Recent Experiments on Vortex Collisions with a Cylinder

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ABSTRACT§

The detailed process of interaction of a vortex with a solid body is important in the unsteady aerodynamics of maneuvering aircraft, especially rotorcraft. This paper extends previous experimental work on the interaction of a rotor wake with a circular cylinder whose dimensions are large in comparison to the vortex core. Previous work has shown that the pre-collision vortex trajectory and surface pressure extrema can be predicted from potential flow analysis. Experimental results are presented on the collision phase. A time history of the collision event in a vertical plane along the top of the cylinder is constructed from rotor-synchronized flow images and correlated with pressure traces assembled from several locations along the top. These results show the sequence of development of secondary vortical flow upstream of the main vortex, separation of the reverse-flow boundary layer, and the final stages of core collision with the surface. Results from a dual-camera system are presented to show temporal evolution at some selected phases. While some evidence is presented on the postulated sudden eruption of the reverse flow boundary layer, this event is yet to be captured from the dual-camera system.

NOMENCLATURE

ABS The side of the cylinder under the advancing-blade side of the rotor disk.
Cpinst \((P_{\text{inst}} - P_\infty) / q_\infty\)
H Vertical spacing between rotor hub center and airframe centerline
Pinst Instantaneous static 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.

X Distance parallel to tunnel axis from rotor hub center
Z Vertical distance from rotor hub center
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

This study grew out of two problem areas: helicopter rotor/airframe interaction, and the initiation of separation in turbulent boundary layers on pitching wings. The former is summarized in Fig. 1, which shows a highly simplified rotor/airframe configuration. By the early 1980s, rotor /airframe aerodynamic interaction was recognized as a fundamental obstacle to designing better rotorcraft\(^1\). It was possible to compute, using vortex methods, the dynamics of a "free wake", tracking the force-free trajectories of the tip vortices and the inboard vortex sheets trailing behind the rotor blades\(^2\). Better yet, it was possible to specify these trajectories using large semi-empirical databases, using the "prescribed wake" approach\(^3\). The prescribed wake has found the wider use in practice because the results from the "free wake" have not been as reliable. In low-speed flight, the wake impinges on, and goes around, the fuselage. This posed a major difficulty to both prescribed-wake and free-wake calculations: the interaction of the vortex system with the airframe was unknown. This prompted basic studies of the wake/airframe interaction. By 1988, it was possible to compute from first principles, and prove by comparison to experiment\(^4\)–\(^6\), many of the first-order phenomena involved in this interaction. The uncertainty was distilled down to the actual collision of the tip vortex with the airframe. Ref. 7 summarizes what has been learned at the authors' organization about this problem.

Ref. 8 summarizes other motivations to study vortex/cylinder interaction. The interaction of vortices
with the surface is a postulated mechanism for the initiation of boundary layer separation. The process is believed to culminate in a violent, focused eruption of boundary layer fluid into the freestream, with the separation then propagating to other spanwise locations on a wing. The timing of such events is critical to the understanding and control of the dynamic stall phenomenon seen over maneuvering aircraft. Even on nominally two-dimensional configurations, this process is believed to occur in a very localized region, and to be fully three-dimensional. Thus the collision process of a vortex with the surface of a cylinder is of basic interest.

**Observed Features**

Ref. 7 describes the features of the tip vortex/cylinder interaction, leading up to the final stages of collision. Many of the observed phenomena can be described using Fig. 1, which is a composite based on two experimental models. The interaction at the front of the wake is based on the experiments at Georgia Tech (Ref. 9), while the interaction at the rear corresponds to the geometry used in the University of Maryland wide-field shadowgraphy experiments (Ref. 10). In both cases, a two-bladed rotor turns above the cylindrical fuselage. The sense of rotation is the conventional one for American helicopters: if one stands over the fuselage, looking out to the front, the rotor goes forward on the right side (the Advancing Blade Side), and comes back on the left (Retreating Blade Side). The tip vortices are left behind by the rotor blades as a pair of helices, convected downwards and downstream. As each filament approaches the cylinder, it begins to be distorted by interaction effects.

The initial distortion of the tip vortex filament conforms to expectations from potential flow theory. Thus the u-component of the vortex convection above the cylinder is retarded at the front part, while it is accelerated at the rear because of the different sense of vortex rotation. The axial velocity in the rotor tip vortex is wake-like, i.e., follows the rotor blade. In Fig. 1, this means that the axial velocity is directed from the Advancing Blade Side (ABS) to the Retreating Blade Side (RBS). During impact, the flow in the core must thus stagnate at the ABS; evidence of this is seen in Ref. 8 as a bulging of the core, and high stagnation pressures on the ABS. However, at the very top of the cylinder, this stagnation must occur after the core itself interacts with the surface boundary layer. This comes very late in the collision sequence to be discussed in this paper.

Before going to the details at the top of the airframe, we summarize what has been seen around the rest of the cylinder, using the results of Ref. 7 and Fig. 1. As stated before, the stagnation of the axial flow on the ABS causes a high-pressure region there in addition to the region of suction expected when the high-speed flow around the vortex approaches the surface. The details of this process remain to be investigated. The stagnating end of the vortex filament then slides down the ABS, and its effects are seen even below the cylinder in the surface pressure distribution.

On the Retreating Blade Side, the axial flow is directed away from the surface. Thus, in the portion of the filament than never interacted with the surface, the flow goes along the filament, away from the cylinder. Visualized in a horizontal laser sheet, the region of seed particle deficit, which indicates the vortex core, appears to move along the filament, reminiscent of the end of a train leaving a tunnel along a curved track. What happens in the region near the cylinder is again not quite clear; however, we can postulate much of it. There must be suction on the RBS, so that boundary layer fluid must be entrained into the region previously occupied by the vortex core. Any rotation remaining from the destroyed vortex must intensify in this region, and a strong core may form again. The suction region propagates down the RBS, but its pressure signature disappears before reaching the bottom of the cylinder. Probably, boundary layer friction dissipates the rotation of the core. Thus, at the bottom of the cylinder, we are left with two "cut" ends of the vortex: one with some remaining jet-like axial flow, on the ABS, and the other with a dissipated rotation and some suction, on the RHS, with a gap in between. The reconnection process, if any, is still a mystery.

Quantitative analysis of these phenomena require better understanding of the interaction process at the top. The trajectory of the tip vortex, and the surface pressures under it on the cylinder surface, have been computed in detail in Refs. 11 - 14. It is seen that the interaction conforms closely to potential flow expectations until the collision process begins to affect the boundary layer significantly. At the top of the cylinder, this occurs when the vortex center is within one core diameter of the surface. Looking through the whole interaction sequence from the experimental data, we see that the surface pressure extremum is reached before the core begins to be significantly distorted. The pressure then returns rapidly to almost the freestream value. This must occur during the collision process. This is one of the aspects studied in this paper.

**New Experiments**

In this paper, we focus on the final sequence in the collision of the tip vortex at the top of the cylinder. The orientation of the vortex filament is nominally perpendicular to the cylinder axis, and to the vertical plane of geometric symmetry. However, it should be noted that the surface is highly curved, and that there is, or was, strong axial flow (out of the plane of the images) in the vortex core. Thus any appearance of two-dimensionality is an illusion.
TEST CONFIGURATION

The details of the test configuration in the vortex collision region are shown in Fig. 4. Other test parameters and dimensions are given in Table 1.

It should be noted that while the flow visualization is at a rotor rpm of 1050, the pressure data was obtained at 2100 rpm. It has been shown that the rotor rpm or the freestream velocity do not independently effect the flow features, but what matters is the advance ratio. This has been taken care of and the advance ratio for both the experiments was kept at 0.1.

FLOW VISUALIZATION

Image Acquisition

Fig. 5 shows a schematic of the region of flow visualization. The flow was illuminated using a pulsed copper vapor laser beam, expanded into a sheet. This produces 5994 pulses per second, each pulse lasting for only 25 to 50 nanoseconds. The cameras were synchronized with the laser pulses. A circular disc graduated in degrees was attached to the rotor shaft and videotaped from above, with the resulting imaged mixed into a window on the flow image and providing an indication of the instantaneous value of the rotor azimuth for each image. The delay between the actual and the indicated azimuth value was calibrated by noting the indicated azimuth on frames which showed different portions of the blade leading edge passing through the laser sheet. Averaging values from 10 such frames determined the true azimuth to an uncertainty of less than 0.5 degree. Smoke from decomposing wax, generated by heating several vertical wax coated wires upstream was used to seed the flow. Given the short pulse duration, the low light intensity and the uncertainty of the quality of seeding in the field of view at the instant of interest, the probability of obtaining clear images with seeding in the desired locations was not very high. The images presented here are the best that were located after a considerable search of the videotapes.

For some of the experiments a dual camera system was used. Two cameras of identical model and settings with identical telephoto lenses were aligned to view the same field. The shutter of each was triggered externally by a TTL pulse at the standard video rate of 29.97 frames per second, with the exposure time set at a 100 microseconds. The pulse train to the second camera was delayed by a specified interval with that going to the first camera. The interval was varied from 10 milliseconds to 0.1 milliseconds. The signals from the cameras were recorded independently on two identical VHS recorders. The cameras were initially aligned by matching the images of a grid board with scale markings, placed in the plane of the laser sheet. The position, direction of view, zoom and focus of the cameras was matched. Subsequent analysis of the images showed that the alignment was accurate to within one pixel on a 640x480 pixel computer screen. Runs with various values of shutter delay were intended to cover the range of the time scales of interest, from the integral scales of the freestream and rotor wake convection to those of the development of instabilities under the vortex. The images from the two cameras show substantial differences in brightness, resulting from different intensifier performance. When successful, however, the technique described above enables capture of two images of the same phenomenon within an interval of 100 microseconds without the complexity of a high speed camera.

Image Analysis

The images thus obtained had to be enhanced to make them clearer. This was done by downloading images from video on to a computer screen using Mediagrabber and doctoring them using Adobe Photoshop to clarify image details. Thus instantaneous flow images could be obtained at a number of rotor azimuth angles. Frames corresponding to multiples of 6 degrees of rotor azimuth from 0˚ to 360˚ were obtained as described. These frames were then used to correlate the vortex locations and flow details with the instantaneous phase averaged pressure data. These frames were also put in sequence based on the rotor azimuth angle and a Quicktime movie was made out of the resulting sequence. Relevent stills from the sequence are presented in this paper to describe different phases of the collision process along the top of the cylinder. Vortex trajectories resolved to 6˚ azimuth were obtained from these frames. This was done by locating the vortex core position on the screen

Table 1: Test Conditions, Dimensions and Uncertainties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freestream Velocity</td>
<td>5 m/s ± 0.25%</td>
</tr>
<tr>
<td>Rotor rpm</td>
<td>1050 ± 1</td>
</tr>
<tr>
<td>Rotor collective pitch</td>
<td>10 deg.</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>0.9144 m.</td>
</tr>
<tr>
<td>Rotor tip path inclination from horizontal</td>
<td>5 deg.</td>
</tr>
<tr>
<td>Vortex strength at origin</td>
<td></td>
</tr>
<tr>
<td>Cylinder diameter</td>
<td>0.137 m</td>
</tr>
<tr>
<td>Rotor tip height above cylinder</td>
<td>0.137 m</td>
</tr>
<tr>
<td>Boundary layer Reynolds number based on surface distance at X = ??</td>
<td>8e4 at x = 0.236 m</td>
</tr>
</tbody>
</table>

markings, placed in the plane of the laser sheet. The position, direction of view, zoom and focus of the cameras was matched. Subsequent analysis of the images showed that the alignment was accurate to within one pixel on a 640x480 pixel computer screen. Runs with various values of shutter delay were intended to cover the range of the time scales of interest, from the integral scales of the freestream and rotor wake convection to those of the development of instabilities under the vortex. The images from the two cameras show substantial differences in brightness, resulting from different intensifier performance. When successful, however, the technique described above enables capture of two images of the same phenomenon within an interval of 100 microseconds without the complexity of a high speed camera.

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coordinates and transferring that location to real space coordinates. The transformation was obtained from a known grid videotaped prior to the experiment.

**PRESSURE MEASUREMENTS**

Pressure on the surface of the airframe was measured using two different types of pressure transducers. Mean pressure was measured by a capacitance-type Barocel pressure transducer whose response is not fast enough to measure unsteady pressure fluctuations as encountered in rotorwake/airframe interactions. Unsteady pressures were measured using 6.35 mm B&K condenser microphones. These microphones have a flat response over a wide frequency range and low internal noise. However, these microphones are not designed to measure steady or quasi-steady pressures. Therefore, the unsteady pressure measurement had to be performed using both the types of pressure transducers. Ample sampling time, equal to 140 rotor revolutions at 2100 rpm, ensured that the mean pressures measured by the Barocel truly represented time-averaged mean pressures. The signal from the Barocel is digitized through a 16-bit analog-to-digital converter and sampled with a HP-1000 A700 minicomputer. The B&K microphones were flush mounted on the airframe surface to allow for maximum dynamic response. The microphone signals are amplified through NEFF DC amplifiers which have a response upto 100 KHz frequency, and then digitized in the A/D converter. The microphone sampling is initiated by a trigger pulse from an encoder mounted on the rotor shaft. The data is sampled once per one-degree blade rotation and averaged over an interval of 6 degrees. Therefore, 360 data points per rotor revolution are sorted into 60 six-degree increments of azimuth resolved data. This process is repeated 100 times and the results are ensemble averaged.

**RESULTS**

Fig.6 shows various stages of the vortex as it sheds off the rotor blade, interacts with the cylinder and finally causes boundary layer separation, and the formation of associated secondary structures. The rotor azimuth angle is used as a measure for sequencing the interaction process.

At \( \psi = 0^\circ \), the vortex core, seen as a dark region with a region of swirling fluid of high brightness surrounding it, is still about half the cylinder diameter away from the top surface. Apart from a slight flattening of the core, due to the blade passage, no other major effects are visible on the core. The \( C_p \) plot shows the blade passage effect as a positive pressure peak, with a slight dip at \( X_b/r = 0.3 \), indicating the effect of the vortex on the airframe. Upto an azimuth of \( 30^\circ \), the primary clockwise-rotating vortex goes unchanged and its effect on the airframe in terms of the negative pressure peak is the same. After about \( 36^\circ \), the vortex core becomes more diffuse and its pressure effect on the surface becomes stronger. This effect increases and reaches a maximum at \( \psi = 42^\circ \).

From \( \psi = 42^\circ \) onwards the flow visualization shows that the vortex core is less than one core diameter away from the airframe. At \( \psi = 48^\circ \), the core distortion becomes evident. At this azimuth that the dynamic vortex-surface interaction begins. Even up to this azimuth, the dissipative effects of the boundary layer have not acted on the vortex. The surface negative pressures peaks are the highest during this phase of the rotor wake/airframe interaction. From here onwards, viscous begin to dominate and start weakening the vortex core. This is indicated by reduction in the sharpness of the core, and the reduction in its size. The pressure traces from \( \psi = 54^\circ \) onwards indicate this also, as a continuous reduction in the negative \( C_p \) peak upto \( \psi = 78^\circ \).

At \( 84^\circ \) of rotor azimuth, the first signs of a secondary structure are seen in the pressure trace as a secondary negative peak. This indicates a region of low pressure upstream of the primary vortex. This region of low pressure is the initiation phase of a secondary vortex. Note that in the pressure plots, at this time we can see four peaks. They correspond to the primary vortex of the second blade, next, the secondary vortex, next , the primary interacting vortex and furthermore downstream the rolled up inboard vortex sheet. The secondary structure is very difficult to capture in the flow visualization because it is weak and is not well defined. In some of the flow images at about this rotor azimuth a triangular region of particle deficit is seen. This is shown in Fig.7 at a rotor azimuth of \( 99^\circ \). None of the flow images shown in Fig.6 actually show the development of such a structure. One of the reasons is the difficulty involved with smoke visualization. Secondly, it seems that there is no exact azimuth at which the secondary structure develops at every revolution. Similar structures were seen at other azimuth angles between \( 95^\circ \) and \( 105^\circ \). It is apparent that, almost, a range of azimuths can be associated, with any amount of certainty, to the initiation of the secondary structure.

The secondary structure gains in strength from \( \psi = 90^\circ \). At about \( \psi = 120^\circ \), the secondary vortex has become stronger than the primary vortex as seen in the pressure plots. Judging from the \( C_p \) plots it seems that the flow begins to separate only beyond a rotor azimuth of about \( 110^\circ \). By this time the peak due to the primary vortex from the following blade has become stronger than that due to both the primary and the secondary vortex of the first blade. From a rotor azimuth of \( 162^\circ \), the blade passage has started to take effect and the whole sequence of events is repeated. Fig.8 shows the progress of the surface effect of the vortex in terms of rotor azimuth angle. This is seen to increase upto \( 48^\circ \).
and then decrease. Fig.9 shows the vortex trajectories resolved to 6 degrees rotor azimuth. There is some kind of a jitter visible over a wide range of azimuth angles. The vortex repeatedly speeds up and slows down as it moves closer to the surface and downstream. The vortex trajectories are not phase averaged and some scatter can be expected from the shown trajectory. It seems that the vortex "bounces" off the surface more than once before it dissipates. Fig.10 demonstrates the use of the two-camera setup for various shutter delays. While the 0.17 ms shutter delay images show almost no difference, the 1 ms shutter delay images show the feasibility of this technique. Minute but distinct changes in the features of the flow field within a few milliseconds, which cannot be captured by a usual low-speed camera, show up in the two camera setup. Figure 11 demonstrates this for a shutter delay of 0.49 ms.

CONCLUSIONS

The close interaction of the vortex with the cylinder and the boundary layer on it, is evident from the jittery motion of the vortex core, its distortion and the and the initiation of secondary structures. The unsteady pressure plots show a good correlation with the flow visualization images. The time scales of interaction seem to be much smaller compared to time scale based on the mean flow. There is some indication of flow stagnation in the boundary layer region followed by separation. While there is an overall periodicity in the interaction process, linked directly to the rotor period, the specific interaction details seem to be spatially and temporally scattered about the overall mean period. It is apparent that the exact nature of the turbulent boundary layer eruption needs to be studied in relation with the vortex impingement. Also essential is to capture the secondary vortex and its effects on the separation. This would require LDV measurements with high spatial resolution within the boundary layer and a clearer boundary layer flow visualization for isolating the secondary processes. The feasibility of high temporal resolution using a two-camera setup was demonstrated. Ability to use the technique with various shutter delays was shown.

REFERENCES

3. Landgrebe et al. The UTRC Generalized Wake