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Characterization of the Near Wake of a Helicopter Rotor*

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Abstract

Vortex characteristics in the near wake of a 2-bladed teetering rotor in steady forward flight are measured using a laser velocimeter. The vortex passage at a measurement point is seen to be repeatable to within 1° of rotor revolution. Velocity was measured in the planes intersected by the rotor-blade tip at the rotor azimuths of $\Psi = 0°, 90°, 180°, 270°$. Variations in tip-vortex characteristics such as core-radius, circulation and axial velocity were obtained as functions of rotor azimuth. Empirical curve fits are described for these variations. The core axial velocity is of the order of the peak tangential velocity at all locations. It is higher than peak tangential velocity over part of the advancing blade side of the rotor. The axial velocity in all cases is wake-like, being directed towards the blade of origin. Wake geometries obtained from the LDV data are also presented here.

Introduction

Most current prediction methods for rotorcraft performance use empirically-derived tip vortex parameters. There are several uncertainties about the near wake which make generalized prediction diffficult, particularly in problems where high precision is needed, as in predicting blade-vortex interactions. The characteristics of the tip-vortex in the near-wake of a rotor are studied in this paper, in a test case of low-speed forward flight in a wind-tunnel. Data obtained in radial-axial planes intersecting the front, rear and the two sides of the rotor tip-path-plane are used to guage the spatial periodicity of the vortex core structure.

There are no spatial symmetry assumptions possible in the case of a rotor in forward flight. This makes it difficult and time-consuming to measure or predict forward-flight flow-fields. However, in one sense, measurements of tip-vortices in forward flight are easier than the case of a rotor in hover. This is because the wake in forward flight is convected away from the rotor quicker. If the test case is set up carefully so that the wake does not recirculate in the test-section of the tunnel, it is possible to obtain very smooth operation, where the periodicity of the flow is nearly perfect. For the above reasons, the periodicity of the results shown here is excellent, the cycle-to-cycle uncertainty in vortex position in the near wake being less than 1 degree of rotor azimuth, confirming the large body of previous work performed in this laboratory.

This is a far cry from most hover flowfield measurements, where facility flow recirculation is a serious and generally-underestimated problem. It appears from recent work[1], that the convenient assumptions of symmetry and periodicity which are usually made about wakes in hover should be carefully examined. In these experiments, it was found that essentially perfect periodicity could be obtained if facility recirculation was eliminated. At the same time, it was found that the interaction between the tip-vortices led to highly deterministic vortex pairing events, which appeared to form the transition from the near-wake regime to the far wake. The quantitative visualization data obtained there should also put to rest the long-held fears that there are "instabilities", leading to vortex-jitter as a fundamental phenomenon in the rotor wake.

Experimental Setup

The experiments were performed in the J.J.Harper low-speed wind-tunnel at Georgia Tech. This a closed-circuit tunnel with freestream turbulence levels of less than 0.5%. The model is a 2-bladed, untwisted, untapered rotor mounted on a teetering hub from the roof of the test-section. The slender rotor shaft and the minimal-size teetering hub serve to produce a rotor configuration very close to the "isolated rotor" ideal. The model-rotor parameters and the test-conditions are shown in Table 1. The forward flight setup in the Harper wind-tunnel is shown in Fig.1.

Table 1: Model-rotor parameters and test conditions

Rotor radius	0.456 m
Blade section	NACA0015
Blade chord	8.75 cm
Collective pitch	10 degrees
Rotor rpm	1050
Advance ratio	0.1
Tip speed	50 m/s
Thrust coefficient	0.0089

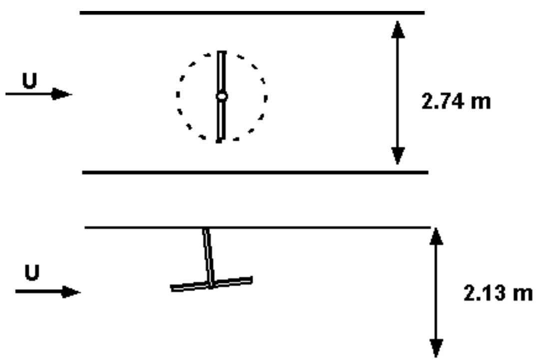

Figure 1. Experimental setup in the Harper Wind Tunnel

Single-component LDV measurements were performed using a 83mm diameter fiber optic probe for transmitting the incident beams and receiving the scattered light in back-scatter. The wavelength of the incident beams was 514 nm, obtained from a continuous wattage 5W Argon ion laser coupled with a Colorburst^{TM} module. It was demonstrated in Reference[2] that the flow-field in the facility is repeatable and periodic. This obviated the need for simultaneous three-component velocity measurement. The LDV measurement locations are shown in Figure 2. The flow is seeded with atomized mineral oil droplets of a nominal particle diameter of 4 microns. The seeding is usually done form downstream of the test-section of the closed return tunnel, so that the flow coming around into the test-section is uniformly seeded, and the larger particles have settled down. Each measurement location is visited three times by the laser-velocimeter, in different runs: once for each velocity component.

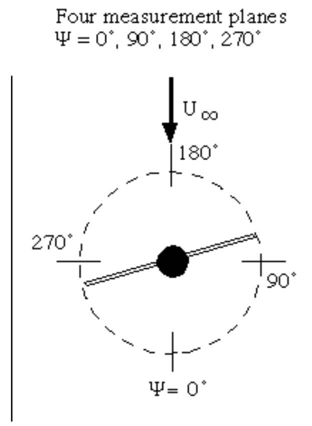

Figure 2. *Velocity measurement planes in the rotor-cycle. The lines at the four azimuths are approximately the vertical planes in which the data was obtained.*

In each visit, the measurement volume and the operating condition are held steady, and the collected data are sorted into "bins" according to the rotor azimuth at the time arrival of each particle.

Flow quality in the Harper Tunnel

It was shown by Mahalingam et al.[2] that the flow-field in the experiments described herein is repeatable and periodic to within a degree of the rotor revolution. This was done by performing a moving window average on the instantaneous velocity data obtained for several cycles at a location where vortex passage occurs. Several random blocks of data were averaged and each average produced exactly the same bin with zero particles, implying that there is no aperiodic fluctuations in this flow-field. This is seen in Figure 3.

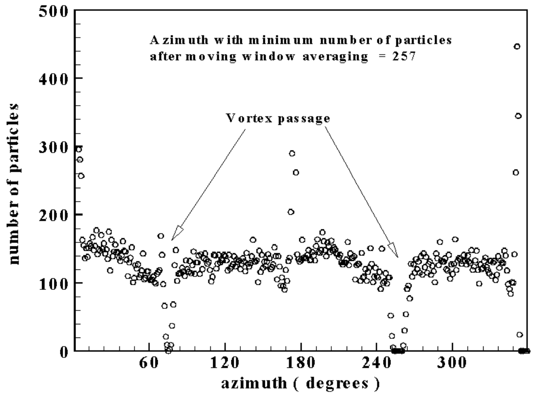

Figure 3. Wake-periodicity in the Georgia Tech forward flight facility. The wake is seen to be repeatable within 1 degree of rotor revolution.

Another test was carried out to decide the minimum number of points that must be used for ensemble averaging. This is seen in Figure 4. The number of bins with zero particle arrival remains unchanged if the number of points in the ensemble average is greater than 20000. Thus, if a minimum of 20000 points is averaged, one can be certain that as many points as possible are obtained in the core as would be allowed by the particle size and concentration. Most of the data presented here have 50000 points in the ensemble average. In some cases, low data rates forced reduction of number of points to 30000 or even 25000.

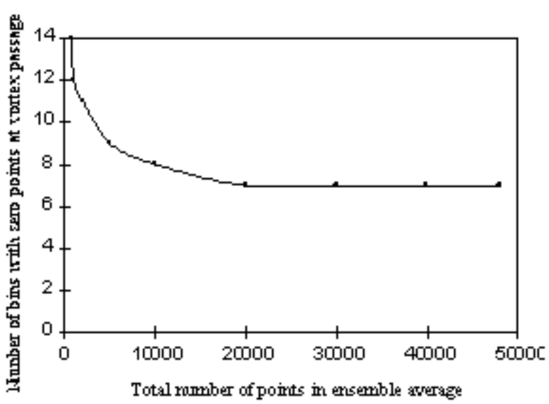

Figure 4. Variation in seed particle deficit in the core with the number of points in the ensemble average. Note that if the number of points in the average is greater than 20000, then it is ensured that as many points as possible are being obtained in the core for the the given particle size.

The influence of the tip-vortex core axial velocity in a vortex airframe interaction was demonstrated by Mahalingam et al[3]. They showed that the core axial velocity was large until 300 degrees of vortex age and was the primary cause of the large suction peak seen on the retreating blade side of the airframe. They showed that both the core axial velocities and the inboard sheet velocities were wake-like. There are considerable differences in the core axial velocities measured by various researchers. Experimenters have measured both jet-like and wake-like velocities[4,5] depending on whether a fixed wing or a rotary wing was studied. Theoretical work by Batchelor[6] postulated a jet-like or wake-like flow in the core of a wing tip vortex. The tip-vortex of a straight wing displays little axial velocity beyond a few chord lengths. Rotary wing meaurements, however, show high core axial velocities. Shivananda[7] used a split-film anemometer to resolve all three components of velocity in the wake of a single-bladed, square-edged rotor in hover. He found a wake-like core. Thompson [8] studied the same rotor blade wake, and resolved all three components of velocity in the vortex using a laser velocimeter. He was able to achieve high data rates using an off-axis light receiving system, and incense smoke particles which were small enough to stay inside the core. He showed not only a wake-like vortex core, but also secondary features inside the core, indicating several layers of vortex sheet roll-up. Vortex measurements using a 3-component laser velocimeter at the University of Maryland on a sigle-bladed rotor in hover[9] found wake-like axial velocity in the vortex core, but the measured velocity profiles appeared to dissipate rapidly within the first 90˚ of wake age, the dissipation being attributed to turbulent diffusion in the inside the core[10]. Berenger et al.[11] performed experiments on a model rotor in forward flight and found core axial velocities of the order of core circumferential velocities. Preliminary results presented in Reference[2] on the advancing blade side of the rotor showed that the wake-like tip-vortex core axial velocity was higher than the core circumferential velocity for the first 180 degrees of vortex age. This is seen in Figure 5. The inboard sheet rolled up into a region of rotation opposite to that of the tip-vortex but with an axial velocity directed wake like. The core radius, circulation and axial velocity were constant over the first 180 degrees of vortex age. Thus, there was no indication of diffusion of the core profiles within the first 180 degrees.

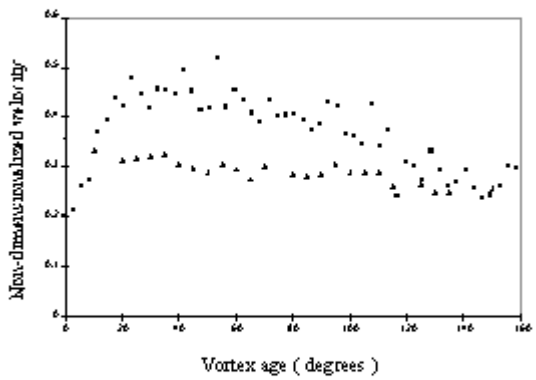

Figure 5. Variation in the maximum core axial and circumferential velocities on the advancing side of the rotor.

In this paper we attempt to quantify the variation of the core parameters in the near wake with the azimuthal location of the blade when that filament of the core was left the blade. We attempt to describe the variations in terms of harmonic functions of the rotor-azimuth angle. Details of this experiment can be accessed at the web-site, http://www.ae.gatech.edu/research/windtunnel/nrwake.html

Results

Tip-vortex velocity profiles

Figure 6 shows axial velocity distributions across the tip-vortex core at various ages at four locations on the rotor cycle. At the rear of the wake, the maximum axial velocities seen are about 0.1 times the tip-speed of the rotor(Vtip). As the vortex age increases from 30 degrees to 90 degrees the axial velocity decreases by 25%. The axial velocity is directed towards the blade the vortex was generated from, i.e., wake-like. On the ABS of the wake, the magnitudes of the core axial velocities are much larger, peaking to about 0.4Vtip. The axial velocity drops by 50% by the time the vortex is 180 degrees old, but after that it remains approximately constant. It is possible that the maximum core axial velocities might be of the order of the rotor tip-speed, with seed particle inertia accounting for the failure to measure this value. The core axial velocities on the ABS are directed wake-like, i.e., pointed upstream. Responding to this change would require the seed particles to accelerate through several hundred to a few thousand G's, with unknown effects on seed particle integrity. Thus the velocities measured on the ABS could very well be an underestimate of the actual values. A different picture is seen on the front of the wake. Core axial velocity starts out at 0.2Vtip and slow drops to half that value. With the arrival of the next blade the core axial velocity peaks rapidly to 0.4Vtip and maintains that value until the vortex is about 240 degrees old. Between vortex ages of 240 and 400 degreesm the axial velocity slows down and becomes constant at 0.2Vtip. Successive blade passage events have different effects on the core axial velocity. The first passage has the effect of increasing the core axial velocity by a factor of almost 1.5. At this time, the vortex helix is close enough to the tip-path plane to see an effect of the blade-passage. The second blade passage(corresponding to the blade that generated the tip-vortex), has little effect on the core axial velocity, primarily due to the fact that the vortex is further away from the blade.

Figure 7 shows circumferential velocity distributions across the tip-vortex core at various ages at four locations on the rotor cycle. The maximum core circumferential velocities are of the order of 0.5Vtip. It is seen the in the very near wake, there is no substantial decaying of the core velocities. At some locations, even beyond 300 degrees of wake age, no substantial reduction is seen in the maximum core circumferential or axial velocities. At the rear of the wake, maximum core circumferential velocities reach 0.2Vtip. This value remained constant until 90 degrees of wake-age, after which the vortex went out of the measurement region. On the advancing and retreating sides, the core circumferential velocities are higher, reaching approximately 0.3Vtip. These values remain fairly constant even upto 180 degrees of wake age. On the front of the rotor, highest circumferential velocities, reaching 0.4Vtip, are measured. Thus, it is seen that velocity profile of the rotor tip-vortex is highly three dimensional in nature, with both core axial and circumferential velocities being extremely significant. This has to be incorporated into current vortex models, which are all primarily two-dimensional in nature. In the absence of the core axial velocity in vortex models, prediction of BVI effects will continue to be difficult problem.

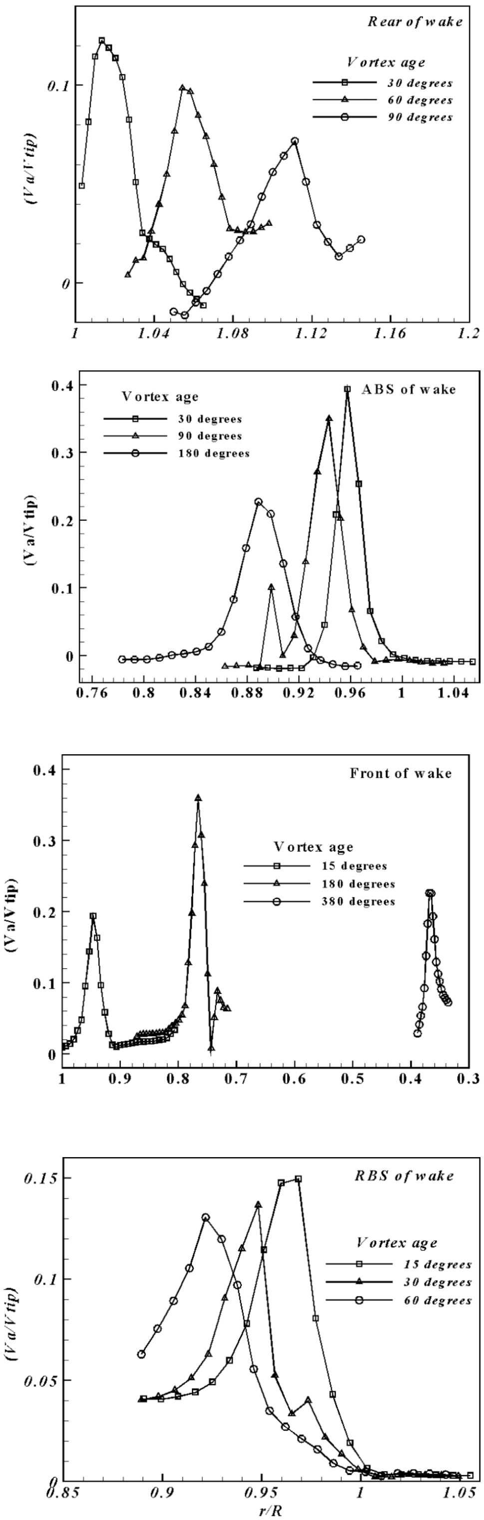

Figure 6. Core axial velocity profiles at different locations on the rotor cycle

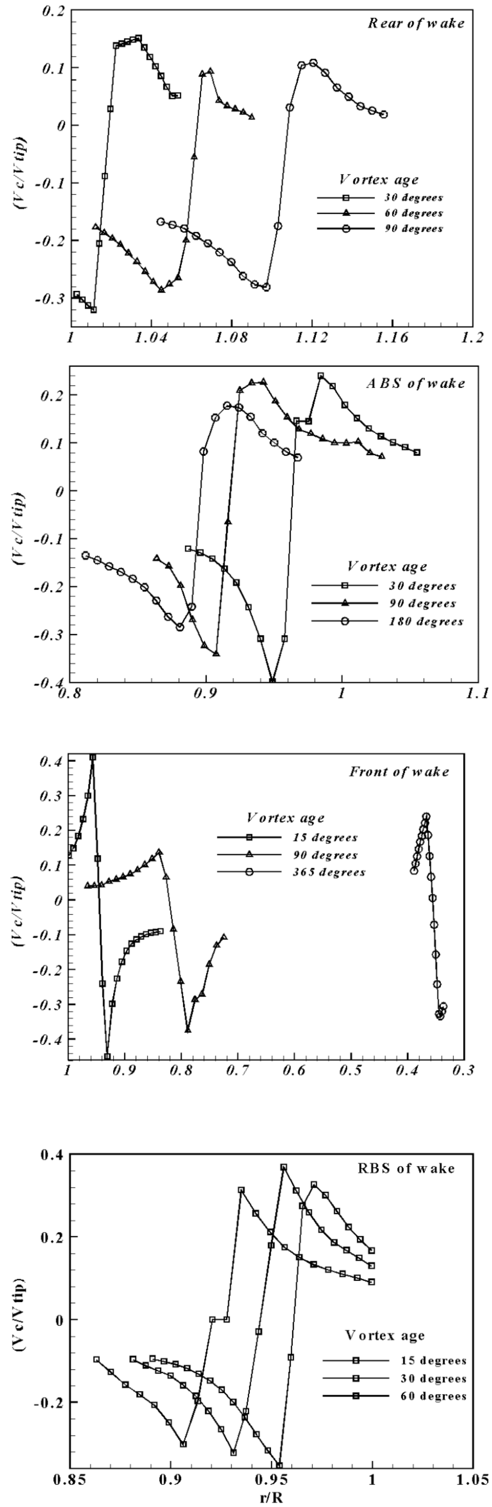

Figure 7. Core circumferential velocity profiles at various locations on the rotor cycle

Azimuthal variation in core parameters

Figure 8 shows the variation in maximum core axial and circumferential velocities measured at four different azimuthal locations and a fixed vortex age of 90 degrees. Similar variations are seen at other vortex ages. Both the axial and circumferential velocities can be represented by using simple harmonic functions of the rotor azimuth angle. The striking difference between the core axial and core circumferential velocity distributions is that the core axial velocity has a second harmonic variation, i.e., a 2-per rev variation. Such variations have been observed before for core circumferential velocity, but in this case core axial velocity varies in that fashion. The maximum core axial velocities measured are on the ABS of the rotor, but core circumferential velocity reaches a maximum on the front of the rotor. Axial velocities on the RBS of the rotor reach about half that on the ABS of the rotor. The mean axial velocity is of the order of 0.2Vtip for a vortex age upto 90 degrees. Core circumferential velocities have a 1-per rev cosine periodic variation, and the amplitude of the variation is of the order of 20% of the mean circumferential velocity. The core axial velocity is higher over a small part of the rotor cycle on the advancing side of the rotor. This is where the three dimensionality of the vortex core may be important in BVI. The dynamics of vortex generation should play a big role in determining the variation of the core parameters over the rotor cycle. These need to be investigated further. Note that these variations are shown for a fixed vortex age. Similar variations can be expected at other ages, presumably with different values of the mean and amplitude of the distribution.

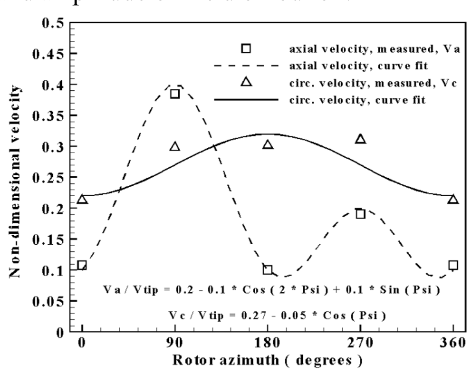

Figure 8. Variation in maximum core axial and circumferential velocity at different shedding locations on the rotor cycle at a vortex age 90 degrees.

Figure 9 shows the variation in core radius and circulation at four different shedding locations and a fixed vortex age of 90 degrees. The core radius was obtained by marking off the solid-body rotation region in thevelocity profiles, and the core circulation was obtained using a simple point vortex model,

$$\Gamma = 2\pi A_c V_c$$

Where Ac is the core radius and Vc is the maximum circumferential velocity.

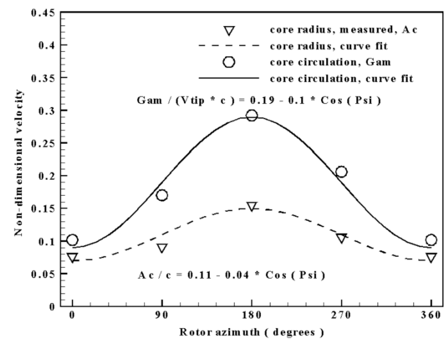

Figure 9. Variation in core radius and circulation at different shedding locations on the rotor cycle at a vortex age of 90 degrees.

Core radius and circulation can both be represented by cyclic functions with respect to therotor azimuth angle. Both vary with the period of the rotor. The mean core radius is 11% of the rotor-blade chord at a vortex age of 90 degrees (approx. 9 mm). The core radius is a maximum on the front of the rotor as is the core circulation. The mean non-dimensionalized circulation is 0.19. As noted earlier, these variations are shown for a fixed vortex age. Similar variations can be expected at other vortex ages. The empirical relations are summarized below.

Core axial velocity

$$\frac{V_a}{V_{tip}} = 0.2 - 0.1\mathrm{Cos}(2\psi) + 0.1\mathrm{Sin}(\psi)$$

Core circumferential velocity

$$\frac{V_c}{V_{tip}} = 0.27 - 0.05\mathrm{Cos}(\psi)$$

Core radius

$$A_c = 0.11 - 0.04\text{Cos}(\psi)$$

Core circulation

$$\frac{\Gamma}{V_{tip}c} = 0.19 - 0.1\text{Cos}(\psi)$$

<u>Wake boundaries in forward flight</u>

Figure 10 shows the ensemble averaged wake boundaries. The top figure shows the boundaries on the advancing and retreating sides of the rotor, while the bottom figure shows the trajectories on the front and rear of the rotor. The vortex trajectories are dominated by wake contraction on the advancing and retreating sides and by convection on the front and rear of the rotor.

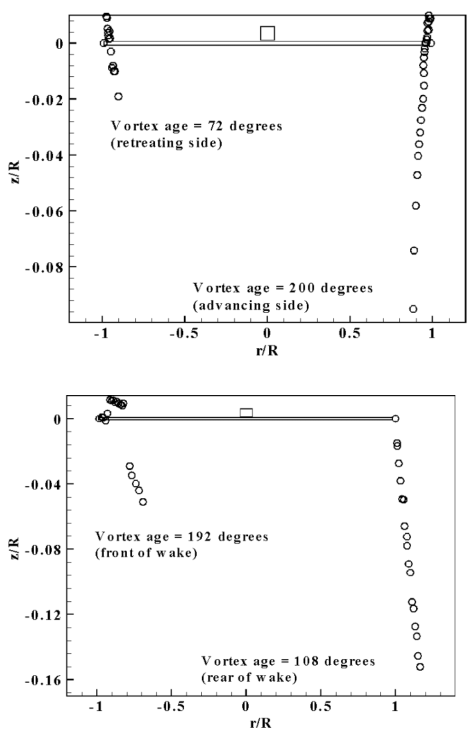

Figure 10. (Top) Wake boundaries on the advancing and retreating sides of the rotor, viewed from behind.
(Bottom) Wake boundaries on the front and rear of the rotor, viewed from the retreating side.

Note that vortex meander has been shown to be minimal in this facility and thus the wake boundaries are a very accurate representation of the vortex path from cycle to cycle. Upwash ahead of the rotor disk causes the vortex paths to rise above the rotor disk on the front, advancing and retreating sides of the rotor. On the rear the vortex is swept downwards and downstream by the local convection. Figure 11 shows the zoomed view of the tip-vortex path on the front of the rotor and the vortex is seen to go above the rotor disk.

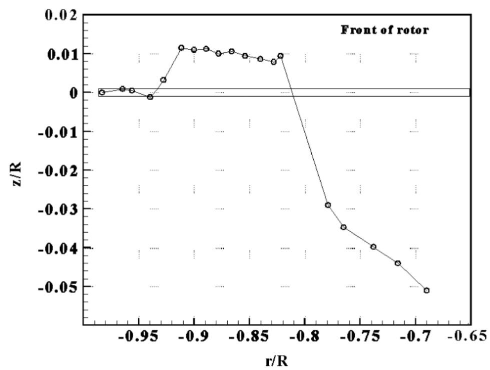

Figure 11. Zoomed in view of the blade-tip region on the front of the rotor shows the motion of the vortex core above the tip path plane.

Conclusions

A series of LDV measurements have been made at selected locations on the rotor cycle. These measurements are used to arrive at the characteristics of the near-wake in particular the tip-vortex core axial and circumferential velocity profiles, core circulation and radius and their variations with vortex age. Core axial velocities are seen to be highest on the ABS of the rotor, where they approach values equal to half the tip-speed of the rotor. Over the rest of the rotor cycle core axial velocities are of the order of 20% of tip-speed. He first 90 degrees of vortex age do not show any amount of diffusion in vortex profiles, over any part of the rotor cycle. Over some parts of the rotor cycle the wake is seen to remain undiffused for much longer, even upto 300 degrees. Core circumferential velocities are generally higher, but of the order of core axial velocities expect over part of the advancing side of the rotor. Core circumferential velocities and radius peak on the front of the rotor. While the core axial velocity has two harmonics in the azimuthal variation, the core circumferential velocity and radius have only 1-per variations.

On the front, advancing and retreating sides the vortex goes above the rotor disk, before beginning to descend, due to upwash at the rotor-disk. On the rear the downwash sweeps the vortex straight down from the rotor disk.

Acknowledgements

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