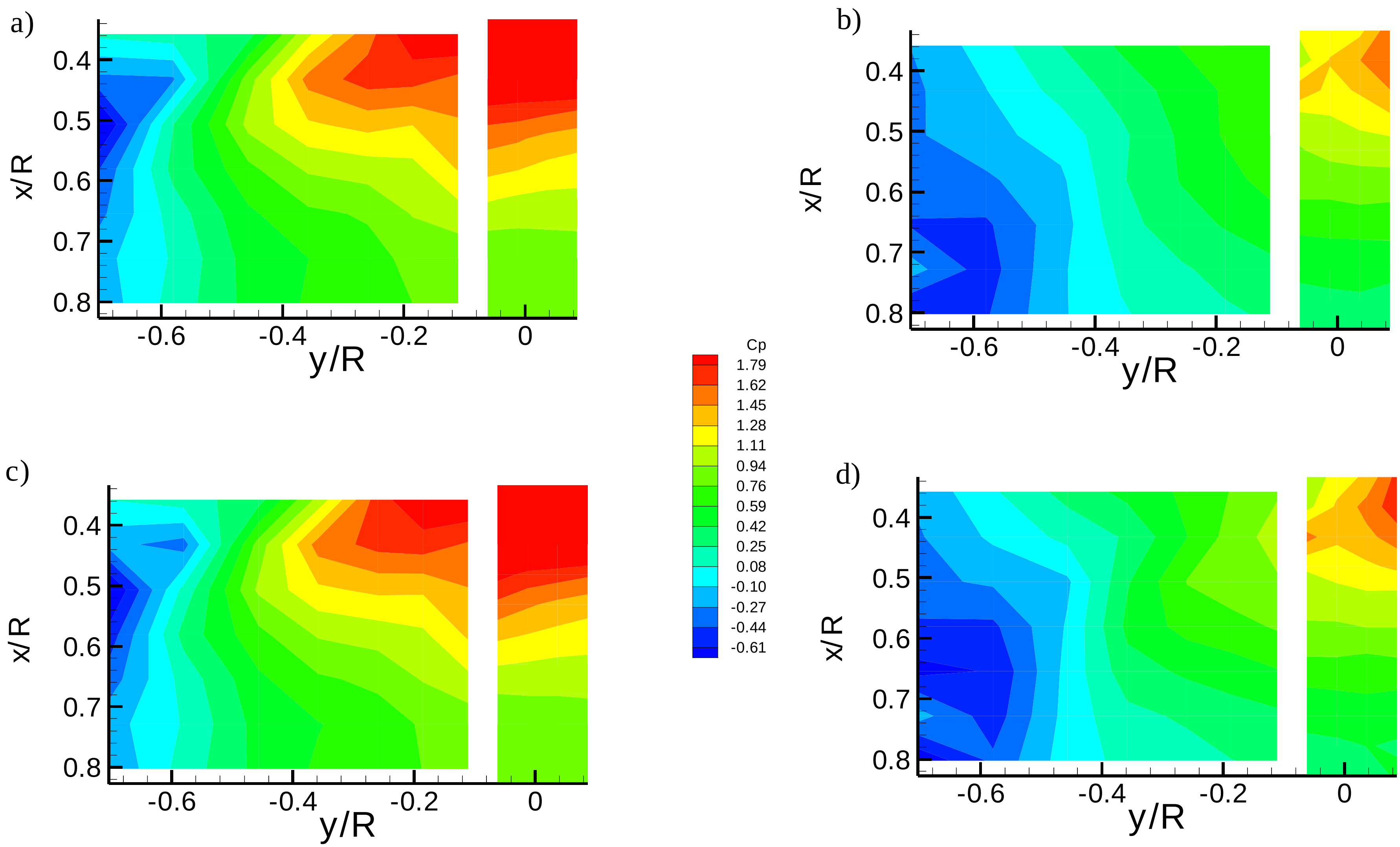

Figure 6: Static Pressure contours over the wing upper surface with segmented flap system at a) 0° b) 30° c) Outboard only flaps at 30° d) Inboard only flaps at 30°

The baseline undeflected flap case is shown in Fig. 6(a). A shift of the wake to the ABS is clearly seen in Fig. 6(b), where all four segments are deflected 30 degrees. The pressures display an expected reduction in maximum Cp. Two other flap deflection configurations were performed as well. Deflecting only the two inboard flaps 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. 6.[5]

It was shown earlier that there is a strong spanwise flow directed towards RBS downstream of the 3D separation line formed on the wing due to vortex interaction. By deflecting the flap and allowing the flow to deflect downstream this spanwise flow is reduced, thus shifting the rotor wake laterally.

Four compression/tension load cells were used to measure the loads on the wing. Fig. 7 demonstrates download reduction on the wing with increasing deflection of all four flap segments. All download data has been non-dimensionalized by the theoretical thrust produced by the rotor at hover conditions of 68.3 kg-m/s^2. 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°, 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.

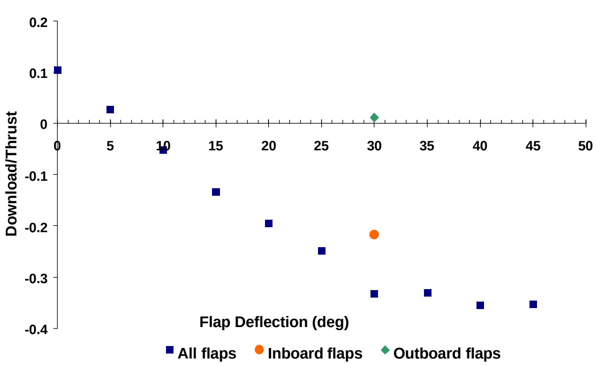

Figure 7: **Variation on download on wing with flap deflection**

At an advance ratio of 0.075, full span flap deflection beyond 15° changed the net wing force to lift. The download force due to the impinging rotor wake is negated at this point, and a lift force is generated, growing with increased flap deflection.

3. Surface Blowing effect 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. Also, 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 conditions, at an advance ratio of 0.075, the baseline download due to the rotor wake is determined by subtracting off 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.

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.

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

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.

CONCLUSIONS

This experiment examined modification of download due to the impact of the rotor wake on the wing. 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 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.

Slotted blowing showed promise in hover, where it reduced download on the experiment by 13 percent. Blowing alone, in low speed forward flight conditions, did not affect the download on the wing noticeably. The Airknife 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.

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.

ACKNOWLEDGMENTS

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