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MEASUREMENTS OF THE NEAR WAKE OF A ROTOR IN FORWARD FLIGHT

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ABSTRACT

This paper describes initial measurements of the near wake of a 2-bladed teetering, untwisted, square-tipped rotor in forward flight. Issues of periodicity and repeatability of the core are studied using laser velocimetry and flow-visualization on the front of the rotor wake where cycle to cycle variations are expected. Core passage uncertainty from cycle to cycle is less than 1 of rotor azimuth. Velocity measurements on the advancing blade side show wake-like core-axial velocities higher than the core circumferential velocity for the first 180 of vortex age. Both the axial and circumferential velocities approach 50% of blade tip speed. The inboard vortex sheet has substantial wake-like velocities and rolls up into a concentrated circulatory region of high wake-like axial velocity rotating opposite to the tip-vortex, within 30 from the blade. The fully-developed values of the vortex core circulation, radius and axial velocity remain constant over 180 of age as current measurements indicate. Measurements on the front, rear and retreating blade side of the rotor are in progress.

INTRODUCTION

Increasing demands for low-noise rotors and smaller rotor-airframe spacings have fueled the need to understand the formation and evolution of the near-wake of a helicopter rotor. Blade Vortex Interaction (BVI) noise is one of the biggest obstacles in community acceptance of helicopters as a commercial transport and is an issue for detection avoidance in military purposes. An overview of BVI noise mechanisms and control concepts is discussed by Yu(1). Recently, a review of prediction methods for BVI by Caradonna et al.(2) shows that most of the prediction methods used today need a good vortex representation, typically obtained from experimental data on the vortex core. BVI usually occurs at very early ages of the tip-vortex, typically within the first 180 . Hence, knowledge of the vortex structure in the near wake is of great use in formulating prediction models.

In the early 1980's the interaction of the rotor-wake with the airframe was cited as the biggest obstacle in rotor performance predictions(3). The wake from the main rotor, especially the tip-vortex, is a primary component in many aerodynamic interactions. Today, rotor-airframe interactions can be predicted relatively easily, once the vortex characteristics are known(4). Smaller rotor-airframe spacings imply that the tip-vortex interacts with the airframe while still very strong and thus the airframe is subject to severe vortex loads and vortex-induced separation. The ability to modify the rotor-wake in order to reduce interaction effects also depends on knowledge of the tip-vortex formation at the blade-tip. The understanding of the near-wake is thus essential to remove many of the obstacles to first-principles-based prediction of rotorcraft aerodynamics.

Wake-modeling has always involved substantial empirical input. Rotor wake measurement and prediction have received wide attention since the 1950's. Some of the early work was done primarily to characterize the wake geometry, circulation and radius(5-7). Recent interest has been directed towards capture the initial stages of vortex roll-up, its subsequent development, transition of the near wake to the far-

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wake and the mechanism of dissipation of the vortex-core.

An important feature of the tip vortex from a rotating blade is the presence of a substantial velocity component directed along the axes of the strong vortices in the rotor wake. This is an aspect which is missing from most vortex representations used in predictions, and is yet of first-order importance to interaction problems. There is considerable debate regarding the magnitude and direction of the core-axial velocity. Theoretical work by Batchelor(8) and Saffman(9) postulated a jet-like or wake-like flow in the core of a wing tip vortex depending on a parameter which was a function of the tip loading. Experiments on fixed wings have shown both jet-like and wake-like velocities(10). Recent measurements by McAlister et al(11) on a two-bladed rotor in hover, showed strong wake like axial velocity. Russell et al.(12) were able to obtain computational comparisions with these velocities using a 3-D Navier-Stokes solver.

Shivananda(13) 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: the axial velocity was directed back along the trajectory of the vortex towards the blade. Thompson (14) 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. There is some flow visualization evidence in the literature on propeller wakes which supports this finding (15). Leishman et al.(16) measured the 3-components of velocity in the tip-vortex core of a 1-bladed rotor in hover and found a wake-like axial velocity . The axial velocity profiles dissipated within the first 90 of wake age. The core diameter increased while the core peak tangential velocity decreased rapidly in the first 180 of wake age.

Another aspect missed in vortex-wake representations is the roll-up of the inboard vortex sheet into a significant circulatory region with a large wake-like axial velocity. This has been observed by Kim(17) on a model rotor and recently by Ghee(18) on a small-scale rotor with a tip-loading representative of a full-scale rotor, and at higher tip speed. This will be discussed in the results section.

Experimental results on the vortex core are not always reliable for the following reason. Most rotorcraft measurements have concentrated on hover measurements since increasing hover payload is one of the biggest objectives in rotorcraft design. However, hover testing is susceptible to vortex-meander due to facility interference and recirculation. Thus, if cycle to cycle variations in vortex location are not taken into account, ensemble averaged vortex parameters appear to have “disspated”. This “experimental dissipation” is very often attributed to the flow itself, often cited as “due to turbulence” whereas it is a result of inadequately-characterized test conditions and averaging. While vortex meandering would occur in full-scale flights, the vortex strength at interaction would not be as small as the experiments would show. It is therefore, very important to carefully address the issue of wake unsteadiness in any vortex measurements. Recent experiments by Caradonna et al(19), have shown that when facility recirculation is eliminated, the wake, even in the limit of hovering flight, is indeed very steady, and strong vortices persist for large vortex ages, for a rotor operated at full-scale Reynolds and tip Mach numbers.

EXPERIMENTAL DETAILS

The experiments were carried out in the J.J.Harper wind-tunnel at Georgia Tech. This a closed-circuit tunnel with freestream turbulence levels of less than 0.5%. The rotor is a 2-bladed teetering rotor of 0.9144 m dia and 10 deg collective and a blade chord of 8.75cm. The rotor is suspended from the ceiling of the tunnel and inclined at an angle of 6 to simulate forward flight conditions. The slender rotor shaft and the minimal-size teetering hub serve to produce a rotor configuration very close to the “isolated rotor” ideal. The rotor blades are untapered and untwisted with a NACA0012 section. The rotor RPM was 1050 for all the measurements, and the tip speed was 50 m/s. The advance ratio for all the experiments was 0.1. The thrust coefficient at these conditions was 0.0089. The forward flight setup in the Harper wind-tunnel is shown in Fig.1.

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 green (514 nm), obtained from a continuous wattage 5W

Argon ion laser coupled with a Colorburst$^{\text{TM}}$ module. It is demonstrated from the results that the periodicity and repeatability of the flow-field obviated the need for simultaneous three-component velocity measurement. The LDV measurement region on the ABS and the set-up is shown in Fig.2. The entire set of measurements will be performed at four shedding locations on the rotor cycle. These are shown in Fig. 3. The parameters used for non-dimensionalizing velocity and circulation are the tip speed and blade chord.

RESULTS

1. Flow-visualization on the front of the rotor

Fig.4 shows the wake development in the front part of the isolated rotor wake in forward flight. These experiments were performed by Kim(20). The top image is an instantaneous snap-shot of the flow-field at a rotor-azimuth of 30 . The image plane is aligned along the vertical plane at 180 of rotor -azimuth. The vortex at the extreme left is about 30 old and is generated from the blade in the picture. The next vortex is 210 old, and generated by the previous blade, while the third is 390 old and was generated in the previous cycle by the blade in the picture. Note that even as late as 390 of vortex age a strong rotational structure is seen. The vortex at 210 interacts with the inboard-sheet from the blade in the picture. This causes the inboard sheet to roll up into a discrete vortex, opposite in sign to the tip-vortex. This will be discussed later in the context of velocity measurements.

The image at the bottom shows an average of four instantaneous snapshots. Apart from a slight smearing out of the smoke patterns, the image is exactly the same as the instantaneous snapshot. The ability to capture the dark spot of unseeded core cross-section, surrounded by the bright, highly-seeded flow, in both images, is clear proof that the jitter is substantially less than 1 core radius, even at 390 of vortex age. A more quantitative demonstration of the periodicity was done using the LDV measurements on the front of the rotor and this is discussed in the following section.

2. Flow-field periodicity and repeatability

Fig.5 demonstrates the periodicity of the flow-field with data from laser velocimetry on the front of the rotor-wake. The figure shows the particle distribution in each azimuth bin of the rotor cycle. Each bin is thus an average of about 150 points, except in bins of core passage, where the particle arrival rate is zero. If there was cycle-to-cycle unsteadiness in the wake, the number of bins with zero core passage would vary depending on the total number of points averaged. Varying the number of points for the ensemble average did not change the number of bins at which the particle arrival rate was zero, provided the average was taken over at least 20,000 points. This is shown in Fig.6. When the average was carried over 10,000 points or less, the number of azimuth bins with zero particles increased. Another test for periodicity was conducted to confirm that the location of minimum particle arrival does not actually change from cycle to cycle. The ensemble averaged particle arrival rate was averaged again using a moving window technique to locate the minimum. The averaging was performed over a data trace of 10,000 or 20,000 points with the starting point randomly chosen. It was found that the minimum of the particle distribution for the measurement location in Fig.5 always occured at a vortex age of 257 for 100 repetitions of the averaging.

Fig.7 shows a comparision between the vorticity field in a plane and the velocity field perpendicular to the plane. These measurements were made as part of a rotor-airframe interaction test case. The plane of measurement seen here is on the front of the rotor wake. The vorticity field was constructed from measurements of two-components of velocity individually measured in the plane. These measurements were made in 1986 by Liou(21). Here positive numbers indicate clockwise vorticity. The velocity field normal to the plane was measured in 1996 by Mahalingam(22). Positive velocities are directed out of the plane of the paper. Thus, the core axial velocity on the front of the wake goes from the ABS to the RBS, i.e, follows the rotor blade. There is excellent correlation between the centers of maximum vorticity and maximum velocity (here it corresponds to the core axial velocity). This demonstrates the repeatability of test-conditions. This is another requirement for making individual component measurements and combining them to get ensemble averaged vortex parameters during post-processing. These measurements indicate that in this particular setup it is feasible to combine individually measured velocity components at each point in the flow-field to arrive at reliable values of core axial velocity, radius and circulation.

3. Vortex velocity profiles on the ABS of the rotor

Fig.8 shows the core circumferential velocity profile as a function of vortex age on the ABS of the rotor. The vortex profiles are not symmetric. They show secondary features on the side of the vortex which is outboard of the rotor. These features in the profile smoothen out as the vortex becomes older and the vortex attains a classical viscous core profile. These secondary features have been observed previously in hover by Thompson(14), who attributed it to effects of rolling up vortex sheets. This effect will persist until the action of viscosity smoothens the profile. This feature needs to be researched further. All the symbols shown are not measurement points. The profiles are interpolated using straight lines between the actual data points.

Fig. 9 shows the core axial velocity profiles for different vortex ages. The axial velocity profiles have a well defined peak with the maximum approaching half the tip speed of the rotor. The axial velocity is confirmed to be wake like, i.e., directed back towards the blade from which the tip-vortex was generated. The axial profiles do not show the same secondary features as the circumferential velocity profile due to following reasons. The resolution at the center of the core is not yet sufficient to capture such variations. The variations present in the outer regions are small compared to the maximum axial velocity in the core and thus are harder to resolve.

4. Variation of core parameters with vortex age on the ABS of the rotor

Fig.10 shows the variation of the maximum core axial and circumferential velocities with vortex age. The core axial velocity increases from a value of about 0.2 Utip (where Utip is the speed of the flow relative to the blade at the azimuth of the measuring location) at 0 of vortex age to roughly 0.5 Utip at 60 of vortex age and proceeds to slowly drop, reaching a value of 0.3 Utip at 160 of vortex age. This is of importance when we consider that the strongest BVI amplitudes occur on the ABS of the rotor, and the axial velocity should play an important role in BVI by its sheer magnitude. The maximum core circumferential velocities start at 0 vortex age at about 0.35 Utip and slowly drop to about 0.3 Utip by a vortex age of 160. The most important feature is that the core axial velocity is higher than the core circumferential velocity for half a cycle after the blade has passed by. Vortex representations that do not include the axial velocity of the tip-vortex, are thus insufficient for prediction of various interactions, especially when the vortex collides head-on with a surface.

Fig.11 shows the variation of non-dimensionalized core radius and circulation with vortex age. Both remain fairly constant upto half a rotor cycle, though there is higher scatter in the core radius. The higher scatter in the core radius is due to the secondary features discussed previously. These features span a distance of half a core radius and this causes some uncertainty in locating the the edge of the viscous core region.

5. Inboard vortex sheet roll -up

It was seen by Kim(17) that on the front of the rotor, the inboard sheet rolls up into a strong vortex rotating opposite to the tip-vortex. It was noted that the circulation in the counter-rotating inboard sheet vortex was 50% of that of the tip-vortex. Also, velocity measurements showed that the inboard sheet vortex possessed large wake-like axial velocities. The inboard sheet vortex convects downstream faster than the tip-vortex, due to its sense of rotation and its image vortex inside the airframe. The pressure signature of the inboard vortex was sharp and this indicated that it was a tightly rolled-up structure. It remained to be seen, however, if this phenomenon occured at different shedding locations on the rotor-cycle.

Fig.12 shows an isometric view of the out-of-plane velocities as the rotor bladecuts through a vertical plane on the ABS. The two tall spikes are due to the tip-vortex from the two blades, one 180 older than the other. Apart from the two tip-vortices another rolled up structure is seen just inboard of the older vortex. This structure is formed by the interaction of the inboard sheet from the current blade with the tip-vortex from the previous blade(vortex age 192). The circulation within the inboard sheet vortex is of the order of a fourth of the tip-vortex core circulation at 192. (The non-dimensionalized tip-vortex core circulation is 0.15 and the inboard vortex circulation is 0.04). The circulation value obtained for the inboard vortex is an underestimate because of the proximity between the tip-vortex and the inboard vortex. Note that the inboard vortex axial velocity is directed back towards the blade even though the sense of rotation is opposite to the tip-vortex. This strengthens the hypothesis that the core axial velocity is a combination of the no-slip condition and the boundary layer roll-up at the blade tip. It is thus confirmed that in forward flight the magnitudes of the inboard sheet parameters are significant enough not to be ignored, and have been seen previously to have significant influences in interactions. Thus, the inboard sheet evolution into a strong structure needs to be part of prediction codes.

Results from four shedding locations on the rotor cycle, at various vortex ages, will be presented in Ref. 23.

CONCLUSIONS

An initial set of measurements of the near wake of a 2-bladed rotor are shown. Periodicity and repeatability, essential for ensemble-averaged velocity measurements, are demonstrated to within 1 of rotor revolution. The core axial velocity and circumferential velocity are comparable, and reach upto half the tip-speed of the rotor blade. The core axial velocity is directed wake-like for this rotor blade. The core circumferential velocity profiles show secondary features on the outboard side of the vortex. The gradients in the profile due to these features smooth out slowly; finally, a classical viscous vortex profile is reached. The core axial velocity increases from the blade tip to a maximum of 50% of the blade tip-speed within 20 of vortex age and slowly decreases beyond that. The maximum core circumferential velocity is fairly constant from the blade tip to 180 of vortex age. The core radius and circulation remain constant for the first 180 of vortex age. In forward flight the tip-vortex from the previous blade interacts with the inboard sheet from the current blade and causes it to roll up. The inboard sheet vortex rolls up into a discrete vortex of circulation of the order but of opposite sign of the tip-vortex. The inboard sheet has strong axial velocities with magnitudes of the order of the core axial velocity, directed towards the blade.

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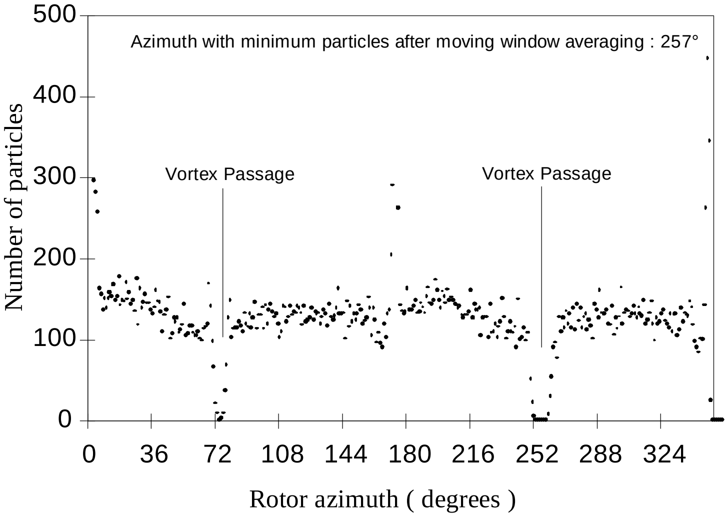

Fig.5. Seed particle distribution at a measurement point with vortex passing through it

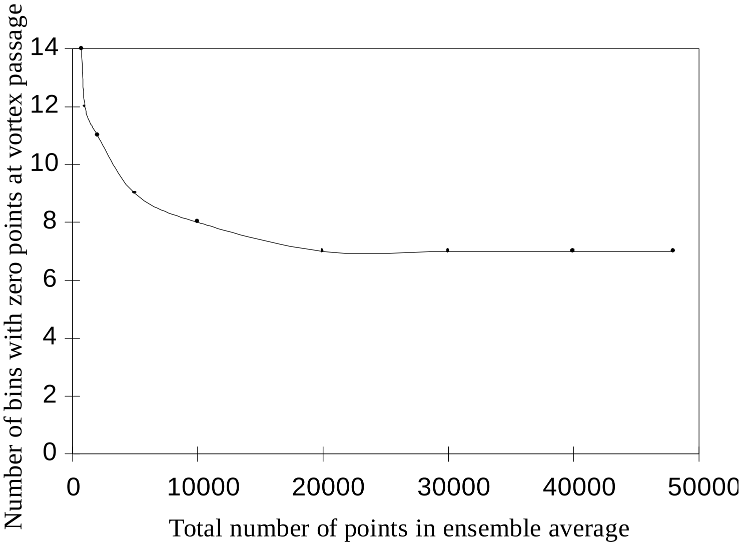

Fig.6. Particle deficit region during core passage through the measurement volume

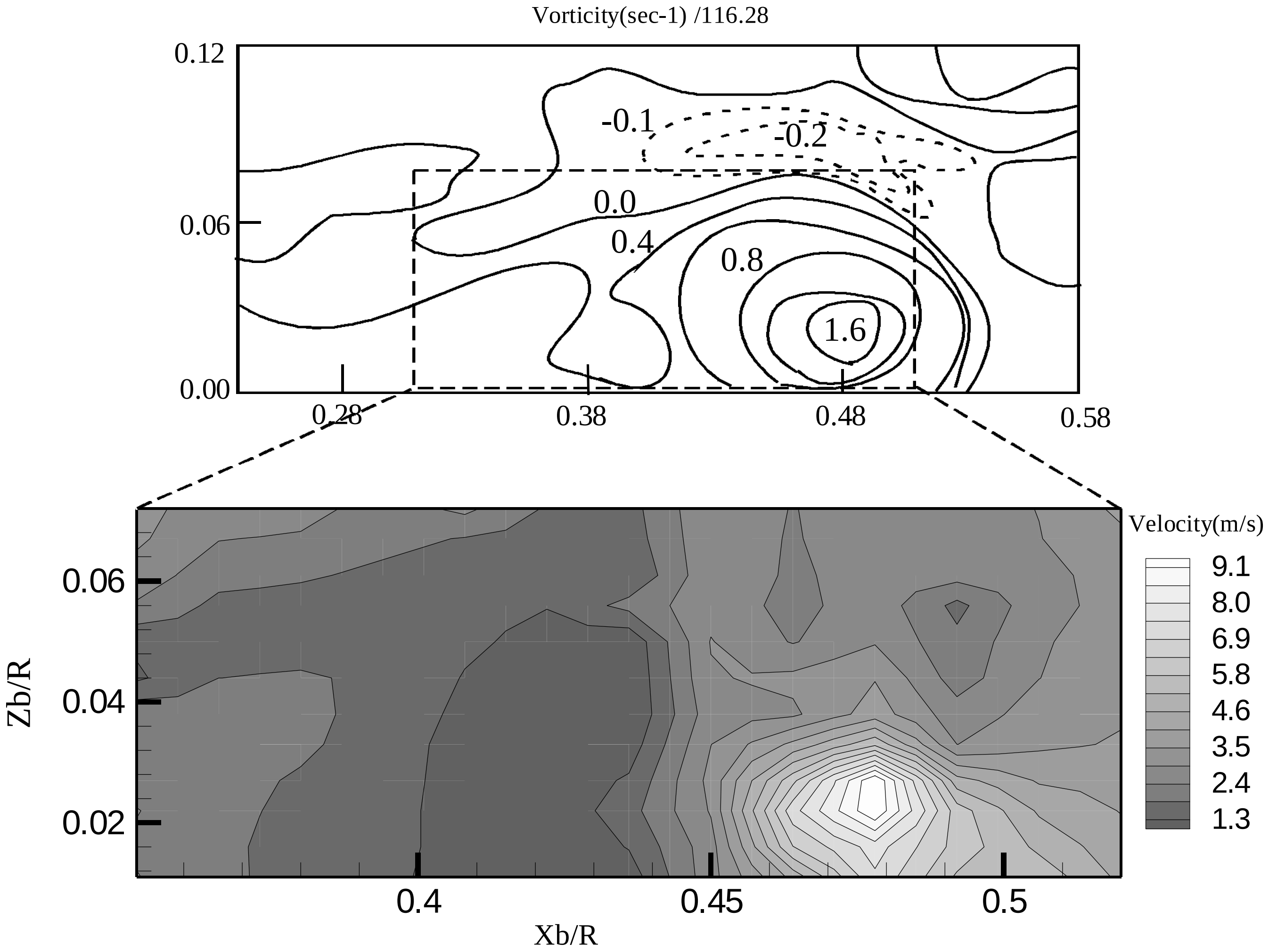

Fig.7. Vorticity contours (Liou,1986) and lateral velocity contours (Mahalingam , 1996) demonstrate repeatability. The plane shown here is approximately the same as in Fig. 4.

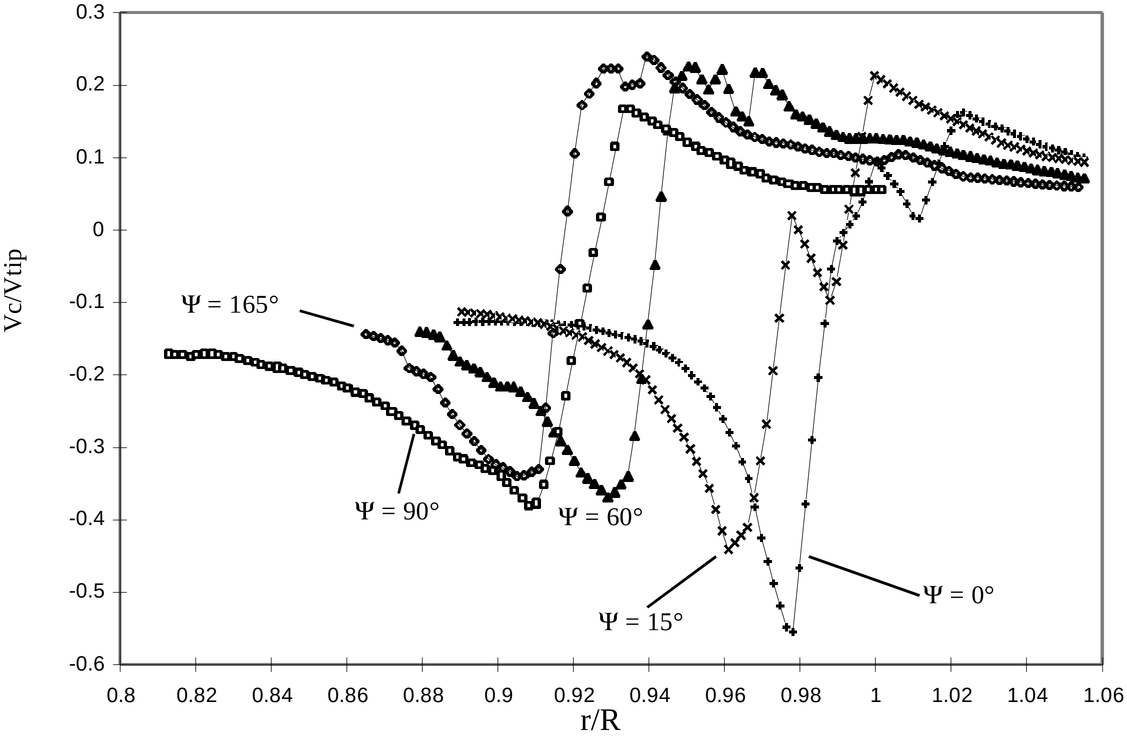

Fig. 8. Circumferential velocity profiles across the tip-vortex at various ages non-dimensionalized by the rotor tip-speed

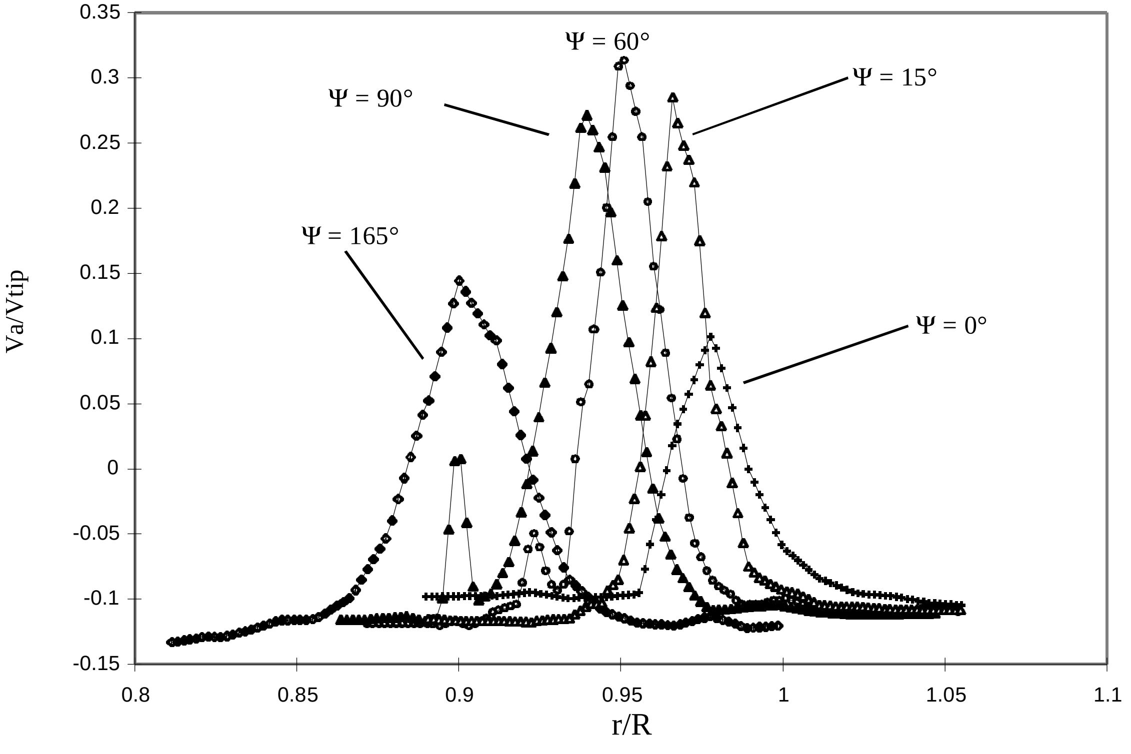

Fig. 9. Axial velocity profiles across the tip-vortex at various ages non-dimensionalized by the rotor tip-speed

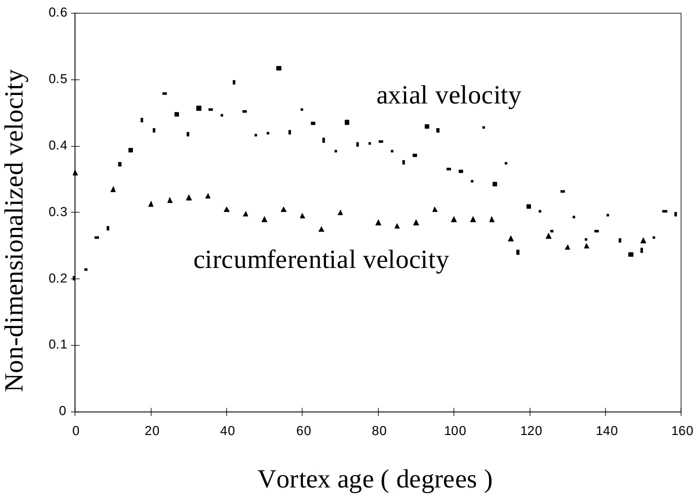

Fig. 10. Variation of core axial and circumferential velocity in the near wake

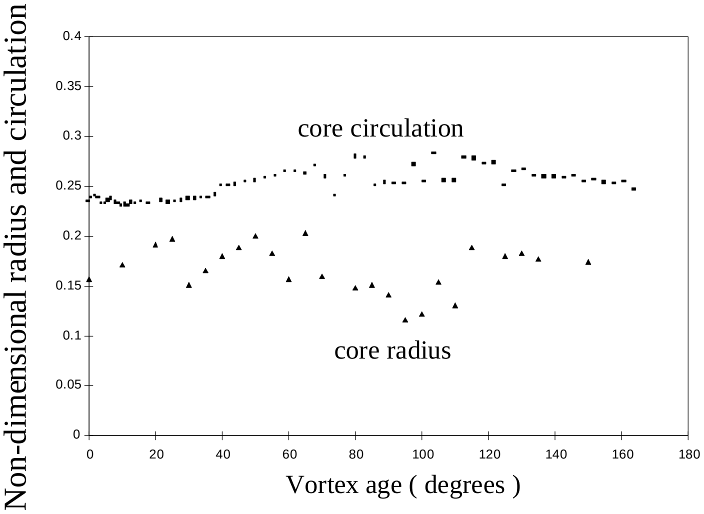

Fig. 11. Variation of core circulation and radius in the near wake

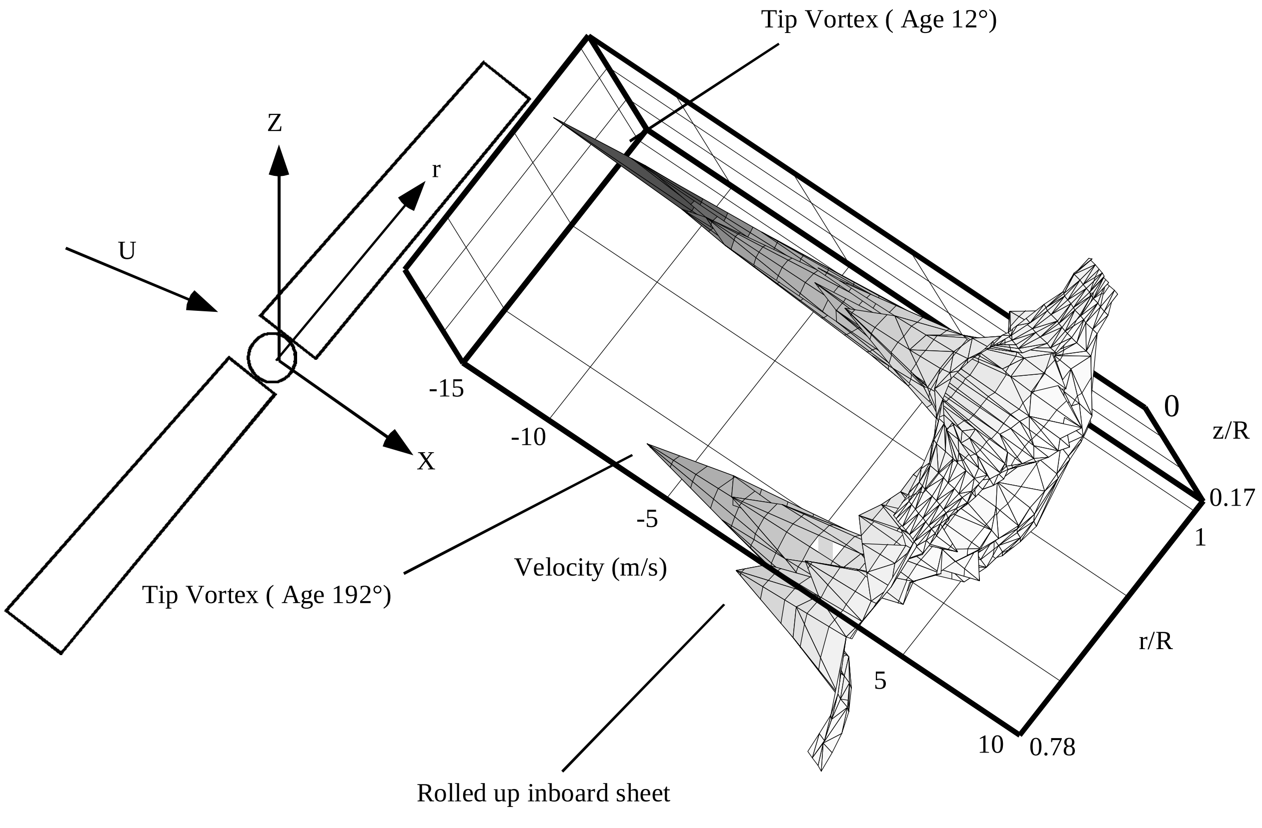

Fig.12. Contours of streamwise component of velocity show tip vortex and inboard sheet axial velocity
Note: Circulation in the inboard sheet vortex is a fourth of the circulation in the vortex at 192°