

Flow Visualizations and Extended Thrust Time Histories of Rotor Vortex Wakes in Descent

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An experimental study is performed on a three-bladed rotor model in two water tanks. The blade pitch, rotational velocity, descent angle, and descent speed are all varied in order to simulate a wide range of rotorcraft operating states, focusing on descent cases where the rotor is operating in or near vortex ring state – an area in which there is currently very little available data. Flow visualization is done by injecting air bubbles and fluorescent dye tangentially from the blade tips to mark the vortex core, showing the development of both short-wave (“sinuous”) and long-wave (“leapfrogging”) 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. Reynolds numbers are of order 10^5 and test runs are performed for extended periods – up to 500 rotor revolutions – demonstrating the repeatability of the patterns of thrust variation. The data indicate that as the instabilities develop, adjacent vortices merge and form thick vortex rings, particularly during descent. Periodic shedding of these rings 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.

Notation

| | | | |
|--------|--|------------|---|
| c | blade chord | V | free stream (towing) speed |
| A | rotor disk area, πR^2 | V_h | velocity induced at rotor in hover, $(T/2\rho A)^{1/2}$ |
| C_T | thrust coefficient, $T/\rho A V_{tip}^2$ | V_{tip} | rotor tip speed, ΩR |
| L | blade length | V_x | rotor forward flight speed, $V \cos \alpha$ |
| N | number of rotor revolutions | V_z | rotor descent speed, $V \sin \alpha$ |
| R | rotor radius | α | descent angle |
| Re_c | Reynolds number based on chord, cV_{tip}/ν | θ | collective pitch angle at 0.75 R |
| T | rotor thrust | λ | short-wave instability wavelength |
| | | ν | kinematic viscosity |
| | | ρ | water density |
| | | σ | standard deviation of mean rotor thrust |
| | | σ_s | rotor solidity ratio |
| | | τ | vortex ring shedding period |
| | | Ω | rotor rotation rate |

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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 (Ref. 1) performed a stability analysis on a single helical vortex in 1928, and more recently, Landgrebe (Ref. 2) and Widnall (Ref. 3) have added to and corrected this study. Gupta and Loewy (Ref. 4) have performed a similar stability analysis on multiple interdigitated helical vortices.

Despite the focus that modern helicopter flight has brought to the problem in the last hundred 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 highly simplified scenarios, there is much progress still to be made on the problem of *real* helical vortices. The current state of rotor wake modeling is that while accurate computations of relatively simple wake flows (such as hover) are beginning to produce results that are quantitatively interesting, computations of rotor wakes that undergo massive interaction with the rotor (such as for the vortex ring state) are currently of only qualitative interest at best.

In the early days of helicopter flight, a number of simplified models appeared – such as the classic momentum theory and the blade element momentum theory (Refs. 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. In view of the acute effect the wake has on the rotor performance, researchers began to undertake more detailed experimental studies of the wake flow field, beginning with wind tunnel testing and smoke flow visualization as early as the 1920s (Refs. 7, 13, 14). Later, experiments were done using hot wire anemometry (HWA) and other techniques (Ref. 15) to measure the velocity field itself. Even more recent work has used laser Doppler velocimetry (LDV) (Refs. 16–18) and particle image velocimetry (PIV) (Refs. 19,20) 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. The current state of the art in rotor wake modeling is “free wake analysis”, a method in which the wake flow field is calculated based on the induced velocities of all the tip vortices as well as the inboard vortex sheets (see Refs. 21, 22). And while such 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. At this point, there is no reliable physical model for rotor wake flow, nor is one possible without better experimental knowledge of the flow than currently exists.

The problem for aerodynamicists is that the flight regimes that are of greatest interest to the rotorcraft community are precisely the ones in which CFD predictions are least accurate. 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 certain circumstances (when the rotor descent velocity approximately matches the wake velocity), the aircraft can encounter a condition known as vortex ring state (VRS), where the tip vortices 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 shedding/reformation cycles that result 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” (Ref. 23).

Although the aerodynamics of rotors in descending flight – and in VRS in particular – has been the subject of research for many years (see Refs. 7–10, 24), that work has largely focused on measurements of the rotor thrust and power with very little flow field visualization, and even less simultaneous measurement of thrust/power and flow fields. This is likely due to the relative “disorder” of such flows and the difficulties associated with facility/model sizing, turbulent diffusion, and injection of flow markers. The present study is aimed at addressing these difficulties and providing a relatively complete description of the wake of the descending rotor and its effect on rotor loading. Ultimately, it is planned to develop a data set with

sufficient information to improve and validate computational methods for the prediction of rotor descent behavior.

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 focus being on the vortex ring state regime. Experiments were performed in a 60 m long water tow tank, which allowed for extended run times that were more than sufficient for the study of long-period unsteady flows such as those encountered in descending flight, and which were much longer than have previously been performed in similar studies (which have generally been conducted in wind tunnels – see Refs. 24, 25). The rotor’s performance is quantified by measurements of its thrust, and this information is correlated with simultaneous flow visualization images.

The time-history characteristics of the rotor’s thrust are examined for a broad range of descent speed, descent angle, and collective angle combinations. By testing the rotor’s performance over a wide variety of configurations, the rotor’s performance can be fully characterized, and the descent conditions in which VRS behavior is observed can be clearly identified. The thrust time-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 thrust fluctuations. For these particular cases, the flow visualization images of the experiment 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 with a three-bladed 25.4 cm diameter rotor model featuring manually adjustable blade pitch. The blades (Fig. 1), which were 9.5 cm long, were molded from carbon fiber reinforced plastic. The blades were untapered, with a 1.9 cm chord, and had a twist of about 5° (compared with twists of $35\text{--}40^\circ$ for typical tilt-rotor aircraft). The low blade twist was chosen in order to minimize rotor separation. The blade airfoils were modified ARAD-10 at the tip and modified ARAD-13 at the root. Each blade had a 0.36

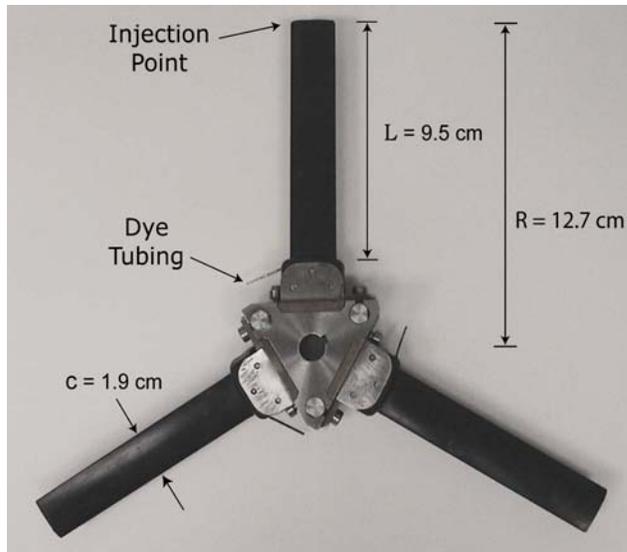


Figure 1: Model 3-bladed rotor. Diameter is 25.4 cm. Dye and air enter the tubes at the root, flow through the blades to the tips, and enter the flow tangentially.

mm ID stainless steel tube embedded along its span, allowing dye or air to be injected into the flow from the tip to mark the vortex cores. The airfoil modifications included a chordwise-linear thickness increase which thickened the trailing edge and provided more room for the dye/air tubes. In addition, the aft camber of the root airfoil was increased.

The rotor was driven by a digitally-controlled microstepper motor (25,000 pulses per revolution), allowing for precise control of both the rotor’s position and velocity. The motor was mounted atop an 89 cm vertical shaft and drove a 23 cm horizontal shaft onto which the rotor was fixed (Fig. 2). The vertical shaft lay downstream of the rotor during descent testing, so as to avoid interfering with the rotor’s inflow. Just beneath the motor was a 2.5 cm thick rectangular mounting plate which supported the model assembly and also measured rotor thrust, using a pair of flexures instrumented with 120 ohm strain gage bridges. The thrust readings were fed to the computer controlling the experiment. Data are corrected for drag tares and low-pass filtered during post-processing to eliminate high-frequency electrical and vibrational noise while retaining the main features of the signal.

To visualize the rotor’s wake, air bubbles and sodium fluorescent dye were released 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

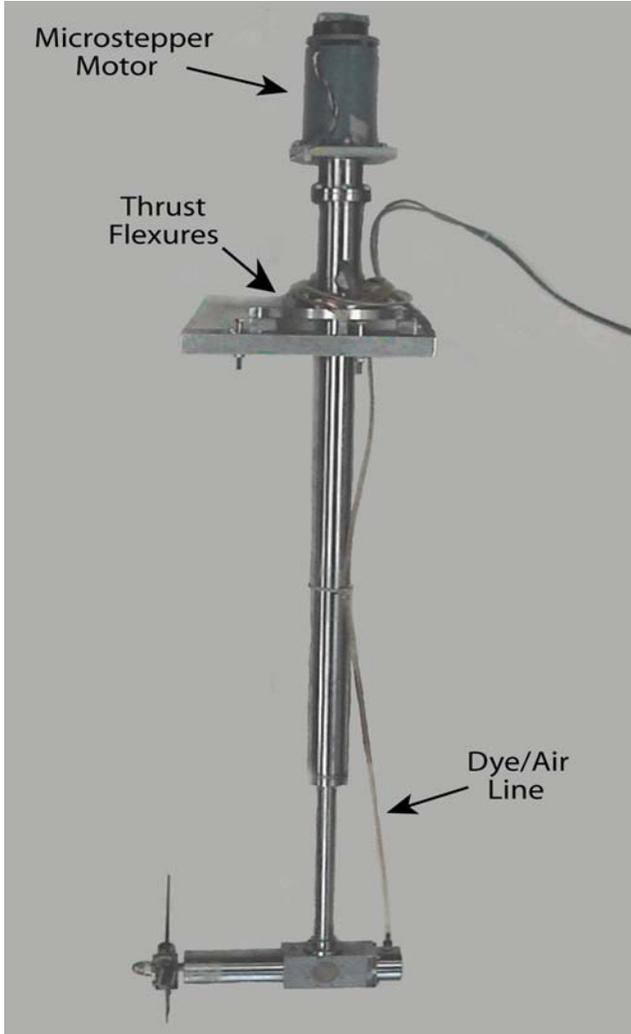


Figure 2: Entire model assembly, showing locations of strain gages and dye tubing. Flow would be from left to right in a descent test.

the vertical shaft through thin, flexible plastic tubing (Fig. 2). The dye reservoir was directly connected to the rotor dye tubes through the horizontal drive shaft. The pressure deficit at the blade tips drew some fluid from the supply tube into the wake, but in order to achieve clear visualization of the flow it was necessary to supply external pressure.

Stationary Tank

Initial testing was performed in a $1.22 \times 2.44 \times 1.68$ m deep stationary water tank at the University of California Berkeley. With the model fixed in place atop the tank, these tests simulated a hovering helicopter's flow field. A 10-W Argon ion laser provided both planar and volumetric 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. Due to the small size of the tank, test runs were relatively brief (and between-test intervals relatively long) in order to minimize recirculation effects which would lead to an unwanted climb condition.

Generally, air was used as the injection fluid for initial experiments because of its non-contaminating nature. Also, in contrast to the neutrally-buoyant dye, which marked the vortex cores but diffused to areas surrounding the core as well, the majority of the air bubbles initially migrated directly to the low pressure vortex cores. Thus in the near-wake of the rotor, before the vorticity had diffused significantly and attenuated the pressure deficit at the cores, the air bubbles nicely captured the details of the filament structure. However, once the transition to the far-wake region occurred, the buoyancy of the bubbles caused them to rise to the surface quickly, rendering the details of the wake indecipherable for distances greater than about one diameter downstream of the rotor. Later tests used neutrally-buoyant fluorescent dye as the injection fluid, which clearly showed the break-up and diffusion of the wake at greater downstream distances.

In general, thrust measurements were not recorded for the stationary tank tests. Rather, these tests were performed primarily for visualization purposes, as the quality of the images was significantly better in the stationary tank than in the towing tank and the structure and evolution of the wake could be more clearly discerned.

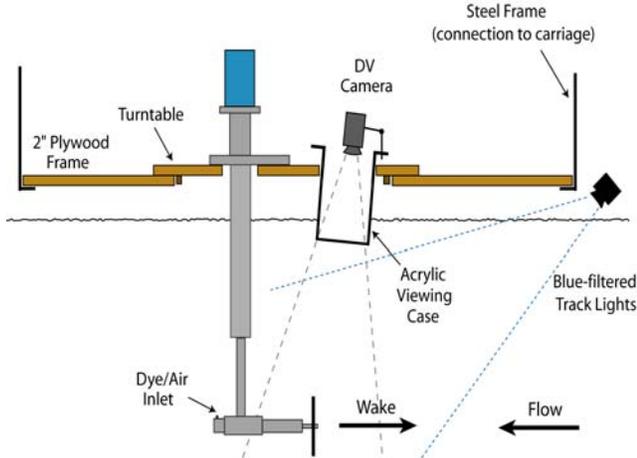


Figure 3: Side view of carriage platform with model assembly mounted on turntable. Direction of travel is from left to right.

Towing Tank

The characteristics of a descending helicopter were simulated by pulling the model through water in the 60 m long tow tank at the University of California’s Richmond Field Station. 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 0–50 cm/s, could be controlled manually or by computer.

The model assembly (Fig. 2) was mounted on a 1.22 × 1.52 m plywood platform, which was suspended just above the water surface 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° increments, from 0° (forward flight) to 90° (vertical descent). A set of halogen track lights with blue dichroic filters was mounted onto the front of the carriage to illuminate the flow and highlight the yellow fluorescent dye. Unfiltered white light was used when air was the injection fluid. For visualization, the video camera was mounted on the platform vertically, looking downward at the flow and fixed in position with respect to the rotor.

Results

All results presented in this paper, unless stated otherwise, refer to experiments conducted at a rotor rotation rate of $\Omega=4$ rev/s ($V_{tip}=319$ cm/s) and at a collective pitch angle of $\theta=11.6^\circ$. This was taken as a

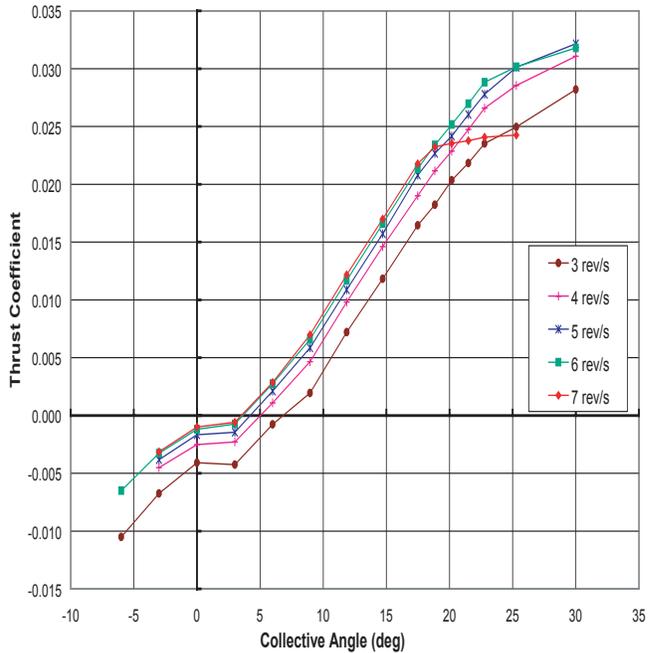


Figure 4: Variation in mean thrust coefficient with collective pitch angle. Values for a range of rotation rates collapse – approximately – to a single curve.

representative case in order to limit the number of experimental variables and also because it produced the best flow visualization results. In addition, since rotor thrust is proportional to the square of the rotation rate, the *non-dimensional* thrust, C_T , should be independent of rotation rate (in the absence of viscous or aeroelastic effects), being a function of the rotor/airfoil geometry and the blade pitch angle only.

This result was tested experimentally for the case of a hovering rotor. The mean thrust coefficient was measured for a wide range of collective angles and rotation rates in the water tow tank. The expected result is that the individual curves – marking the variation in thrust coefficient with collective angle – for each of the rotation rates tested ($\Omega=3-7$ rev/s) should collapse to a single curve. However, Fig. 4 shows a displacement of the five curves that is a regular function of rotation rate (except for the highest speed). For the rotation rates tested here, blade Reynolds numbers ranged from $Re_c=45,000-106,000$, a region which is certainly subject to viscous effects. However, the regularity of the displacement, regardless of collective angle, is surprising. The lift variation seen in Fig. 4 could be accounted for by a twist of about 5°, which is certainly possible given the present blade construction. It is therefore considered plausible that aeroelastic twist may also be

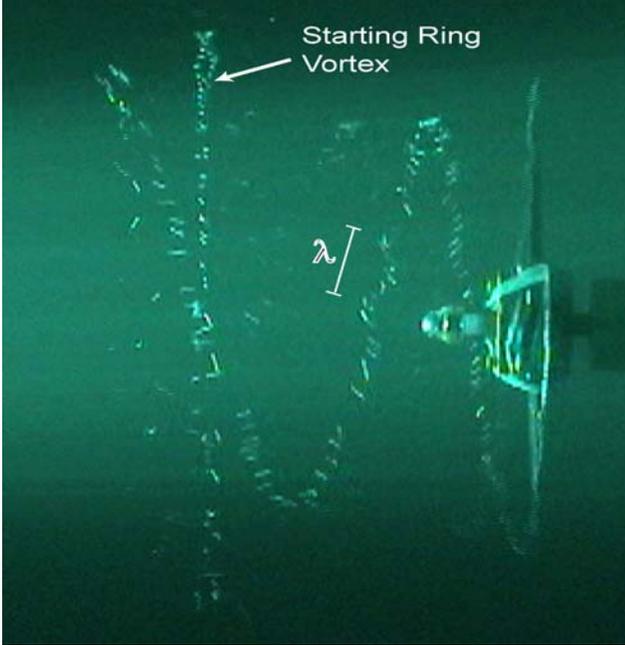


Figure 5: **Three-dimensional flow visualization image of rotor using air injection from tip of one blade. Rotor speed is $\Omega=3$ rev/s. The short-wave sinuous instability of the vortex is just visible.**

occurring.

The stalling of the lift trend at the highest rotor speed is also notable. Whereas the lower speed curves show continued increases in C_T at collective angles as high as 30° , the $\Omega=7$ rev/s curve plateaus at about 20° . Normally, stall would be expected to be more likely to occur at lower speeds. A possible explanation is that, at this high speed and collective, the lift is enough to twist the blades and lead to a major separation.

Nevertheless, the high thrusts obtained for all higher collective cases (C_T is over 0.03, with a blade loading coefficient, C_T/σ_s , of over 0.2) are surprising and not currently understood. Future studies will include surface flow visualizations, torque measurements, and higher stiffness blades to determine the nature of this behavior.

Flow Visualization

Flow visualization testing in the stationary water tank yielded numerous images clearly showing the development of the rotor wake and the instabilities that cause it to break down. In Fig. 5, 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 – which was discussed by Leishman (Ref. ?) and Fukumoto and Miyazaki (Ref. 11) and analyzed theoretically by Widnall (Ref. 3) and Gupta and Loewy (Ref. 4) – can clearly be seen along the filament in the near-wake of the rotor. Ortega *et al.* (Ref. 26) have suggested that this is an elliptic instability of the vortex cores that develops cooperatively on adjacent helix turns, though this observation is unable to be verified here with air being released from only one blade. In this case the wavelength of the instability is approximately 3.75 cm, or $2c$.

Figure 6 shows a series of two-dimensional images of the upper half of the rotor plane with dye being injected from all three blade tips. This view of the wake shows cross-sections of the cores of the three tip vortices and illustrates the influence that each vortex filament has on its neighbors. The induced velocities of adjacent turns cause the helices to expand and contract, thus altering their propagation speeds and resulting in the classic “leapfrogging” or “vortex pairing” phenomenon often seen with parallel vortex rings. This effect – which was studied computationally by Jain and Conlisk (Ref. 12) and experimentally by Ortega *et al.* (Ref. 26) – can be seen in the pairing of the second and third vortex cores downstream of the rotor in (b) and (c), and quickly leads to the complete merger of all three vortices in (e). The merger of adjacent tip vortices is a general phenomenon of rotors regardless of the number of blades – for example, Ortega *et al.* (Ref. 26) observed it in the wake of a two-bladed rotor. However, with fewer blades the adjacent helix turns are farther apart and thus the leapfrogging and merging processes take longer to transpire. The location where the three vortices merge – about half a diameter downstream of the rotor – can be taken as the point where the wake loses its helical structure.

Thrust Measurements

Instantaneous thrust measurements were recorded during the descent experiments in the towing tank. These tests were conducted over a range of towing speeds from 0–50 cm/s, descent angles from $\alpha=0-90^\circ$, and collective angles from $\theta=6-18^\circ$. Descent runs 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

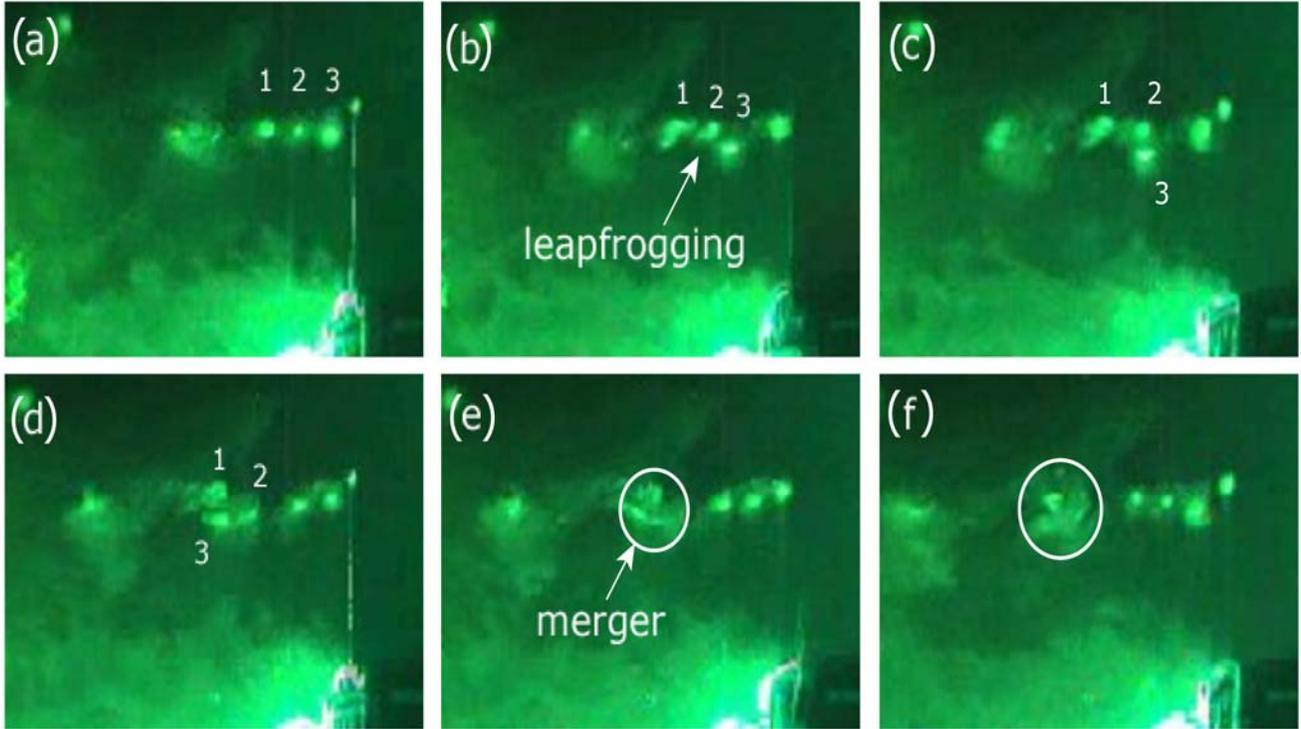


Figure 6: Two-dimensional flow visualization images of upper half of rotor in hover using fluorescent dye injection from all three blade tips. The “leapfrogging” of one vortex filament over another can be seen in (b) and (c) as the three vortices orbit about each other and finally merge in (e).

(due to the starting transients 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 7 shows a thrust coefficient time-history for a hovering rotor. The mean thrust coefficient was 0.0078 and the peak-to-peak fluctuation amplitude was 12% of the mean. Figure 8 shows a thrust coefficient time-history of similar form, but for a rapid descent at a fairly shallow descent angle ($\alpha=30^\circ$). Note that the mean thrust coefficient, 0.018, 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 steep descent angle, the rotor thrust characteristics were markedly different. In some such cases, the thrust exhibited very large, regular fluctuations. Figures 9–10, for instance, show thrust time-histories typical of this type of behavior.

These plots exhibit classic VRS characteristics, with very large, regular thrust oscillations. The sustained

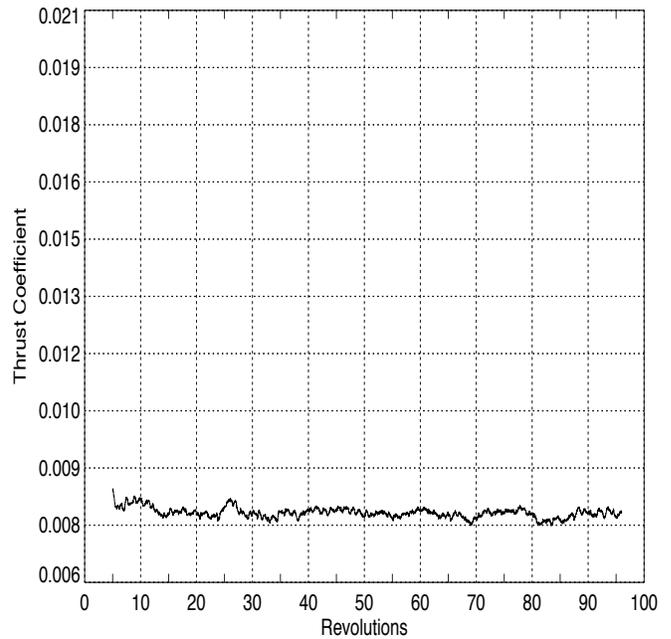


Figure 7: Thrust time-history for a hover test ($V=0$). Mean thrust coefficient is 0.0078 and fluctuation is 12% of the mean.

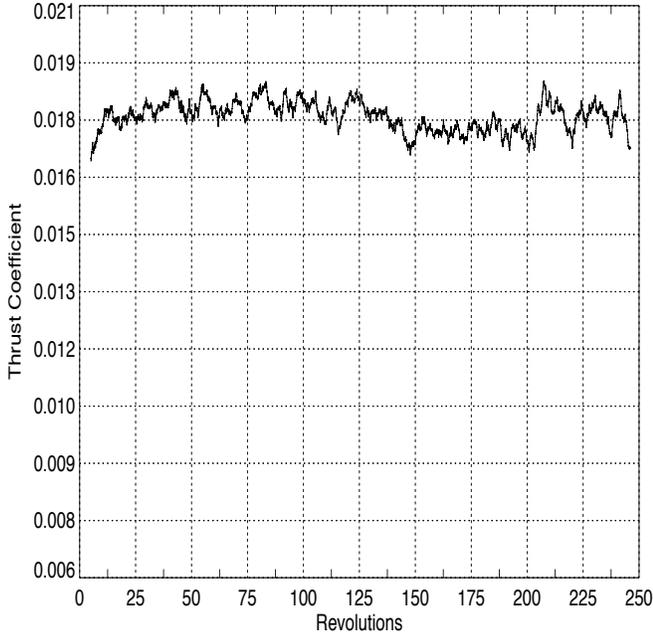


Figure 8: Thrust time-history for a fast, shallow descent run ($V_x/V_h=1.62$, $V_z/V_h=-0.93$). Mean thrust coefficient is 0.0181 and fluctuation is 12% of the mean.

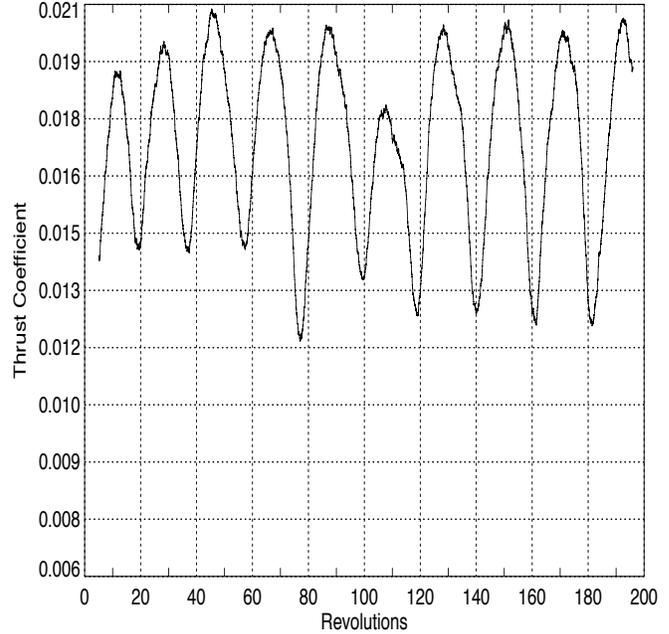


Figure 10: Thrust time-history for another VRS case with $\alpha=50^\circ$ and $V/V_h=1.5$ ($V_x/V_h=0.96$, $V_z/V_h=-1.14$). Mean thrust coefficient is 0.0173 and fluctuation is 50% of the mean. Fluctuation period in this case is only about 20 revolutions.

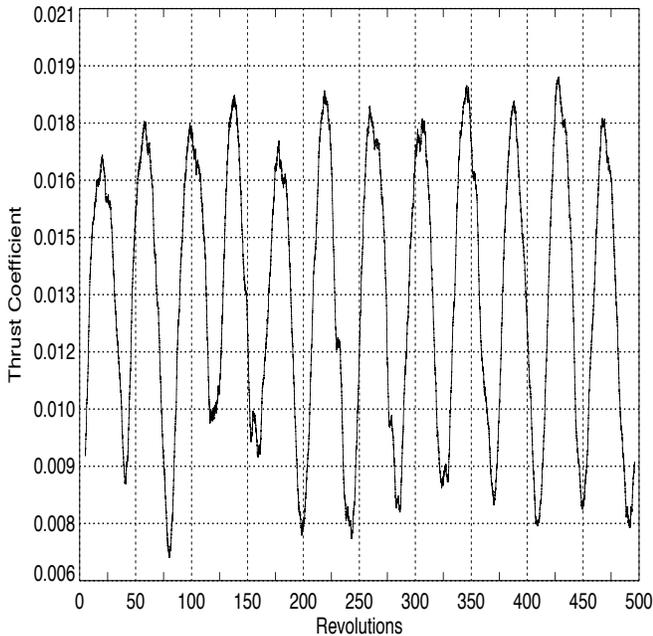


Figure 9: Thrust time-history for a classic VRS case: $\alpha=60^\circ$, $V/V_h=1.25$ ($V_x/V_h=0.62$, $V_z/V_h=-1.08$). Length of run is 500 rotor revolutions instead of 100, but performance parameters are unchanged. Mean thrust coefficient is 0.0135, fluctuation amplitude is 94% of the mean, and fluctuation period is about 43 revolutions.

regularity of the thrust oscillations was verified by performing long runs of over 500 blade revolutions (see Fig. 9). (For most runs, a run of 100 revolutions will suffice.)

Other descent configurations demonstrated very similar oscillatory characteristics, but with significantly different amplitudes and periods of fluctuation. Figure 10 shows a thrust coefficient time-history that appears very similar to Fig. 9. However, in this case – where the descent angle was 50° and the towing speed was $V/V_h=1.5$ – 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.

Obviously the descent configuration greatly influences the oscillatory behavior of the rotor thrust and thus can spell the difference between a routine bumpy ride and a catastrophic loss of control for a descending aircraft. This difference can be seen by comparing the thrust envelopes – the region between maximum and minimum thrust levels – for two descent angles over a range of towing speeds. Figure 11 shows the maximum, minimum, and mean thrust values for (a) $\alpha=90^\circ$

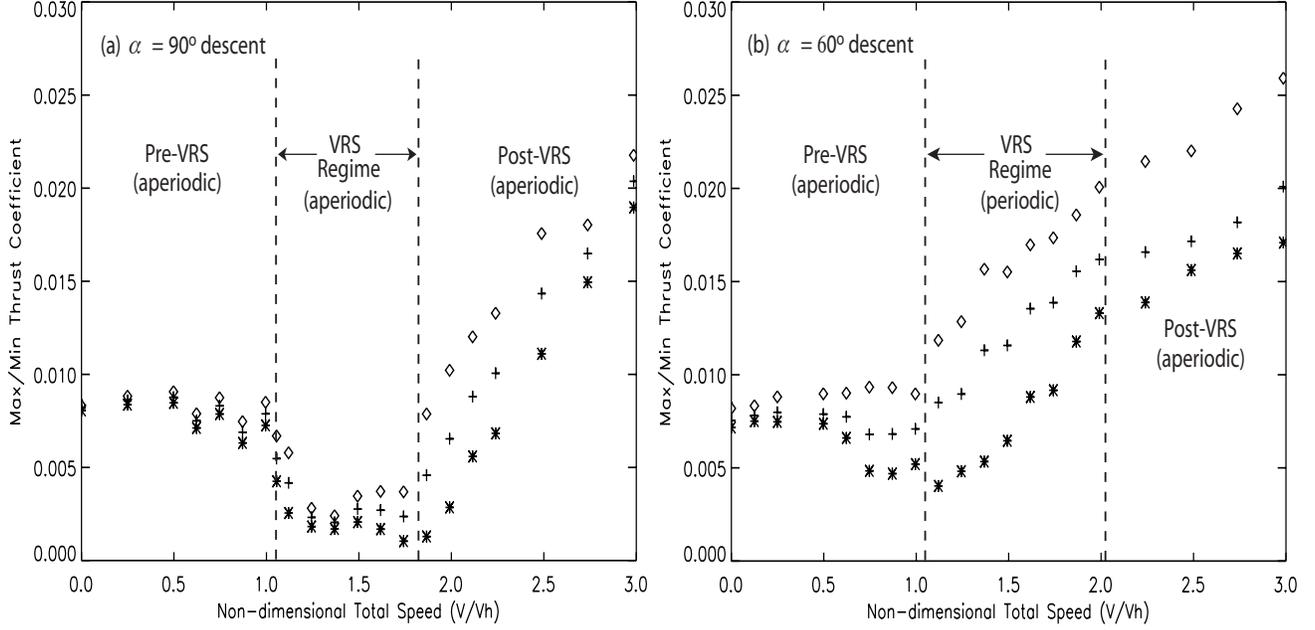


Figure 11: Thrust coefficient envelopes – maximum and minimum thrust levels – for (a) 90° descent and (b) 60° descent configurations.

and (b) $\alpha=60^\circ$ descent configurations. For the vertical descent case ($\alpha=90^\circ$), the thrust levels dropped precipitously as the descent speed increased to about 20 cm/s ($V/V_h=1.0$). However, there was no noticeable thrust periodicity accompanying the loss of lift as one would see with a classic vortex ring state case, and thus the envelope is relatively narrow. As the descent rate increased further, thrust was recovered and eventually reached two to three times hover thrust levels as the rotor encountered turbulent wake state and windmill brake state.

The rotor's behavior in $\alpha=60^\circ$ descent is similar, with loss of lift at approximately 20 cm/s ($V/V_h=1.0$), followed by recovery and increased lift as the descent speed reaches windmill brake state. The major difference between the two cases is in the size of the envelope. In vertical descent, the thrust levels drop drastically in the 20–40 cm/s descent speed range, yet the difference between maximum and minimum thrust levels is relatively small (compared to the mean) and also somewhat random. However, in the case of the $\alpha=60^\circ$ descent, the rotor experiences only a slight reduction in lift once VRS is reached, but also large, regular oscillations in thrust as well. Thus the thrust envelope for this case is noticeably larger – covering a significant proportion of the total thrust. Controllability of the helicopter under these conditions is a major ques-

tion. In this case it should be noted that the variation in thrust (the expansion of the thrust envelope) occurs at speeds as low as $V/V_h=0.5$ – well before the fully-developed VRS region. The thrust variations in this region are still aperiodic, though quite large. If controlled flight is sustainable in this region, this could constitute an operationally useful precursor to the full vortex ring state. Note that no such precursor is seen for vertical descent.

The mean thrust levels in Fig. 11 are also very revealing. In the $\alpha=60^\circ$ VRS region, the mean thrust is half-way between the maximum and minimum values, as one would expect for a highly-organized, periodic oscillation pattern. But in the higher and lower speed regions the thrust pattern is entirely aperiodic, and this is reflected in the fact that the mean thrust values are no longer midway between the maximum and minimum but closer to the minimum values. In the $\alpha=90^\circ$ descent configuration the mean thrusts appear to lie half-way between the maximum and minimum curves, but in this case the thrust patterns are aperiodic for all descent speeds and the mean values happen to lie in the middle of a fairly random distribution of thrust values.

Figure 12 provides a detailed look at the dynamics of the vortex ring formation and shedding process that precipitates the thrust oscillations discussed above. In

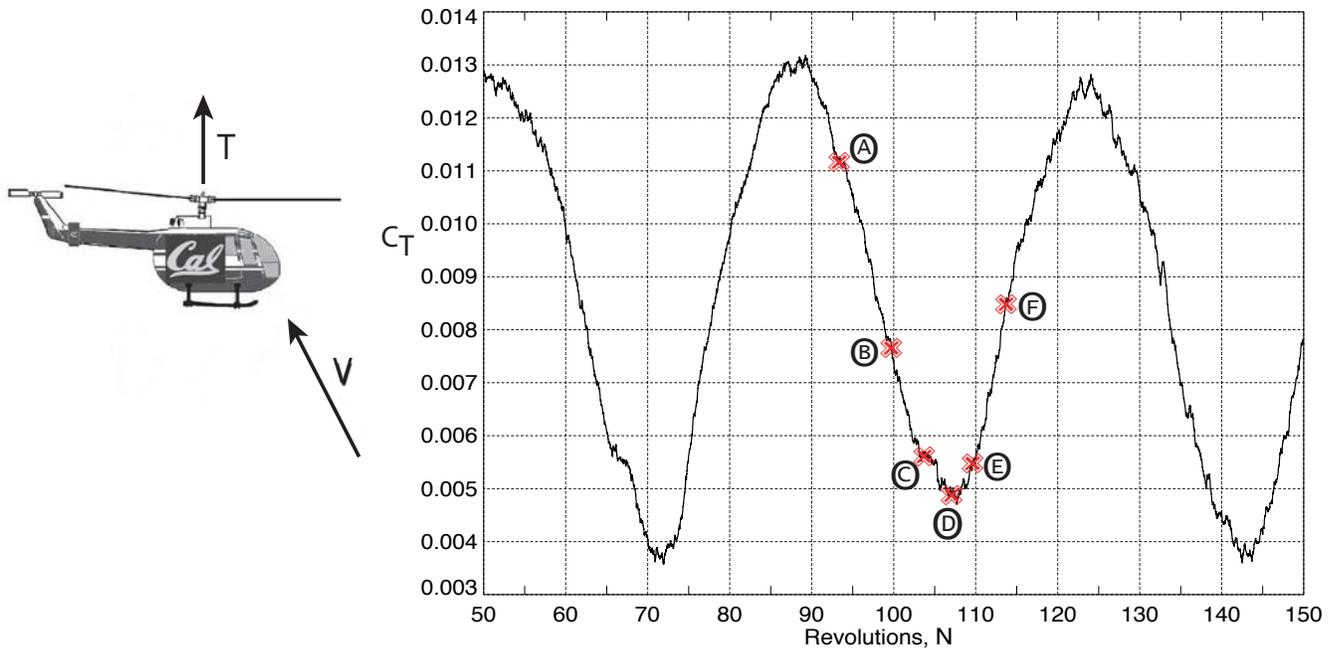
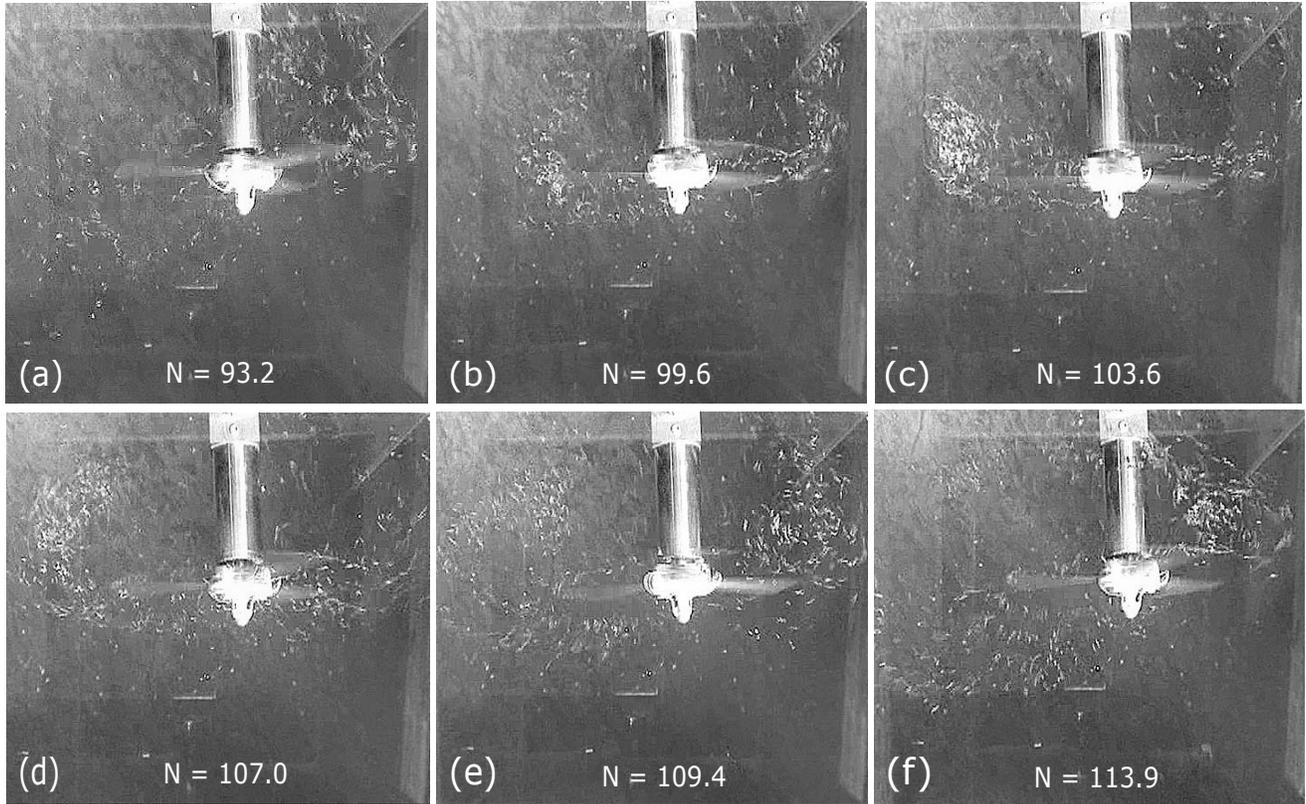


Figure 12: Sequence of images depicting the various stages of vortex ring formation and shedding during VRS. Number of revolutions (N) since the beginning of the run is shown in each image for reference. Corresponding thrust coefficient time-history shows the resultant loss and recovery of lift during the cycle. Helicopter at lower left represents the rotor orientation and incident flow direction. Test parameters for this case were: $\alpha=60^\circ$, $V/V_h=1.0$, $\Omega=3$ rev/s, $\theta=11.9^\circ$ ($V_x/V_h=0.50$, $V_z/V_h=-0.86$). Mean thrust coefficient was 0.0086 and peak-to-peak variation was 121% of the mean, with a fluctuation period of 36 revolutions.

(a), the rotor is relatively free of vorticity and the flow seems fairly orderly – hence the thrust is near its peak level. The incoming flow keeps the tip vortices near the rotor plane after they are generated and they begin to roll up into a thick ring in (b), interfering with the rotor’s inflow and causing the thrust level to drop accordingly. In (c), a strong, tight ring can be seen to have formed at the back (downstream) side of the rotor as the thrust approaches its minimum value. At this point, the ring begins to expand and separate from the back of the rotor slightly in (d) and (e), just as it starts to take form at the front (upstream) side of the rotor. This “halo” geometry, where the vortex ring is approximately equal in size and strength at the front and back side of the rotor – and slightly stretched out as a result of the back side detachment – roughly coincides with the absolute minimum thrust level seen in the cycle. Finally, in (f), the ring has almost fully detached from the rotor plane and is quickly convected away upstream as the thrust level rebounds sharply.

This entire sequence of images – showing the complete formation, strengthening, and shedding process – spans only 21 revolutions, although the total peak-to-peak oscillation cycle takes about 36 revolutions. Given the metronomic regularity of the thrust time-history for this run, as well as those shown in Figs. 9–10, it seems clear that this process is highly deterministic and that the detachment of the vortex ring was not due to some flow disturbance or anomaly. In fact, the vortex ring formation process described above – where the ring takes shape and gains strength at the back side of the rotor, then begins to detach and stretch out just as the ring starts to grow at the front side – was observed during every thrust oscillation cycle in this test case.

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 for quantifying the magnitude of the thrust fluctuation levels and thus defining this boundary. Betzina (Ref. 24) has proposed using three standard deviations of the thrust coefficient (3σ) normalized by the mean value. This measure is more consistent than simply the peak-to-peak amplitude of the oscillations, and also less dependent on the length of the run and will thus be used in this study.

Figure 13 shows a contour plot of this parameter

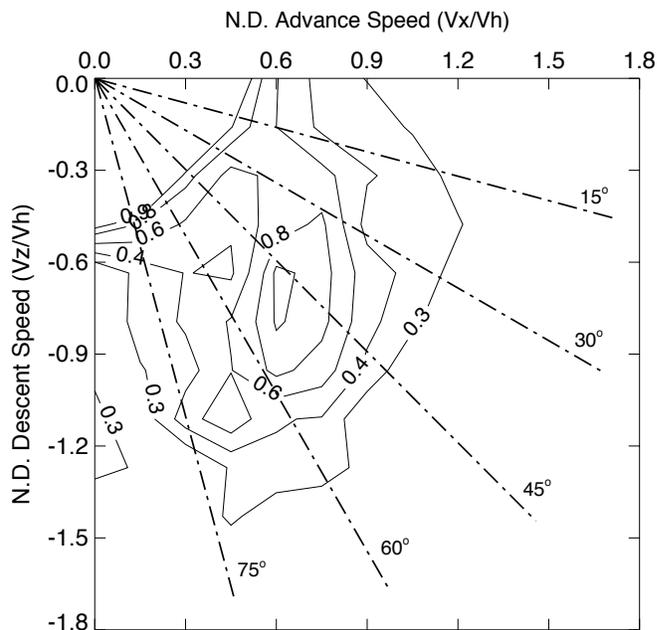


Figure 13: **Relative magnitude of thrust oscillations, $3\sigma/C_{T_{avg}}$ ($\theta=11.9^\circ$ runs only).**

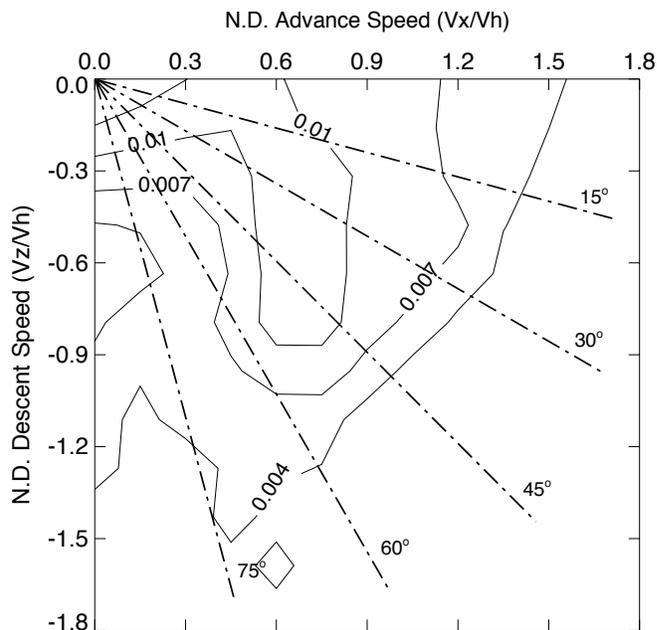


Figure 14: **Amplitude of peak-to-peak thrust coefficient oscillations, $C_{T_{max}} - C_{T_{min}}$ ($\theta=11.9^\circ$ runs only).**

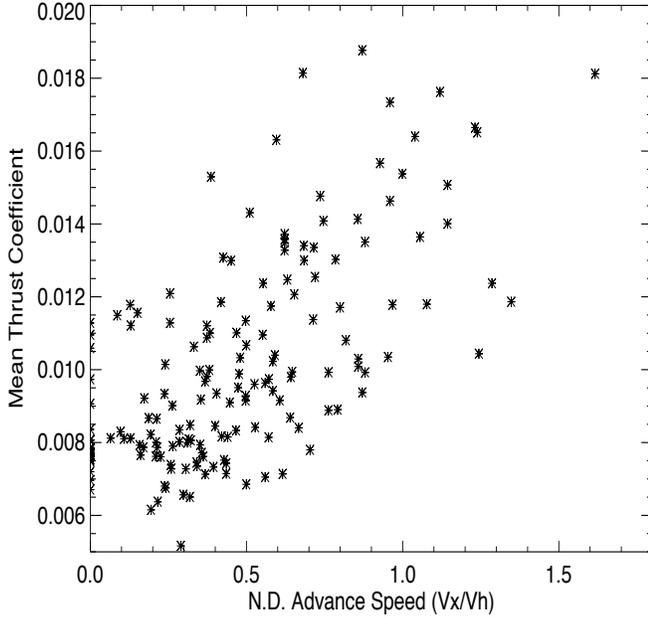


Figure 15: Mean thrust coefficient versus non-dimensional advance speed, V_x/V_h ($\theta=11.9^\circ$ runs only).

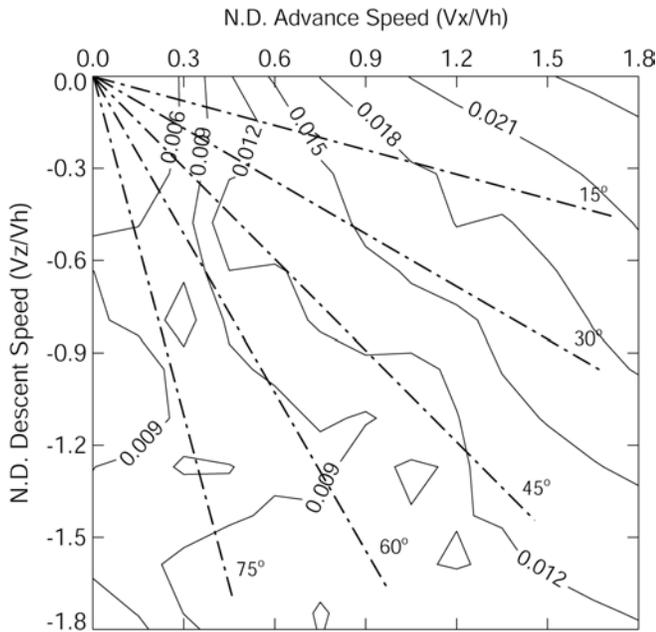


Figure 16: Mean thrust coefficient with respect to non-dimensional advance and descent speeds, V_x/V_h and V_z/V_h ($\theta=11.9^\circ$ runs only).

for all test runs, plotted with respect to advance and descent speeds, V_x/V_h and V_z/V_h . Clearly the area featuring moderate forward and descent rates exhibits the most dramatic oscillations, as discussed earlier. It is difficult for anyone but an experienced helicopter pilot to specify how large the thrust fluctuations must be for the rotor to be considered in VRS. However, judging by the relative magnitude of the thrust fluctuations shown in Fig. 13, the region in the center of the plot – between about $\alpha=30^\circ$ and 70° – is clearly set apart from the rest of the flight envelope.

Figure 14 shows the peak-to-peak amplitude of thrust fluctuations. Although not apparent from Fig. 13, 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 less dramatic.

This latter point can be illustrated by plotting the mean thrust coefficient versus the non-dimensional rotor advance speed – the forward flight speed, V_x , normalized by the induced velocity at the rotor plane, V_h . This plot, shown in Fig. 15, demonstrates the approximately linear increasing trend of the rotor thrust with forward flight speed. This feature is also apparent in Fig. 16, a contour 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. 17. At larger advance speeds ($V_x/V_h > 1.0$) the wake is quickly swept away from the rotor by the free-stream flow, thus allowing very little interaction between the rotor and wake and thus little fluctuation in the thrust. Likewise at very low advance speeds ($V_x/V_h < 0.2$) the wake self induction convects the rotor away from the rotor, again minimizing rotor/wake interaction and thrust fluctuation. However, at moderate advance ratios the wake self-induction and the freestream flow partially negate each other, minimizing the wake convection and allowing very strong rotor/wake interaction. This explains the wide scatter of the fluctuations seen in Fig. 17 for $V_x/V_h = 0.2-1.0$.

As discussed above, for the VRS cases, the oscillation frequencies and amplitudes varied significantly, depending on the descent configuration. The oscillation periods ranged from 20 to 50 revolutions, and the amplitudes of the fluctuations measured from 50% to 95% of the mean. Figure 18 shows the relationship between the oscillation period and the non-dimensional advance speed for the cases with observable, organized

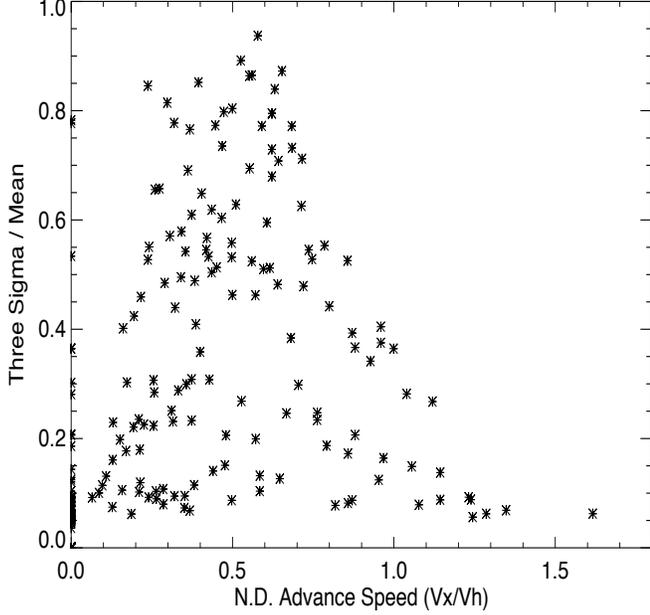


Figure 17: **Relative magnitude of thrust oscillations, $3\sigma/C_{T_{avg}}$, versus non-dimensional advance speed, V_x/V_h ($\theta=11.9^\circ$ runs only).**

VRS-like oscillations. Data are plotted for a range of collective angle settings ($\theta=6-17.5^\circ$), with a different power law regression for each setting. The trend shown here is not unusual – one would expect the vortex ring to be less stable and thus to be shed more rapidly as the advance rate increases. What is unusual is how well the power law relationships represent the data. The four regression equations, along with their correlation coefficients, are:

$$\begin{aligned} \theta=6.0^\circ: & \quad \tau = 26.6 (V_x/V_h)^{-1.34} & \quad R^2 = 0.96 \\ \theta=9.0^\circ: & \quad \tau = 18.6 (V_x/V_h)^{-1.41} & \quad R^2 = 0.98 \\ \theta=14.7^\circ: & \quad \tau = 11.7 (V_x/V_h)^{-1.35} & \quad R^2 = 0.87 \\ \theta=17.5^\circ: & \quad \tau = 9.3 (V_x/V_h)^{-1.70} & \quad R^2 = 0.79 \end{aligned}$$

The relationship observed here between oscillation period and collective angle – that for a given advance speed, the shedding period increases with collective angle – provides some clue as to the dynamics of the vortex ring shedding process. As the collective angle (and, therefore, the total lift) are increased, the strength of the tip vortices increases proportionally. In the vortex ring state regime, this equates to a stronger vortex ring with a greater self-induced velocity. This self-induction is effectively the force holding the growing ring to the rotor plane and preventing it from convecting away with the free stream. Hence, with greater self-induced (downward) velocity comes longer attachment periods between the ring and the rotor plane.

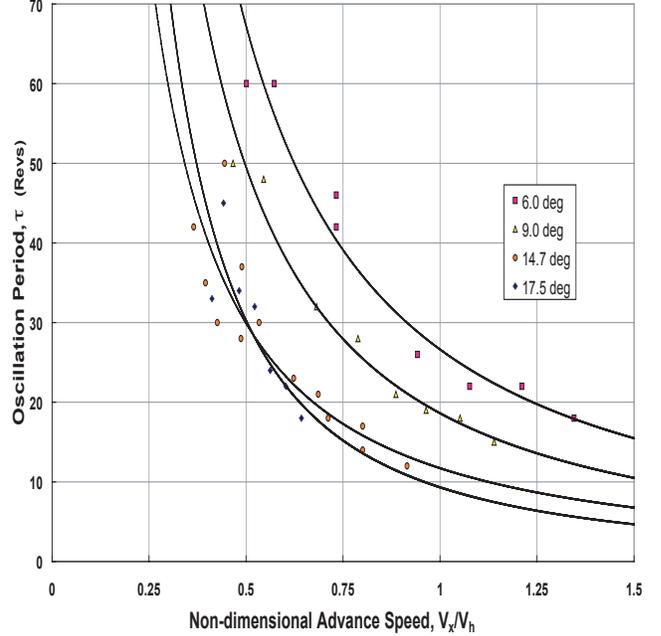


Figure 18: **Variation of the oscillation period, τ , with non-dimensional advance speed, V_x/V_h , for cases with observable VRS-like fluctuations. The data points shown are the “organized” fluctuations only. Collective angles range from $\theta=6-17.5^\circ$.**

Conclusions

Flow visualization and thrust measurement experiments have been performed on a three-bladed rotor model in two water tanks. 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. Some of the specific conclusions from this study are:

1. Flow visualization images 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. The location where the wake breaks down and loses its structure can be seen to be approximately one diameter downstream of the rotor.
2. Flow visualization images from the descending rotor operating in the VRS regime show the merger of the individual tip vortices and the formation of a thick vortex ring. This ring would remain just above the rotor plane for a period of 20–50 revolutions (depending on the advance and descent speeds, and on the rotor rotation rate) before

abruptly detaching and convecting away upstream while another ring would begin to form.

3. 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.
4. 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.
5. Thrust fluctuations observed in the VRS regime were most severe for descent angles of $\alpha=20\text{--}50^\circ$ and for descent speeds of $V/V_h=1.0\text{--}1.5$. 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 can have disastrous effects on the performance and control of a rotorcraft and thus deserve further study. A major question that should be considered concerns whether a rotor has the ability to overcome the inflow variations imposed on it by the wake oscillations.
6. In VRS cases, the vortex ring shedding period exhibits a decaying power law dependence on the advance speed, indicating that the ring is less stable and more susceptible to being swept away from the rotor as advance speed increases. Additionally, the shedding period appears to increase slightly with collective angle.
7. To gain a more complete understanding of the flow physics in this flight regime it will be necessary to perform PIV experiments on the critical descent configurations identified in this paper. By collecting quantitative information about the flow field in the VRS regime it should be possible to better understand the nature of the highly regular vortex ring shedding/formation process was observed here. And with knowledge of the dynamics of VRS, it should eventually be possible to mitigate or avoid the severe thrust fluctuations associated with it.

Acknowledgments

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