Rotor-Wake-Induced Flow Separation on a Lifting Surface




S. M. Foley
Graduate Research Assistant
School of Aerospace Engineering

R. B. Funk
Graduate Research Assistant
School of Aerospace Engineering

P. A. Fawcett
Graduate Research Assistant
School of Aerospace Engineering

N. M. Komerath
Professor
School of Aerospace Engineering.

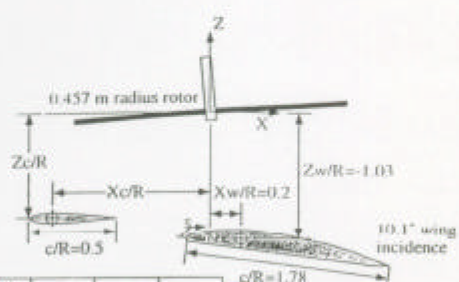
Georgia Institute of Technology
Atlanta, Georgia 30332-0150

Rotor wake vortex interaction causes flow separation on the upper surface of a lifting surface at low angles of attack, where the time-averaged flow would be expected to remain fully attached. This phenomenon is studied using a full-scale UH-1 stabilator and a two bladed teetering rotor in a wind tunnel. A large once-per-rev pressure fluctuation is observed. Strong time-averaged spanwise flow is observed downstream of the unsteady separation line. The vortex interaction effect decreases with increasing advance ratio. These results are insensitive to small perturbations of the flowfield caused by movement of a small lifting surface upstream.

Introduction

Fin buffeting, wing download, and degradation of stabilator effectiveness have been observed on rotorcraft where the rotor wake interacts with those surfaces, and identifying the mechanisms responsible for these problems is of intense interest. This note describes the finding of flow separation induced by rotor-wake–vortex interaction on the upper surface of a lifting surface at low angles of attack, where the time-averaged flow would be expected to remain fully attached. The flowfield is perturbed by varying the location and attitude of an upstream lifting surface to confirm that the separation phenomenon is indeed real and persists over a wide range of flow conditions. Though such upper-surface flow separation is counterintuitive at first glance, the phenomenon becomes evident when one is able to see the vortex interacting with the upper-surface flowfield. This is enabled by laser-sheet visualization. The three-dimensional unsteady nature of the separation is also shown by videotaping tuft behavior on the upper surface. Surface pressure variations are measured using microphones and static pressure taps.

Figure 1 shows a full-scale UH-1 helicopter stabilator (called a wing here) with a 0.813-m chord and 1.194-m span, mounted at 10.1-deg angle of attack. A two-bladed teetering rotor of 0.914-m diameter and constant NACA 0015 blade section is mounted through the roof of the 2.1 m × 2.5 m wind tunnel (Ref. 1). Rotor speed (600 to 2100 rpm) and tunnel speed vary the advance ratio, μ. Waxed wires upstream create thin sheets of intense seeding. A strobed copper-vapor laser sheet illuminates periodic phenomena. Upstream of the wing, an untwisted NACA 0012 canard, 0.229-m chord and 1.067-m span, is held on a three-axis traverse, able to move vertically and longitudinally and to pitch. The canard test positions used to perturb the rotor-wake–wing interaction are listed in Fig. 1.



canard position	Xc/R	Zc/R	incidence
1	-0.9514	-0.7361	0°
2	-0.9514	-0.7361	15°
3	-0.9514	-0.5694	15°
4	-0.9514	-0.5694	0°

Fig. 1. Model setup.

Results

Steady attached flow was verified in the rotor-off condition for the canard–wing configuration using spatial correlation velocimetry (Ref. 2). The flow was attached and smooth, as expected. With the rotor added, Fig. 2a shows the vortex trajectory, measured for the canard positions listed in Fig. 1, at an advance ratio μ of 0.06. The rotor wake vortices approach the wing upper surface and appear to bounce off the boundary layer. As μ increases from 0.075 to 0.10 (Figs. 2b and 2c), the trajectory moves further downstream until at $\mu = 0.10$ the vortex no longer interacts with the wing. Perturbation of the vortex trajectory using the canard thus has little effect on the phenomena occurring over the wing, and the phenomena observed are thus not limited to a particular combination of circumstances.

Unsteady Separation

As the vortices approach the wing, the boundary layer stagnates and separates. Such stagnation has been seen and measured in Ref. 3 on a surface with no pressure gradient. Here, the situation is aggravated by the adverse pressure gradient on the wing surface. Figure 3 shows the smoke streaklines leaving the surface at a sharp angle and not reattaching to the surface layer. The separation line moves over a wide range in Figs. 3a, 3b, and 3c for different rotor azimuths, Ψ, and must cause severe unsteady loads. No frames were seen where flow was fully attached over the wing.

Figure 3 shows the clear demarcation between regions of attached and separated flow: an apparent near-vertical jet of fluid shooting into

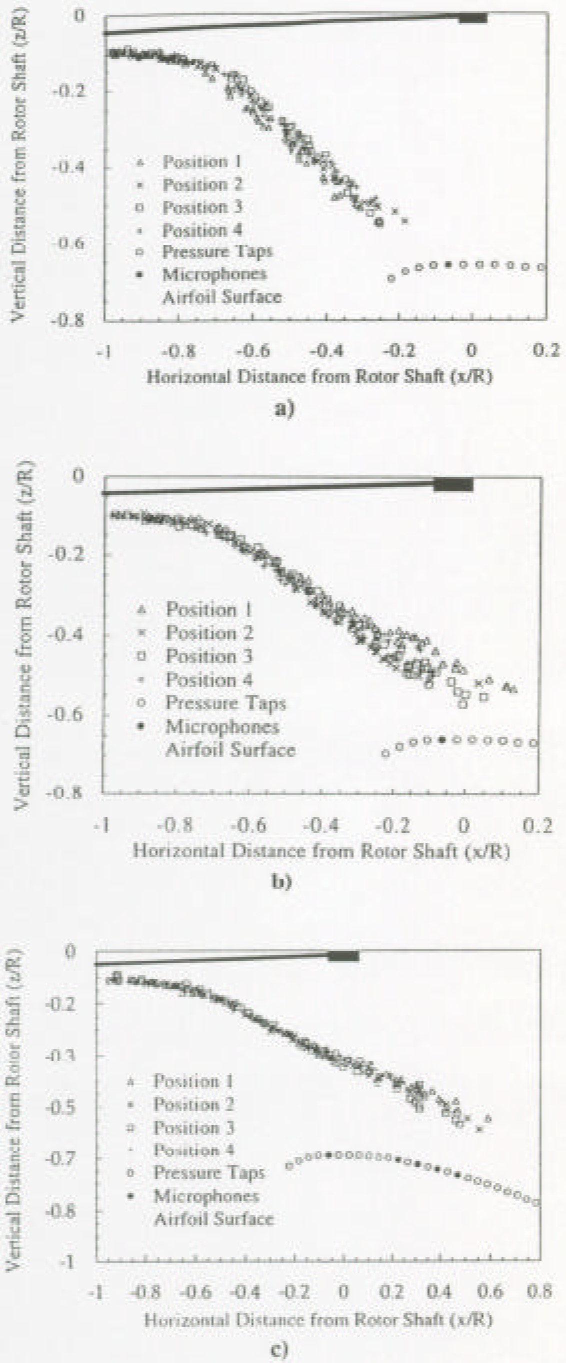


Fig. 2. Changes in vortex trajectory with canard position: a) μ = 0.06, b) μ = 0.075, c) μ = 0.01.

Fig. 4. Upper-surface tuft visualization.

the external flow from the boundary layer. This is reminiscent of the Van Dommelen–Shen singularity, which is postulated to cause abrupt jets during vortex–boundary-layer interaction (Ref. 4). After interaction, the vortices are still visible but more diffused. Obviously, their strength must be affected. The wake is now greatly distorted, and it is likely that the inboard vortex sheet may exchange positions with the tip vortices.

Spanwise Flow Visualization Using Tuft Videography

Figure 4 shows a digitized video image of surface tuft behavior on the stabilator upper surface. The tufts do not have sufficient frequency response to follow the periodic fluctuations, and are more representative of the time-averaged flowfield. Downstream of the vortex interaction region, a very strong spanwise flow appears. Thus, despite the "lifting" of the smoke streaklines in the planar laser-sheet visualization, a two-dimensional separation with steady flow reversal does not occur; rather, a spanwise flow is generated. This is thus a case of unsteady three-dimensional flow separation, according to the Sears–Telionis definition (Ref. 5).

Surface Pressure

Microphones and static pressure taps were interspersed along a single chordline. The instantaneous pressure is the sum of the mean and the microphone pressures. Figure 5a–5c show the mean C_P distributions for varying μ and the freestream cases with no rotor. The mean C_P for $\mu = 0.06$, Fig. 5a, is dominated by rotor downflow and the vortex–wing

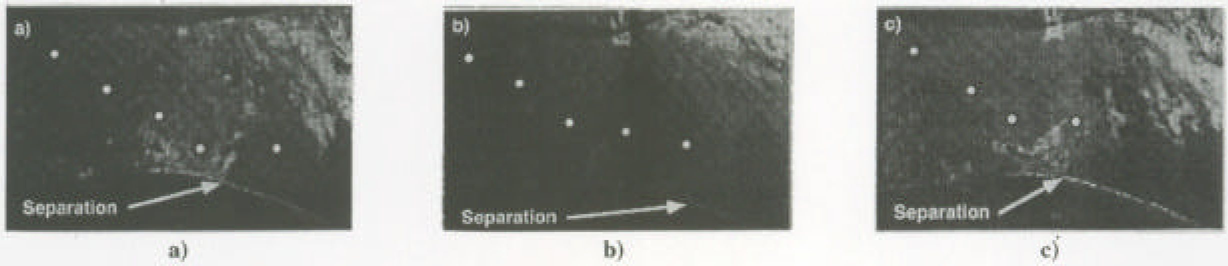


Fig. 3. Separation.

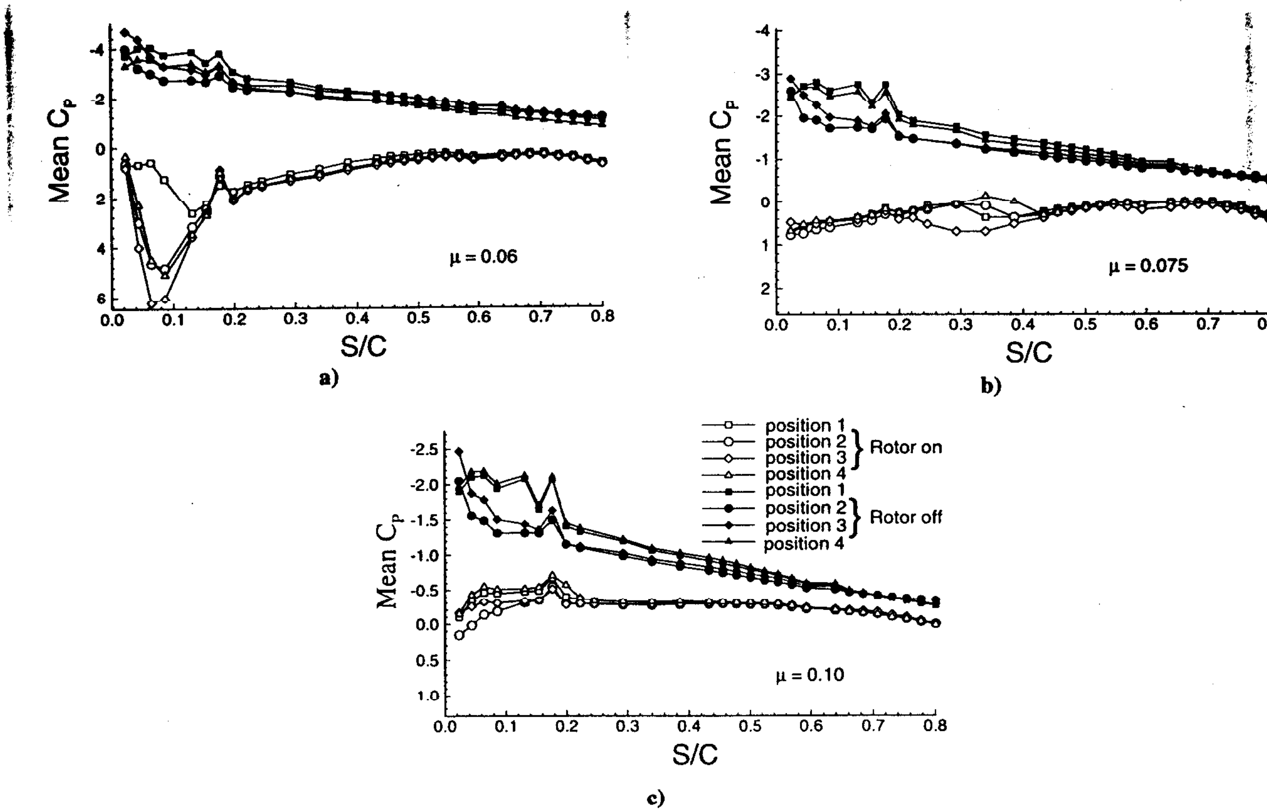


Fig. 5. Time-averaged pressures: a) μ = 0.06, b) μ = 0.075, c) μ = 0.01

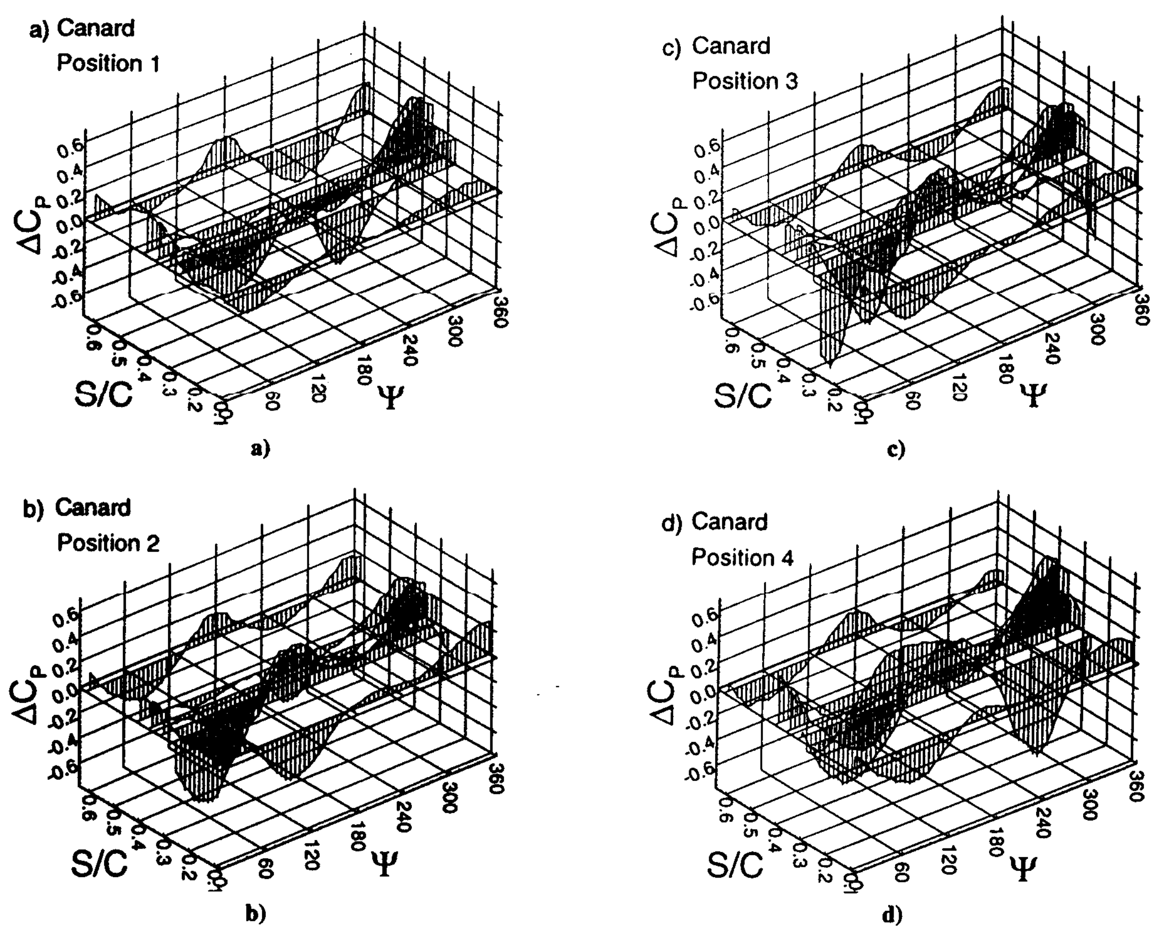


Fig. 6. Unsteady pressures: a) canard position 1, b) canard position 2, c) canard position 3, d) canard position 4.

interaction. Downflow deceleration increases the pressure during vortex interaction (Fig 5a), at the third and fourth pressure taps. With increased interference from the canard, the greatest at position 3, the peak in C_P increases.

Fig. 5b shows a more complex distribution over the wing for μ = 0.075. Near the leading-edge stagnation point, C_P is close to unity. Downstream, C_P decreases because of suction, but then rises to a peak where the vortex and wing interact. The peak is highest at position 3. Past the peak, the distribution flattens out and approaches the freestream value. C_P values are on the order of 1 for $\mu = 0.06$ and 10^{-1} for $\mu = 0.075$ and 0.10. As μ increases, the rotor downflow effect decreases and the freestream effect increases. While Figs. 5a and 5b show a peak in C_P due to vortex–wing interactions, Fig. 5c shows the characteristic suction of an airfoil in a freestream: the vortex is far off the wing. Visualization for $\mu = 0.10$ showed attached flow with a turbulent region containing the vortices above it.

Phase-Resolved Pressure

Figure 6a–6d show unsteady pressure at six locations for four canard positions for $\mu = 0.075$. Phase averaging with an azimuth resolution of 6 deg gives a Nyquist frequency of 3150 Hz, sufficient to capture the sharpest pressure spikes in this problem. Figure 6a shows 2/rev peaks corresponding to the blade-passage effect (Refs. 2, 4), offset from 0 and 180 deg azimuth because the line of sensors was offset from the axis of symmetry. The signal is dominated by a 1/rev variation, with a smaller 2/rev one. This 1/rev variation is due to the divergence in the trajectories of the vortices from the two blades.

Discussion

Several surprising phenomena have emerged. Current prediction methods for tilt-rotor aircraft interactional aerodynamics are likely to miss such phenomena, especially if the rotor wake is time-averaged before interaction. If a time-resolved wake were used, periodic separation and reattachment would be expected, as opposed to the unsteady three-dimensional separation with time-averaged spanwise flow which emerges. The separation is a possible contributor to the observed download on the wing, and a driver of large vibratory airloads on the wing as well as on control surfaces of all rotorcraft. The wing pressure distributions and periodic variations are much more complex than expected. Large excursions of separation points are to be expected, forcing vibrations. Another surprise is that no actual collisions of the vortex with the surface are seen, nor are the large pressure spikes typical of such collisions.

Conclusions

1) Unsteady three-dimensional flow separation occurs on short-aspect-ratio wings at low incidence due to rotor-wake–vortex interaction.

2) Strong time-averaged spanwise flow is observed downstream of the unsteady separation line.

3) A large 1/rev pressure fluctuation is observed.

4) The vortex interaction effect decreases with increasing advance ratio.

5) These results are insensitive to small perturbations of the flowfield caused by movement of a small lifting surface upstream.

Acknowledgments

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