ROTOR TIP-VORTEX / AIRFRAME COLLISION FEATURES
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ABSTRACT

This paper describes progress towards understanding the interaction between a vortex-dominated wake from a two-bladed rotor, and a solid cylinder surface. Prior work had taken this problem to the level where the flow was predictable except for the details of the collision between the tip vortex and the surface. The substantial role of the core axial velocity, postulated from pressure data on the airframe, is now confirmed by direct velocity measurements. Both the tip vortex core and the inboard vortex sheet have substantial wake-like velocities: further evidence that the axial velocity is due to the no-slip condition. The vortex shows interior structure: Outside the core, there are multiple thin regions of jet-like velocity, attributed to the induced effect of the rolling-up vortex sheets. This appears to resolve the contradiction between Euler results (jet-like axial velocity) and experiments (wake-like core). During the collision, the axial velocity at the top of the airframe persists even after the flow has stagnated on the Advancing Blade Side. Further evidence of the blade-wake genesis of this flow. Axial velocity scales with advance ratio between the 2100 rpm case and the 1050 rpm cases, allowing matching of pressure, flow visualization and other velocity data between these cases. Suction peaks on the RBS stay for a long duration. The levels of suction observed are far above what can be explained using potential flow theory alone. Flow vis on the sides is correlated with pressure results: correlates with the surface suction observations.

NOMENCLATURE

ABS The side of the cylinder under the advancing-blade side of the rotor disk.
Cp_unsteady \( (P_{uns} - P_{\infty}) / q_{\infty} \)
H Vertical spacing between rotor hub center and airframe centerline
P_uns Unsteady surface pressure
q_{\infty} Free stream dynamic pressure
R Rotor radius
RBS The side of the cylinder under the retreating-blade side of the rotor disk.
Xb Distance parallel to tunnel axis from cylinder nose
Zb Vertical distance from cylinder top surface
U_{\infty} Tunnel freestream velocity.
\( \phi \) Circumferential location of points on the surface of the airframe cylinder, measured from the top of the airframe
\( \mu \) Rotor advance ratio, \( U_{\infty}/\Omega R \)
\( \psi \) Rotor azimuth in degrees, measured from downstream position
\( \Omega \) Rotor angular velocity.

INTRODUCTION

Progress in the last few years has enabled us to understand and compute many of the features of the interaction between a rotor wake and nearby surfaces. With this knowledge, the long-term goal of being able to compute the flow around a complete rotorcraft configuration, to the accuracy and confidence needed to predict hover payload and low-speed handling characteristics accurately on a radically new design, is becoming quite realistic. This paper focuses on one of the remaining problems: the presence of a substantial velocity component directed along the axes of the strong vortices in the rotor wake. This is an aspect which is missing from two-dimensional vortex representations, and is yet of first-order importance to the wake/airframe interaction problem. The measurements presented here show that these features may be even more important in modeling the near wake of the rotor, with relevance to problems such as blade-vortex interaction.

The tip vortices shed from the rotor blades convect downstream and downward. These interact with the airframe in hover and low-speed forward flight conditions, resulting in periodic vortex induced loads on the airframe. When the vortex impinges on the airframe, it interacts with the boundary layer, causing separation and apparently vorticity redistribution. Since the early eighties, research on this interaction has been steadily increasing. The potential trajectories of the tip-vortex have been calculated (Refs.1,2) and experimentally documented (Ref.3). To date experimental work at Georgia Tech and computational efforts at Ohio State University have been able to isolate details of the first order phenomena associated with the interaction at the front part of the airframe. Researchers at Ohio State University (Refs.4,5) have used a three dimensional interacting boundary layer approach to treat the close approach of a vortex to a cylinder, using data from the Georgia Tech model as a
starting point. They were able to predict the development of a secondary vortex and correlate its pressure signature with experimental results.

**Issues**

Recent experimental work on this problem is documented in Ref.6. While the azimuth at which the boundary layer interaction on the top of the airframe is initiated has been located to within 6 degrees, what happens to the vortex after that is still a debated question. Lee et al. (Ref.7) postulate vorticity redistribution by convection, which causes the reduction of the suction peak on the top of the airframe within 1 ms. The axial flow in the tip vortex has not been captured for most part of the interaction. Capturing the changes in the axial flow during the interaction would prove to be a significant advance in understanding the entire flow field after the collision. Fig.1 summarizes the state of knowledge on this problem at the author’s organization and elsewhere.

There is considerable debate regarding the axial velocity in the vortex core, even about its sign. Early theoretical work by Batchelor8 postulated a jet-like flow in the core of a wing tip vortex. It is well-known that leading edge vortices over sharp-edged delta wings have strong jet-like cores until vortex breakdown occurs. Magnitudes as high as 3 times the freestream speed have been observed. These are explained using potential flow concepts as the velocity induced by the vortex filaments in the vortex sheet rolling up along the edge. The tip vortex of a straight fixed wing, on the other hand, displays little if any axial velocity9 beyond a few chord lengths. They postulated a difference between the axial velocity from a square-edged rotor tip versus a rounded tip. Measurements on rotating wings tell a different story. Shivananda10 used a split-film anemometer to resolve all three components of velocity in the wake of a single-bladed, square-edged rotor in hover. He found a wake-like core: the axial velocity was directed back along the trajectory of the vortex towards the blade. Thompson et al.11 studied the same rotor blade wake, and resolved all three components of velocity in the vortex using a laser velocimeter. They were able to achieve high data rates using an off-axis light receiving system, and incense smoke particles which stayed inside the core. They showed not only a wake-like vortex core, but also secondary features inside the core, indicating several layers of vortex sheet roll-up. There is some flow visualization evidence in the literature on propeller wakes which supports this finding. A limited set of measurements made by Liou12 above the cylinder model used in the present paper, in the core of the tip vortex from the present two-bladed rotor, found only a wake-like direction inside the core. The data were too limited to examine secondary features.

Recently, Sankar et al.13 have succeeded in resolving the near wake tip vortex from a rotor blade using computational solutions of the Euler equations. They found several layers of vorticity in the core, attributed to rolling-up vortex sheets. The axial velocity induced by these was predominantly jet-like. Recent vortex measurements using a 3-component laser velocimeter at the University of Maryland on a single-bladed rotor in hover14 found wake-like axial velocity in the core, but the measured velocity profiles appeared to dissipate very rapidly within the first 90 degrees of wake age, the dissipation being attributed to turbulence inside the core.

Resolution of these observations is needed to form general models for vortex interaction with the airframe. On the other hand, it appears that with these resolved, the vortex-airframe interaction can be understood to a surprisingly detailed level.

**PRESENT SCOPE OF WORK**

This paper starts by summarizing previous results on the pressures and flow-visualization on the sides of the airframe, where the effects of core axial velocity from the cut vortex filament are expected to be seen. We next describe measurements of the axial velocity in the tip vortex and in the inboard vortex sheet (which is the blade wake), as they interact with the top of a cylindrical airframe. With these measurements in hand, we re-examine the correlation between results from flow visualization near the airframe surface and pressure measurements on the surface during vortex collision with the surface.

**EXPERIMENTAL DETAILS**

The experiments were carried out in the J.J.Harper low-speed wind-tunnel at the Georgia Institute of Technology. This a closed-circuit tunnel with freestream turbulence levels of less than 0.5%. Details of the test configuration are given in Fig. 2. The advance ratio for all the experiments was 0.1. Table 1 shows the test parameters.
PRESSURE MEASUREMENT

The pressure data shown were acquired by superposing high-response condenser microphone data on time-averaged static pressures from a Barocel. The unsteady data sampling was triggered by an optical encoder mounted on the rotor shaft. The data are averaged over 6 degs rotor azimuth and ensemble averaged over a 100 rotor revolutions. The time averages were constructed from static pressure signals using a much longer period.

FLOW VISUALIZATION

Flow visualization was done by expanding a collimated and video-synchronized pulsed Cu-Vapor laser beam into a sheet. A two-camera setup is used for the experiments. This setup has shown the capability to resolve time-scales down to 0.1 millisecond. Two identical intensified video cameras are focussed on the same area and the shutter of one is delayed by a predetermined time interval. This simulates a high-speed camera by providing two flow images separated by a very small time interval.

LDV MEASUREMENTS

The streamwise and vertical components of velocity were measured above the airframe using a 5-watt Argon-ion laser with the beams being projected from outside the test-section. Light was collected in the backscatter mode. The lateral component of velocity, which is essentially along the axial direction of the tip vortex above the airframe, was measured using a fiber optic probe within the airframe. In the present set of experiments, we were unable to obtain a satisfactory signal-to-noise ratio with a 12.5mm diameter quartz window installed flush with the airframe surface. The window had to be removed for the measurements: this precluded any attempt to interpret data closer than 12.5mm to the surface. For this reason, measurements were not made in the boundary layer during the final stage of collision, where the tip vortex core is within 12.5mm of the surface.

With the fiber optic probe, the solid angle of light collection was substantially higher even in the backscatter mode than it was in the earlier configuration where the collection optics were placed outside the test section. This made it possible to re-examine the feasibility of core velocity measurements. Data at several locations were checked for repeatability. In most of the measuring grid shown, the data rate was high enough (several hundred per second) to enable collection of 100,000 individual points per measuring location, in order to sort out the ensemble-averaged periodic velocity with a resolution of 1 degree of azimuth. In the collision region, the data rates fell below a hundred per second, and the number of points was reduced to 30,000. The results shown below demonstrate that the flowfield was periodic enough to enable successful measurement of velocity profiles with such azimuth resolution.

RESULTS

Scaling with Advance Ratio

In previous work, we have shown that for an advance ratio of 0.1, the vortex trajectory at 1050rpm is slightly different from that at 2100 rpm. The pressure traces corresponding to the vortex interaction, however, do scale with square of velocity when the rpm is changed at constant advance ratio. In the present work, we found that the lateral velocity component associated with vortex passage also scaled by a factor of two when the tip speed was changed by a factor of two at constant advance ratio. With this finding, the data taken at 2100 rpm can be scaled to the 1050 case reliably.

Correlation Between Flow Visualization, Pressure and Axial Velocity

Figure 3 shows the correlation between instantaneous pressure, flow-visualization and LV measurements at the beginning and end of the collision phase. Even late into the interaction phase on top of the airframe, there is clearly a vortical region as shown both by the velocity vectors and the suction peak.

Fig. 4(a,b) show the effects of the interaction on the airframe surface on the ABS in

<table>
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<tr>
<th>Table 1: Test Conditions, Dimensions and Uncertainties</th>
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<tr>
<td>Freestream Velocity</td>
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<tr>
<td>Rotor rpm</td>
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<tr>
<td>Rotor collective pitch</td>
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<tr>
<td>Rotor diameter</td>
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<tr>
<td>Tip path inclination from horizontal</td>
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<tr>
<td>Vortex strength</td>
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<tr>
<td>Cylinder diameter</td>
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<tr>
<td>Rotor tip height above cylinder</td>
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<td>Boundary layer</td>
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<td>Reynolds number</td>
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terms of the unsteady pressures. The maximum effect of the suction due to the vortex is seen to convect downstream with time. It is interesting to note that there is a vortex suction effect as late as 100˚ of rotor azimuth at 60˚ on the ABS of the airframe. This means that it takes about 50˚ of rotor azimuth (about 8 ms) for the vortex to convect from the top to 60˚ and from Xb/R of 0.47 to 0.57. In this time the effect of the vortex reduces but gradually, implying that this is the time for the dissipation initiated on the top of the surface to transmit through the vortex core when the cut end reaches an azimuthal section at 60˚. A similar convective motion of the other cut end is seen on the RBS, but with an accompanying suction peak due to axial velocity in the vortex directed away from the RBS.

Fig. 5(a,b) shows the unsteady pressure trace on the ABS at two azimuthal stations on the ABS of the cylinder. The postulated stagnation peak due to the jet like axial velocity in the core impinging on the cylinder is clearly seen. Surprisingly, a suction peak persists, which could probably be attributed to the swirl present in the cut end. This is indicative of the cut end being normal to the cylinder with an inner jet like core and a thin outer swirl.

Fig. 6 describes expectations from the present results on the vortex behaviour after being cut on top of the airframe.

CONCLUSIONS
From the latest results it appears that after the tip-vortex filament is cut on top of the airframe it is convected down the sides. There is evidence of a suction peak due to the axial velocity in the cut filament on the RBS. On the ABS there is evidence that swirl in the cut filament persists long after the dissipation takes place on the top of the airframe. A stagnation region due to a jet like impingement by axial velocity in the core has been measured on the ABS. These are described in the results section.

1. The interaction on the top of the airframe is now understood to a point where the primary unknown in the axial velocity distribution.

2. The important phases of the interaction have been differentiated and have been correlated in terms of the effect on the airframe and the effect on the vortex.

3. The interaction on the sides of the airframe is seen to behave according to the postulated mechanism and needs to be confirmed with more flow-visualization.

4. There is a stagnation peak as predicted which becomes evident only at a cylinder azimuthal station of 45˚.

5. The suction peak due to the vortex persists with a thinning swirl region upto 60˚ on the cylinder azimuthal station.

6. Suction due to the axial flow is seen on the RBS with similar convective trends as the ABS.

7. Flow visualization correlated well with pressure and velocity measurements on the top of the airframe.

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REFERENCES