Experimental Investigation of Rotor Vortex Wakes in Descent

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January 5, 2004

An experimental study is performed on a three-bladed rotor model in a water tow tank. The rotor’s rotational velocity, the rotor plane angle of attack, and the carriage speed are all varied in order to simulate a wide range of rotocraft operating states. The focus is on descent speeds and angles where the rotor is operating in or near vortex ring state. Circulation Reynolds numbers are of order \(10^5\) and chord Reynolds numbers are of order \(10^4\). Flow visualization is done using air bubbles and fluorescent dye injected tangentially from the blade tips to mark the vortex core, showing the development of both short-wave and long-wave instabilities on the helical vortices in the wake. Strain gages are used to record transient loads, allowing a correlation between the rotor thrust performance and the development of the vortex wake.

The data indicate that as the instability develops, the adjacent vortices merge and form thick vortex rings, especially during descent. Periodic shedding of vorticity from the wake associated with vortex ring state is observed, resulting in peak-to-peak thrust fluctuations of up to 95% of the mean and occurring at regular intervals of 20 – 50 rotor revolutions, depending on flow parameters.

Nomenclature

\[ \begin{align*}
  c &= \text{blade chord} \\
  A &= \text{rotor disk area}, \pi R^2 \\
  C_T &= \text{thrust coefficient}, T/\rho AV_{tip}^2 \\
  R &= \text{rotor radius} \\
  Re_c &= \text{Reynolds number based on chord}, \frac{V_{tip} c}{\nu} \\
  T &= \text{rotor thrust} \\
  V &= \text{towing speed} \\
  V_{tip} &= \text{rotor tip speed}, \Omega R \\
  V_x &= \text{rotor forward flight speed}, V \cos \alpha \\
  V_z &= \text{rotor descent speed}, V \sin \alpha \\
  \alpha &= \text{descent angle} \\
  \lambda &= \text{short-wave instability wavelength} \\
  \mu &= \text{rotor advance ratio}, V_x/V_{tip} \\
  \nu &= \text{kinematic viscosity} \\
  \xi &= \text{rotor descent ratio}, V_z/V_{tip} \\
  \rho &= \text{water density} \\
  \sigma &= \text{standard deviation from mean rotor thrust} \\
  \theta &= \text{rotor collective pitch angle} \\
  \Omega &= \text{rotor rotational speed}
\end{align*} \]

Introduction

An accurate understanding of the physics of helical vortex wakes has long been regarded as one of the most difficult problems in fluid dynamics. With implications on the performance of propellers, wind turbines, and helicopter rotors, the problem is of practical interest to many. Even before the days of modern production helicopter flight, the issue of the nature and stability of ring vortices and helical vortices had been analyzed extensively. Levy and Forsdyke\(^4\) performed a stability analysis on a single helical vortex in 1928, and more recently, Landgrebe\(^2\) and Widnall\(^3\) have added to and corrected this study. Gupta and Loewy\(^4\) have performed a similar analysis on multiple interdigitated helical vortices. Despite the focus that modern helicopter flight has brought to the problem in the last hundred years, the physics of vortex wakes remains a challenging and unresolved issue.
years, and despite the power of modern computers and experimental tools, a true grasp of the physics of helical vortices has remained elusive. While somewhat reasonable approximations of their behavior can be made under restricted and simplified scenarios, there is a great deal of progress still to be made on the problem of real helical vortices. In fact, not even the simplest case of a stationary (hovering) rotor generating a steady vertical helical wake can be computationally modeled with much accuracy at distances greater than a few diameters downstream of the rotor.

In the early days of helicopter flight, a number of simple models appeared – such as the classic momentum theory and the blade element momentum theory\textsuperscript{5,6} – which were capable of predicting gross performance characteristics for a rotor (such as thrust and power) but were unable to capture the detailed dynamics of the wake flow field. Realizing the powerful effect of the wake on the rotor performance, researchers began more detailed studies of the wake flow field, beginning with wind tunnel testing and smoke flow visualization as early as the 1920s.\textsuperscript{7-9} Later, experiments were done using hot wire anemometry (HWA) and other probe techniques\textsuperscript{10} to measure the velocity field itself. Even more recent work has used laser Doppler velocimetry (LDV)\textsuperscript{11-13} and particle image velocimetry (PIV)\textsuperscript{14,15} as non-invasive means of achieving the same. The power of modern computers has recently been harnessed by researchers using more sophisticated, detailed models of the flow field. Current methods in computational fluid dynamics (CFD) utilize ‘free wake analysis’, attempting to calculate the velocity that is induced at a point by all of the vortices in the wake as well as by the blades.\textsuperscript{16,17} And while CFD techniques have led to significant progress over the past ten years in the understanding of simpler cases of flight such as hover, they are not yet capable of predicting the behavior of the wake in more complicated flight states where the aircraft is maneuvering or descending. They are also inadequate for dealing with the true complexities of rotocraft flight like blade stall, airframe interaction, main rotor/tail rotor interaction, shock waves, and turbulence.\textsuperscript{18}

The problem for aerodynamicists is that the flight regimes in which CFD predictions are least accurate are precisely the ones that are of greatest interest to the rotocraft community. When a helicopter is descending rapidly, the very thing that makes the wake solution so difficult – the intense interaction between the rotor and its vortex wake – causes large, unsteady dynamic loads on the blades. Under the right circumstances (when the rotor descent velocity approximately matches the wake velocity), this condition, known as vortex ring state (VRS), can cause the tip vortices to merge together, forming a thick vortex ring that remains near the rotor plane, disrupting the inflow and causing a dramatic reduction in lift. This unstable ring typically undergoes a chaotic shedding and re-formation pattern that results in large fluctuations in thrust that make the aircraft quite difficult to control. As retired test pilot Mott F. Stanchfield says, “In my opinion, a mature VRS is the most hazardous condition that exists in the realm of helicopter aeronautics.”\textsuperscript{19} In fact, VRS has been identified as the likely cause of the April 8, 2000 crash of the Marine’s V-22 Osprey tiltrotor aircraft near Marana, Arizona. In this operations test accident, it is believed that the aircraft – operating in helicopter mode – experienced VRS on its right rotor only, causing it to bank sharply and then nose-dive 250 ft to the ground, killing all 19 people on board.\textsuperscript{20} Prior to this event it was not widely known that a dual-rotor craft would experience such an unusual roll control problem in VRS, which illustrates just how poorly understood this condition still is today.

The purpose of the present experimental study is to explore the physics of the wake evolution in VRS and other descent configurations. Flow visualization and thrust measurement results are presented from experiments performed on a model rotor in a wide range of operating states – from hover to forward flight to rapid descent – with the main focus being on the vortex ring state regime. Experiments were performed in a 70 m long water tunnel, which allowed for much longer test runs than have previously been performed in similar studies (which have generally been conducted in wind tunnels).\textsuperscript{21,22} The rotor’s performance is quantified by measurements of its thrust, and this information is correlated with flow visualization images.

The time-history characteristics of the rotor’s thrust are examined for a broad range of descent
speed and angle combinations. By testing the rotor’s performance over a wide variety of configurations, the rotor’s performance characteristics can be fully characterized, and the descent conditions in which VRS behavior is observed can be clearly identified. The thrust histories of these periodic shedding cases are then compared in order to determine how the descent configuration affects the amplitude, frequency, and overall “orderliness” of the observed fluctuations. For these particular cases, the flow visualization images of the experiment are expected to provide clues as to the nature of the vortex wake formation and shedding phenomenon that makes VRS such a dangerous flight regime.

**Experimental Setup**

**Rotor Model**

Experiments were performed using a three-bladed 25.4 cm diameter rotor model with manually adjustable blade pitch. The blades (Fig. 1), which were 9.5 cm long, were molded from carbon fiber plastic. Each blade had a 0.356 mm ID stainless steel tube embedded along its span to allow dye and air to be injected into the flow from the tip in order to mark the vortex cores. The blades were untapered, with a 1.9 cm chord, and had a twist of about 5 deg (compared with twists of 35—40 deg for typical tilt-rotor aircraft). The low blade twist was chosen in order to avoid dynamic stall and maintain a clean flow over the blades. The blade airfoils were ARAD-10 at the tip and modified ARAD-13 (the camberline was modified) at the root, although the thicknesses were increased slightly to accommodate the dye tubes.

The rotor was driven by a digitally-controlled microstepper motor (25,000 pulses per revolution), allowing for precise control of the rotor’s position and velocity. The motor was mounted atop a 89 cm vertical shaft and drove a 23 cm horizontal shaft onto which the rotor was fixed (Fig. 2). Just beneath the motor was a 2.5 cm thick rectangular mounting plate which supported the model assembly and also served as a force plate, with a pair of 120-ohm strain gages glued to it for measuring the rotor’s thrust. The thrust readings were fed to the computer controlling the experiment. The gages were calibrated to produce thrust readings in units of force, and also to correct for the drag force on the model as it was pulled.
through the water. A bandpass filter was used to eliminate high-frequency electrical and vibrational noise while retaining the important details.

To visualize the rotor’s wake, air bubbles and sodium fluorescent dye were leaked from the blade tips in a direction tangential to the blade path. The dye and air were supplied to the dye reservoir at the base of the vertical shaft through thin plastic tubing (Fig. 2). The dye reservoir was directly connected to the rotor dye tubes through the horizontal drive shaft. The pressure deficit in the vortex cores drew some fluid into the wake, but in order to achieve clear visualization of the flow it was necessary to force additional dye or air to the blades using an external pressurized canister.

Stationary Tank

Initial testing was performed in a 1.22 × 2.44 × 1.68 m deep stationary water tank. With the model fixed in place on top of the tank, this test simulated a hovering helicopter’s flow field. A 10-W Argon ion laser was used for both two- and three-dimensional illumination. For the two-dimensional lighting tests, a vertical light sheet was aligned with the axis of the rotor. In all cases, a digital video camera recorded the flow from the side of the tank, perpendicular to the wake direction and the light sheet.

Generally, air was used as the injection fluid for initial experiments because of its non-contaminating nature. The buoyancy of the bubbles, however, caused them to rise to the surface quickly, rendering the details of the wake incoherent for distances greater than about one diameter downstream of the rotor. In the near-wake of the rotor, however, the air bubbles could better capture the details of the vortex filaments. Later tests used neutrally-buoyant fluorescent dye as the injection fluid, which more clearly showed the break-up and diffusion of the wake at greater downstream distances. No thrust measurements were recorded for any of the stationary tank tests. Rather, these tests were performed solely for visualization purposes, as the quality of the images was significantly better in the stationary tank than in the towing tank.

Towing Tank

The characteristics of a descending helicopter were simulated by pulling the model through the water in a 70 m long towing tank. The 2.4 m wide, 1.5 m deep tank features a large, low-speed carriage running along a set of rails on top of the tank. The carriage speed, which for these tests ranged from 0—40 cm/s, could be controlled manually or by computer.

The model assembly was mounted on a 1.22 × 1.52 m plywood platform, which was supported by a steel frame connected to the carriage (Fig. 3). The model could be rotated using a turntable on the plywood platform, enabling the descent angle of the rotor to be varied in 0.5 deg increments, from 0 deg (forward flight) to 90 deg (vertical descent). A set of blue-filtered halogen track lights was mounted onto the front of the carriage to illuminate the flow and highlight the yellow fluorescent dye. For visualization, the video camera was mounted vertically on the platform, looking downward at the flow and fixed in position with respect to the rotor.

Results

All results presented in this paper refer to experiments conducted at a single rotor rotational speed of Ω = 4 rev/s and for a single collective angle of θ = 7 deg (at the tip). This was taken as a representative case in order to limit the number of experimen-
Flow Visualization

Flow visualization testing from the stationary water tank yielded a number of images which clearly show the development of the rotor wake and the instabilities that cause it to break down. In Fig. 4 air bubbles are injected from the tip of only one blade for the sake of clarity. The large starting ring vortex can be seen on the left, expanding and slowing down as the rest of the wake passes through it. In this three-dimensional image, the short-wave “smooth sinuous wave type” instability discussed by Leishman and analyzed theoretically by Widnall and Gupta and Loewy can clearly be seen along the filament in the near-wake of the rotor. In this case the wavelength of the instability is approximately 3.75 cm, or 2c.

Figure 5 shows a series of two-dimensional images of the upper half of the rotor with dye being injected from all three blade tips. This cross-sectional view of the wake illustrates the influence that each vortex filament has on its neighbors. The induced velocity effect causes adjacent turns of the helices to contract and expand, thus altering their descent velocities and resulting in the classic “leapfrogging” phenomenon often seen with parallel vortex rings. This effect can be seen in the pairing of the second and third vortex cores downstream of the rotor in b) and c), followed quickly by the complete merger of all three vortices in e).

Thrust Measurements

Instantaneous thrust measurements were recorded during the towing tank runs. These tests were typically performed for 100 rotor revolutions, although some were conducted for longer periods in order to verify the trends observed during shorter runs. The data sampling rate was 200 samples per revolution, and the first and last five revolutions of the run were ignored (due to the transient starting effects from the carriage motion, and also to the width of the filtering window).

For many of the runs, thrust levels remained relatively steady over the duration of the experiment. This was generally the case for hover, slow descent, and very steep or very shallow descent angle runs. Figure 6 shows a thrust coefficient time-history plot for a stationary (hovering) rotor. The mean thrust coefficient was 0.0078 and the peak-to-peak fluctuation amplitude was 12% of the mean. Figure 7 shows a thrust coefficient plot of similar form, but for a rapid descent at a fairly shallow descent angle (α = 30 deg). Note that the mean thrust coefficient, 0.0181, is more than two times greater than in the hover case, but the total fluctuation amplitude is still only 12% of the mean.

However, for experiments featuring a combination of moderate descent speed and angle, the rotor thrust characteristics were markedly different. In these cases, the thrust exhibited very large, regular fluctuations. Figures 8-10, for instance, show thrust history plots typical of this type of behavior.

These plots exhibit textbook VRS characteristics, with very large, regular thrust oscillations. An illustration of the physical process yielding these dramatic thrust oscillations is shown in Fig. 11. As the
Figure 5: Two-dimensional flow visualization images of upper half of rotor using fluorescent dye injection from all three blade tips. The “leapfrogging” of one vortex filament over another can be seen in b) and c) as the three vortices orbit about each other and finally merge in e).

Figure 6: Thrust history plot for a hover run ($\mu = 0$). Mean thrust coefficient is 0.0078 and fluctuation is 12% of the mean.

Figure 7: Thrust history plot for a fast, shallow descent run ($\mu = 0.102$). Mean thrust coefficient is 0.0181 and fluctuation is 12% of the mean.
Figure 8: Thrust history plot for $\alpha = 60$ deg, $V = 25$ cm/s ($\mu = 0.039$). Mean thrust coefficient is 0.0137 and fluctuation amplitude is 84% of the mean. Fluctuation period is about 42 revolutions.

Figure 9: Thrust history plot for the same descent configuration as Fig. 8 but for 500 rotor revolutions instead of 100. Performance parameters are nearly identical: mean thrust coefficient is 0.0135, fluctuation amplitude is 94% of the mean, and fluctuation period is about 43 revolutions.

Figure 10: Thrust history plot for a run with $\alpha = 50$ deg and $V = 30$ cm/s ($\mu = 0.06$). Mean thrust coefficient is 0.0173 and fluctuation is 50% of the mean. Fluctuation period in this case is only about 20 revolutions.

vortices are generated, they accumulate and quickly form a thick vortex ring. This ring rolls up just above the rotor plane, interfering with the rotor’s inflow and causing the marked reduction in thrust observed in Figs. 8-10. The ring grows thicker and thicker before abruptly “detaching” from the rotor and convecting away upstream, resulting in the complete recovery of rotor thrust. As the metronomic regularity of the thrust history plots illustrates, this process would repeat itself indefinitely, and in a very predictable way – suggesting that the detachment of the vortex ring was not due to some flow disturbance or anomaly. In order to verify the regularity of this process, the same parameters ($\alpha = 60$ deg, $V = 25$ cm/s) used for the run shown in Fig. 8 were repeated for the run shown in Fig. 9, but the duration of the run was extended to 500 revolutions. Clearly the pattern held, as the two plots are nearly identical. The mean thrust coefficients for the two cases were 0.0137 and 0.0135, their peak-to-peak variations were 84 and 94% of the mean, and the average fluctuation periods were approximately 43 revolutions and 41 revolutions.

Other descent configurations demonstrated very
similar oscillatory characteristics, but with significantly different frequencies and amplitudes of fluctuation. Figure 10 shows a thrust coefficient plot that appears very similar to Figs. 8 and 9. However, in this case – where the descent angle was 50 deg and the descent speed was 30 cm/s – the thrust oscillations were smaller in magnitude (peak-to-peak variation was 50% of the mean) and of shorter period (approximately 20 revolutions). The mean thrust coefficient in this case was slightly higher though, at 0.0173.

Summary Statistics
A primary interest of the rotorcraft community is the determination of the VRS boundary – the region of the flight envelope in which VRS conditions are likely to be encountered. Numerous methods have been employed in the past for defining this boundary, including the mean thrust coefficient reduction and the total peak-to-peak thrust oscillations. Betzina has used a variation of the latter method: three standard deviations (3σ) normalized by the mean thrust. This measure is said to be more consistent than the peak-to-peak amplitude of the oscillations, and also less dependent on the length of the run.

Figure 12 shows a contour plot of this parameter for all test runs, plotted with respect to the advance ratio, \( \mu \), and the descent ratio, \( \xi \). Clearly the area featuring moderate forward and descent speeds exhibits the most dramatic oscillations, as has been discussed earlier. It is difficult for anyone but an experienced helicopter pilot to truly identify how large the thrust fluctuations must be for the rotor to be in VRS. However, judging by the relative magnitude of the thrust fluctuations shown in Fig. 12, the region in the center of the plot – between about \( \alpha = 20 \) and 50 deg – is clearly set apart from the rest of the flight envelope.

Figure 13 shows the peak-to-peak amplitude of thrust fluctuations. Although not apparent from Fig. 12, it is clear that the amplitude of the thrust oscillations is still quite large in forward flight regimes. However, the mean rotor thrust in forward flight is significantly greater than in descent, thus the relative magnitude of the oscillations is still small.

This latter point can be illustrated by plotting the mean thrust coefficient versus the rotor advance ratio – the forward flight speed normalized by the rotor tip speed. This plot, shown in Fig. 14, demonstrates the approximately linear increasing trend of the rotor thrust with forward flight speed. This feature is also apparent in Fig. 15, a surface plot of the mean rotor thrust coefficient versus the forward and descent speeds.

The behavior of the thrust fluctuations with respect to the forward flight speed is not quite as straightforward, as shown in Fig. 16. At very low or very high advance speeds there is little rotor/wake interaction and thus the thrust fluctuations are minimal. However, at moderate advance speeds the thrust fluctuations can be much more severe, depending on the rate of descent. This explains the wide scatter of the fluctuations seen in Fig. 16 for \( \mu = 0.02 - 0.05 \).

As discussed above, for the VRS cases, the oscillation frequencies and amplitudes varied significantly, depending on the descent configuration. The
Figure 12: Three times the standard deviation of thrust measurements ($3\sigma$) normalized by mean thrust coefficient.

Figure 13: Amplitude of peak-to-peak thrust coefficient oscillations ($C_{T_{\text{max}}} - C_{T_{\text{min}}}$).

Figure 14: Mean thrust coefficient versus advance ratio ($\mu$).

Figure 15: Surface plot of mean thrust coefficient with respect to advance ratio, $\mu$, and descent ratio, $\xi$. 
oscillation periods ranged anywhere from 20 to 50 revolutions, and the amplitudes of the fluctuations measured from 50% up to 95% of the mean. Figure 17 shows the relationship between the oscillation period and the advance ratio for the cases with observable, organized VRS-like oscillations. The trend shown here is not unusual – one would expect the vortex ring to be less stable and thus to be shed more rapidly with increasing advance speed. What is unusual is how well the curvefit represents the data. This fit, which shows the oscillation period varying with the advance ratio to the -1.5 power, has a correlation coefficient ($R^2$) of 0.92.

**Conclusions**

Flow visualization and thrust measurement experiments have been performed on a three-bladed rotor model in a towing tank. Descent angle and speed have been varied in order to simulate a wide range of descent configurations, with particular emphasis on the vortex ring state regime. Flow visualization results from the hovering rotor capture both the short- and long-wave instabilities that develop in the near-wake of the rotor and precipitate its rapid breakdown. Flow visualization results from the descending rotor in the VRS regime were less clear, but nonetheless show the merger of the individual tip vortices, forming a thick vortex ring. This ring remains just above the rotor plane for a period of 20 - 50 revolutions before abruptly detaching and convecting away upstream. Correlations between flow visualization images and instantaneous thrust measurements indicate a severe reduction in rotor thrust when the vortex ring is “attached” to the rotor, followed by a full recovery of thrust once it is shed. The regularity of the vortex ring shedding/formation process over 100 - 500 revolution periods indicates that the process is quite stable and is likely dictated by the size of the ring and the amount of vorticity it can contain.

Thrust fluctuations observed in the VRS regime were most severe for descent angles of $\alpha = 20 - 50$ deg and for descent speeds of $V = 20 - 30$ cm/s. In this region, the peak-to-peak amplitudes of the thrust fluctuations were approximately 80 - 95% of the mean thrust. Thrust oscillations of this magnitude will have a potentially disastrous effect on the performance and control of a helicopter or a tiltrotor aircraft and are thus deserving of further study. To gain a fuller understanding of the flow physics in this flight regime it will be necessary to perform PIV experiments on the critical descent configurations iden-
identified in this paper. By accumulating quantitative information about the flowfield in the VRS regime it should be possible to understand the nature of the vortex ring shedding/formation process that causes these severe thrust fluctuations, and how to mitigate or avoid these effects.

Acknowledgements

This work was supported by the NASA Ames Research Center under Grants NCC 2-5388 and NCC 2-5507. The author is grateful for the help and guidance provided by Frank Caradonna, Jason Ortega, Ömer Savaş, and William Tsai. The author was the recipient of the National Defense Science and Engineering Graduate Fellowship.

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