The Near Wake Of A 2-Bladed Rotor In Forward Flight

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Abstract

The velocity fields in the near wake and the blade tip flowfield of a square-tipped, rectangular planform, 2-bladed teetering rotor have been measured, in low-speed forward flight. A technique for establishing periodicity of the flowfield from laser velocimeter data is shown. The vortex trajectories and wake structure in low-speed forward flight are shown to a vortex age of 488 degrees. Harmonic variations of the axial velocity distributions in the tip vortices are observed. The issue of wake rollup and transition from near to far wake is addressed. It is seen that with periodicity ensured, phase-resolved measurements prove the persistence of the vortex to large ages, as well as the absence of turbulence inside the core of the rotor tip vortex.

Introduction

One of the most daunting challenges for helicopter aerodynamicists is accurately predicting rotor loads, noise and vibration. Due to problems with numerical dissipation, first-principles-based full-physics computations of rotor aerodynamics are not able to capture the structure and evolution of rotor tip vortices beyond about 90 degrees of vortex age. Consequently, computational models of rotor wakes rely on empirical parameters derived from experimental data. There is limited data on the tip vortices of rotary wings, and the usage of vortex models from fixed-wing wake measurements increases the level of uncertainty. There is also considerable confusion in the literature about the rate of decay of vortices, especially in the rotary wing case. Fixed-wing vortices are known to persist for durations on the order of 1 minute or more, so that following aircraft have been known to encounter strong vortices as far as 15 kilometers behind large preceding aircraft. However, several attempts to measure rotary wing vortices, reported in the literature, have been unable to track the vortices beyond roughly 180 degrees of age, with severe "diffusion" or dissipation of the core reported by 90 degrees. Since this does not correspond to predictions using expected values of fluid mechanics variables, turbulence inside the core, and turbulent diffusion, have been postulated as the causes for measured decay rates. This in turn implies the need for extensive development of computational fluid mechanics methods to accurately capture turbulent transport in vortex-dominated flows. Other papers have reported "meandering" and "jitter" of vortices, and again the question is whether these are fundamental phenomena or results of the particular features of the experiments in question. In this paper, we continue to show measurements where periodicity is ensured by careful experiment design, and the periodicity of the measurements are proven. The results of such measurements continue to show that the rotor tip vortex does indeed persist as should be expected.

Current vortex models used in routine aerodynamic prediction are two-dimensional and ignore the presence of a strong velocity directed along the axis of the vortex. Continuing measurements reported by Thompson et al [1] and Liou et al [2], Mahalingam et al [3] showed that the presence of axial velocity is of first-order importance in the prediction of vortex airframe interactions. There is, however, disagreement on the direction and magnitude of the velocity. Batchelor [4] examined the axial velocity in the core of trailing vortices from a theoretical perspective. He has shown that lack of viscosity results in a jet-like profile, while a wake-like profile is induced by the presence of viscosity. Experiments on fixed and rotary wings have shown jet-like and wake-like axial velocity profiles [5 – 10].

Since all vortex models require empirical data, accurate measurements of the vortex properties are vital. Unfortunately, measurements of vortex properties may not always be reliable. Perhaps the largest source of error comes from aperiodicity. In many rotor facilities, the flow field does not repeat with the expected n/rev variations. The meander is often due to recirculation or strong vortex interactions with the facility's walls. This results in long-time-scale fluctuations which appear chaotic. The effect of this on single point measurements is to smooth the vortex core properties when the data

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are ensemble averaged. Core properties, therefore, appear to diffuse or dissipate rapidly since the high gradients are smeared over many rotor cycles. Several experimentalists have attempted to compensate for the observed meander in both fixed and rotary wing experiments [5, 12 - 13]. These methods used either a gating criteria based on vortex location during the analysis phase, or a mathematical or statistical correction based on the observed levels of vortex meander. However, experiments have shown that if facility recirculation is removed, the rotor wake can be extremely periodic [14], even at realistic full-scale blade Reynolds numbers and tip Mach numbers. Therefore, it is very important to quantify the levels of vortex meander to ensure that "clean" measurements of the vortex core properties are made.

The near wake of a two-bladed isolated rotor was studied using Laser Doppler Velocimetry (LDV). Periodicity in the setup is excellent, thus it provides an environment for clean measurements. The vortex core properties as well as the vortex trajectories were examined. Vortex core properties for wake ages up 110° on the front, Retreating Blade Side (RBS) and the rear of the rotor were measured. On the Advancing Blade Side (ABS), vortex core properties were measured up to 488° of wake age.

Experimental Setup

Tests were conducted in the John Harper 7'x9' tunnel at Georgia Tech. It is a closed circuit tunnel powered by a 600hp electric motor. The turbulence level in the tunnel is 0.5%. The rotor is an untwisted, constant chord NACA 0015 two-bladed teetering rotor with a 45.72 cm radius and a chord of 8.57 cm. Rotor solidity is 0.12 and collective is fixed at 10°. The rotor runs at 1050 RPM and is spun by a 2hp electric motor mounted to a frame above the test section. The tip speed is 50 m/s, and the advance ratio is 0.10. The corresponding thrust for this condition is 0.0089. An optical trigger produces a 1/revolution pulse. This pulse is used for phase averaging the data. The green line (514nm) of a 5W argon-ion laser was used for single component LDV. Fiber optics transmit the beams to a 83mm diameter probe in the test section. 350mm and 700mm lenses were used to focus the beams and also collect the scattered light. The probe is mounted to a three axis linear traverse. The traverse and probe are outside of the rotor wake to avoid adversely influencing the flow. Atomized mineral oil was used for seeding. Velocity measurements are sorted into bins by rotor azimuth at the time of arrival.

The characteristics of the vortex in forward flight depend on the where in the rotor cycle they were shed. Therefore, measurements were made at four azimuthal locations to capture all of the possible shedding patterns. Figure 1 shows the measurement planes located on the ABS (ψ = 90), the front (ψ = 180), the RBS (ψ = 270) and the rear of the rotor (ψ = 0). Each plane was oriented so that the axial and circumferential velocities were perpendicular and parallel respectively to the plane.

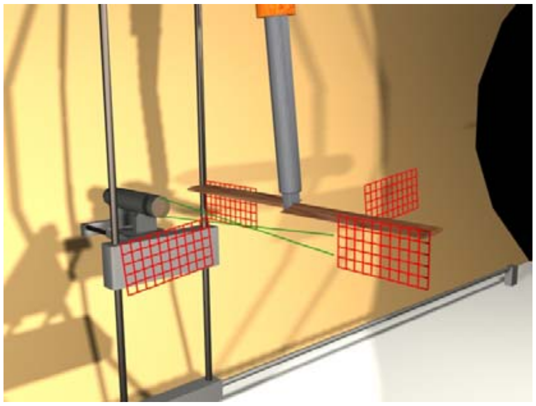

Figure 1 - Harper Tunnel test section. Also shown are the measurement grids.

Flow Quality within the Harper Tunnel

As previously mentioned, quantifying the level of aperiodicity is of extreme importance on measurements of the vortex core properties. Flow visualization and LDV measurements were used to examine the periodicity of the flow in the Harper Tunnel [10]. A snapshot of the flow at the front of the rotor is shown in Fig. 2. Visible in the image is the blade and rotor hub as well as three tip-vortices. The blade is coming out of the page and rotor azimuth is 210°. The flow was frozen using a 20ns light pulse from a copper vapor laser. Four images of the same rotor azimuth and from several different runs were superimposed (Fig. 3). There is little to no change in the locations of the vortices, demonstrating that the flow is not only periodic, but also highly repeatable.

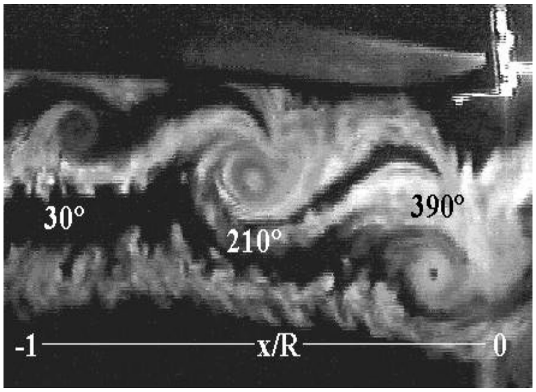

Figure 2 – "Instantaneous" laser sheet image along tunnel centerline

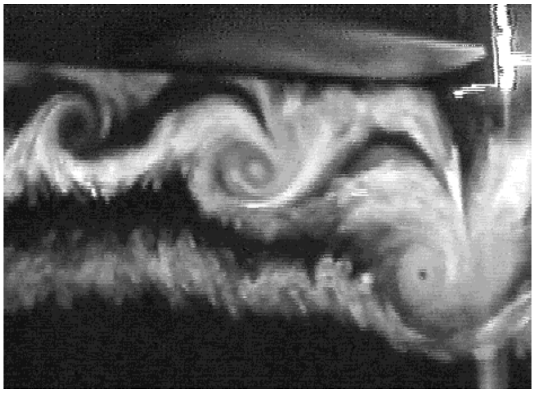

Figure 3 - Average of four "instantaneous" images

Flow visualization can only provide a qualitative measure of the periodicity. As a quantitative measure, LDV data was examined. The particle distribution of 50,000 LDV seed particles is shown in Figure 4. The bin size is 1° of rotor azimuth and the average number of particles per bin is 150. Sections with zero particles are due to vortex passage through the measurement volume. If the wake showed significant aperiodicity, then the number of bins with zero particles would be a function of sample size. Data sets of varying sample size were examined to determine its effect on the number of bins without particles. A significant change in the number of bins without particles was noticed for samples sizes less than 10,000. For sample sizes greater than 20,000, the number of bins with zero particles remained constant.

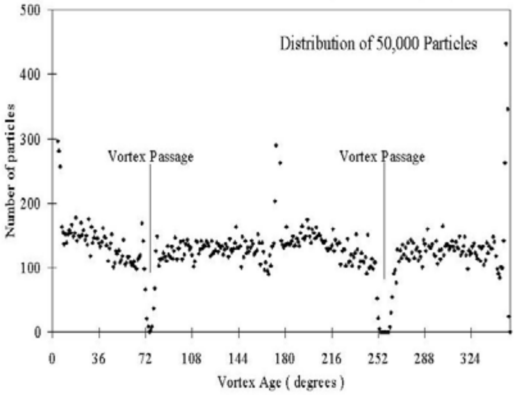

Figure 4 - Seed particle distribution at a point with core passage

To determine the exact periodicity of the flow, a moving average was performed to locate the center of the vortex. A sequence of points was selected at random from within raw LDV traces from the ABS and front of the rotor. The sequence was then sorted by azimuth and the moving window average computed. Window size ranged between 3 and 9 bins wide. The absolute deviation from the mean core center from the front and ABS of the rotor is shown in Figure 5. It was obtained by averaging the results of 10 moving window averages for each window size. The deviation from the mean is up to 3.5° for sample sizes less than 5000. However, for sample sizes greater than 5000, the deviation is less than 1° of rotor azimuth. Since this flow field has less than 1° of aperiodicity, accurate measurements of the vortex properties can be obtained.

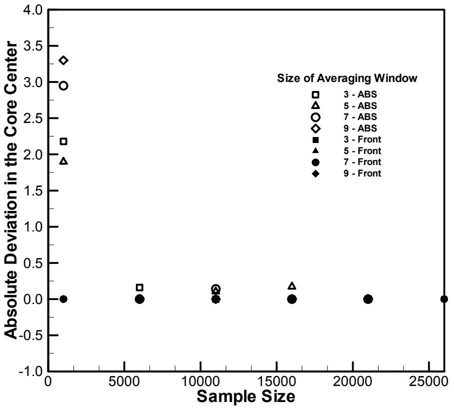

Figure 5 - Absolute deviation from the mean core center

Results and Discussion

Evolution of the Axial Velocity

The evolution of the core axial velocity is shown in Fig. 6. Data from the front of the rotor has been removed for clarity. On the ABS, the axial velocity starts out at 22% of tip-speed and climbs to 54% of tip-speed by 24° of vortex age. Then it gradually decays to about 25% of tip-speed by a vortex age of 162°. Data from the RBS shows the peak axial velocity starting out much higher at nearly 80% of tip-speed and then dropping and leveling off to an average of 20% of tip-speed by 6° of vortex age. Vortices shed from the rear of the rotor start out at 20% of tip-speed and eventually decay and level off at about 8% of tip-speed by 72° of vortex age.

The high starting velocity on the RBS suggests that axial velocity may actually reach the tip-speed of the rotor during formation. The no-slip condition on the blade could be a possible explanation of this phenomenon. Seed particle dynamics could play a role in why higher velocities were not measured at other stations. On the RBS, the blade and the flow direction are the same. As a result, seed particles are more easily entrain into the vortex flow and can then more rapidly represent the true fluid velocity. However, on the ABS the flow is opposite to the direction of blade movement so seed particles entrained into the vortex flow must reverse direction. The finite inertia of the particles prevents them from instantaneously representing the true fluid velocity, thus there is a finite delay before they can represent the true fluid velocity. This could explain the sudden increase in observed axial velocity on the ABS.

One feature that all of the data share is a distinct period variation. The period of the variation is 1.62ms or approximately 10° of azimuth. The corresponding Strouhal number based on blade-tip thickness and tip-speed is 0.16.

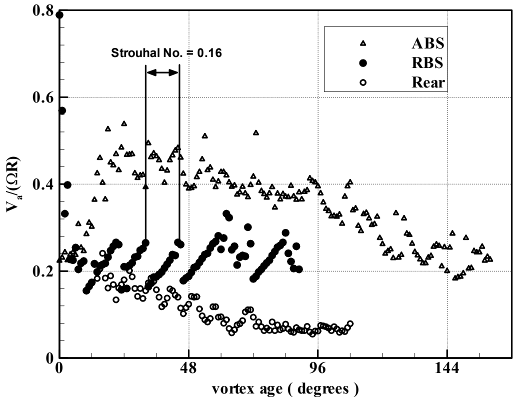

Figure 6 - Evolution of the peak core axial velocity

Evolution of the Circumferential Velocity

Measurements of the peak circumferential velocity from the ABS are shown in Figure 7. The other three stations are shown in Figure 8. All data show similar trends - the velocities come to a maximum within the first 6° and then decay before leveling. Velocities on the ABS and on the rear of the rotor are approximately 10% less than the velocities measured on the front and RBS of the rotor. Data from the RBS shows a peak velocity of 45%, followed gentle decay to 30% of tip-speed by a vortex age of 50°. The ABS side shows a much sharper drop from a peak of 35% of tip-speed to 20% of tip speed in the same period.

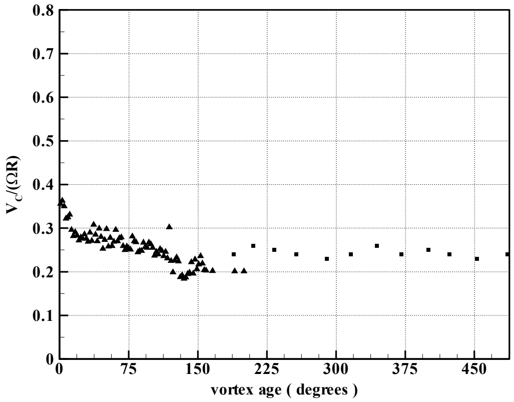

Figure 7 - Evolution of the peak core circumferential velocity on the ABS

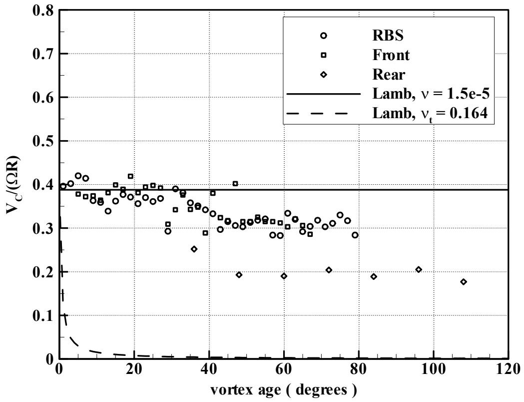

Figure 8 - Evolution of the peak core circumferential velocity

Other researchers have also reported decay in the circumferential velocities of the vortex core. Some have suggested that the decay is due to turbulent diffusion. Lamb [15] developed an expression for the circumferential velocity of a trailing vortex core as a function of circulation, core radius and downstream distance. It can be written as

$$V_c = \frac{\Gamma}{2\pi r}\left[1 - e^{-\frac{V_{tip}}{4\nu x}\times r^2}\right]$$

The expression can be non-dimensionalized with tip-speed and blade tip thickness as the vortex core diameter. Using vortex age as downstream distance, the expression becomes

$$\frac{V_c(\psi)}{V_{tip}} = k_1\left[1 - e^{-\frac{0.0675}{\upsilon\times\psi}}\right]$$

It should be noted that Lamb's expression assumes small axial gradients, small core velocities compared to freestream and a rectilinear vortex.

If a value of k_1 equal to 0.39 from Fig. 8 is used along with a kinematic viscosity, υ, equal to $1.5\text{x}10^{-5}$, then the evolution of the circumferential velocity for a laminar vortex is represented by the solid line in Figure 8. An estimate of the decay properties of a vortex with a turbulent core can be found by using Prandtl's mixing length model. Using the blade tip thickness and the experimentally measured velocity gradient, the resulting eddy viscosity, υ_t, is equal to 0.164. The Lamb model using the eddy viscosity results in the dotted line in Figure 8.

The estimate of the laminar vortex decay shows no appreciable decay of the peak circumferential velocity in the vortex ages measured. On the other hand, the turbulent estimate results in a drop to 1% of tip-speed within the first 12° of vortex age. Clearly the measured decay rate does not match either the laminar or the turbulent case. However, it is much closer to the laminar estimate than the turbulent one. This implies that vortex models do not need to include turbulence models.

Vortex Core Velocity Fluctuations

The core axial velocity profile is shown in Figure 9. This profile corresponds to a vortex age of 12° shed from the ABS. The Root Mean Square (RMS) velocity rises both near and in the vortex core. These locations correspond to areas with high velocity gradients. The increase in RMS velocity is due to the azimuthal resolution of these measurements. At these locations, the high gradients result in velocity fluctuations within the bin and, therefore, result in non-zero RMS values. The effect of the velocity gradients was computed and removed from the RMS velocity. This is represented by the squares in the figure. It is clear that the velocity fluctuations in the vortex core are less than those found in the freestream. This strongly suggests that the flow with the vortex is not turbulent.

This finding, along with the findings of periodicity, show that there is no need to measure velocity components simultaneously in this flow. Reynolds stresses are not an issue, since "turbulence in the core" is essentially a non-existent problem. Using multicomponent laser velocimetry, as advocated by some researchers, was found in the early 1980s in our facilities to cause an order of magnitude increase in the alignment and run times required to conduct a given experiment [16]. Basically, the available laser power is divided into multiple beams, with several other beams discarded. The data acquisition rate is limited by the worst-performing component, and as a result of facility run-time constraints, data acquisition quality standards are often relaxed (usually by reducing the fringe count and other tolerances). Due to the lower signal-to-noise ratio, the amplifier gains must often be increased as well. The net result is a lower number of data points acquired per location, lower azimuth resolution, higher root-mean-square values and poorer statistical averaging accuracy. In contrast, usage of single-component measurements with proper attention to experiment design and data acquisition can result in much cleaner data (better signal quality), with far higher statistical stability.

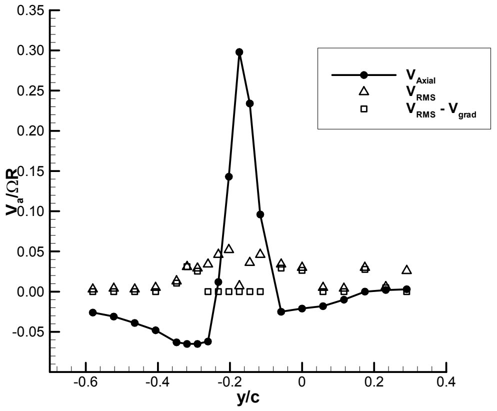

Figure 9 - Core axial velocity profile. 12° of wake age, shed from the ABS

Trajectories

The boundaries formed by the tip-vortices on the ABS and RBS are shown in Figure 10, and the boundaries on the front and rear of the rotor are shown in Figure 11. Contraction of the wake is the dominant feature on the ABS and RBS of the rotor, while convection is dominant on the front and rear of the rotor. As was mentioned before, vortex meander in this setup has been shown to be a non-issue. These are, therefore, accurate representations of the vortex trajectories.

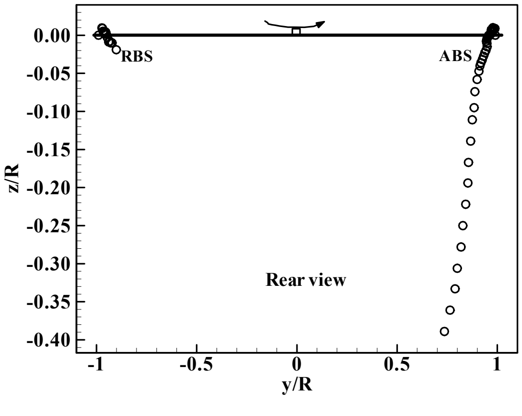

Figure 10 - Wake boundaries on the ABS and RBS

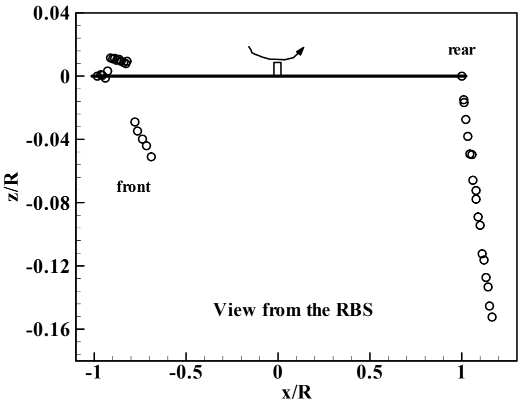

Figure 11 - Wake boundaries on the front and rear of the rotor

Evolution of the Core Radius

The evolution of the core radius is shown in Figure 12. The ABS has been removed for clarity. Data from the RBS and front show a slight increase in size from 6% to 7% of the chord. On the rear of the rotor there is an increase from 4% to 6% by an age of 72° followed by a decay to 4% by an age of 108°. The data from the ABS is shown in Figure 13. The data in the near-wake shows a slight increase from 5.5% of the chord to 6.3% by a wake age of 36°. After this increase, there is a decay to 4.5% of the chord by a wake age of 120°. In the far-wake, the radius varies by 1.5% about a mean of 6%. An increase in the core radius in the far wake is expected. Over the same wake age, the circumferential velocity decays by approximately 10%. In order to conserve angular momentum, the core radius must also increase.

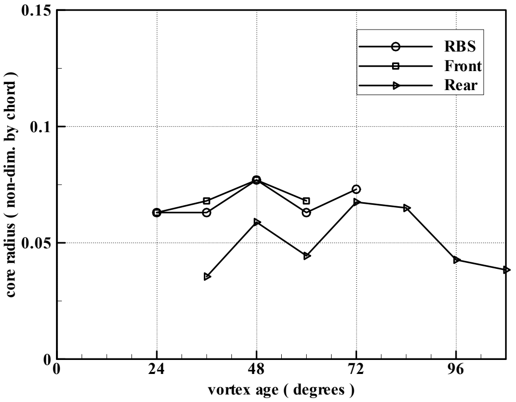

Figure 12 - Evolution of the core radius

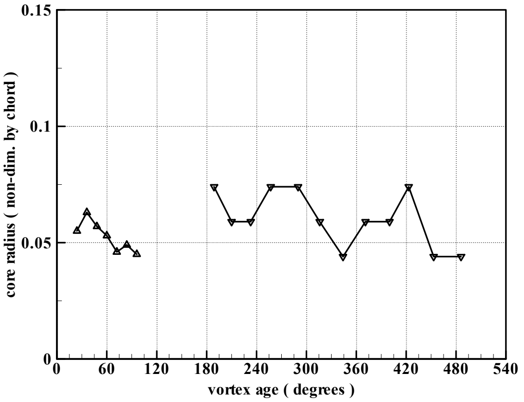

Figure 13 - Evolution of the vortex core radius on the ABS

Measurement Uncertainty

The data presented here were taken during two tunnel entries approximately six months apart. The data for vortex ages up to 180° were taken during the first entry and the extension of the ABS measurements were made during the second. Issues such as periodicity are addressed using quantitative metrics. The uncertainty of the reduced velocity data within a given set of runs is seen to be well within the symbol sizes used to plot them: the consistency of points in Figure 5 illustrates this. There is however some discrepancy between the runs conducted six months apart. This is seen in Figure 7 where there is a difference between the points reduced from the two sets of runs, at roughly 180 to 200 degrees wake age. The peak core circumferential velocity appears to have an offset of 4 to 5% of tip-speed when compared to the first set of measurements. We are currently trying to determine the cause for this discrepancy.

Conclusions

Vortex modeling for accurate rotary wing air load, vibration and noise prediction requires empirically derived parameters from experimental data. Thus, accurate experimental measurements are critical to enabling accurate predictions. LDV measurements were made on the tip-vortex properties of an isolated rotor in low-speed forward flight. It has been shown that the periodicity of vortex passage across a measurement location in the near wake is satisfied to within 1° of rotor azimuth. This enables precise measurements of the tip-vortex properties. From these measurements, we have concluded the following:

1. The peak core axial velocity exhibits a periodic variation in the near wake. This suggests some type of shedding phenomenon. The Strouhal number based on tip-speed and blade-tip thickness is 0.16.
2. Comparisons of the decay rates of the measured peak core circumferential velocity and those predicted by a turbulent Lamb vortex clearly indicate a lack of turbulence in the vortex core.
3. A technique for estimating the level of velocity fluctuations introduced by the measurement technique was developed. Once applied to the measured data, measurement fluctuations in the vortex core were equal to or less than those measured in the freestream.
4. Conclusions 2 & 3 clearly indicate a lack of turbulence in the vortex core. Therefore, turbulent models are not necessary in vortex modeling to capture the wake vortex evolution in the near and moderate-distance wake.
5. Wake boundaries on the ABS and RBS are dominated by contraction, on the front and rear they are dominated by convection.
6. Evolution of the core radius from the near to far wake shows a slight increase in the core radius.
7. Given the demonstrated periodicity and Conclusions 2 – 4, it is shown that simultaneous measurements of all 3 components of velocity is neither needed, nor does it enhance productivity or accuracy in any way in such flows.

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