AIAA JOURNAL
Vol. 36, No. 7, July 1998

# Challenges in Understanding the Vortex Dynamics of Helicopter Rotor Wakes

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**Many experimental challenges are encountered when attempting to understand the complex vortical wakes generated by helicopter rotors. The problems are illustrated by means of several examples, including blade/vortex interactions, vortex perturbations, wake instabilities, and vortex/surface interaction phenomena. Specific emphasis is placed on flow visualization and quantitative measurements using laser Doppler velocimetry.**

## Introduction

THE flowfields of helicopter rotors comprise many significant fluid dynamic phenomena such as strong blade tip vortices, the possibilities of flow separation/stall on the retreating blade, and the formation of shock waves on the advancing blade tip. Whereas these individual phenomena are not different from those found on fixed-wing aircraft, they are usually highly time dependent and three dimensional and so appear in rather more complicated forms on helicopter rotors. All of these phenomena have important effects on rotor performance, blade loads, aircraft vibration levels, and rotor acoustics. The most dominant flow features, however, are the strong vortices trailed at the tips of each blade. Unlike a fixed-wing aircraft, these tip vortices remain close to the rotor and produce a complicated induced velocity field that has a primary influence on blade loads and rotor performance. The strength and proximity of the tip vortices result in powerful interactions between individual vortex filaments and also between blades and airframe surfaces. The incomplete understanding of these problems in vortex dynamics acts, in part, as a barrier to improved helicopter designs with better performance, reduced noise, and lower vibration levels.

The complexity of a helicopter flowfield during forward flight is shown in Fig. 1. The blade tip vortices are known to be very persistent and may not significantly diffuse or dissipate for many rotor revolutions after their creation. Note that the vortices may closely interact with other blades over several different parts of the rotor disk, a phenomenon known as blade/vortex interaction (BVI). The problem of BVI is especially pronounced in low-speed descending flight, such as approach to landing, or during maneuvering flight. It can produce very high blade loads and can generate obtrusive noise.[1] The tip vortices may also interact with the airframe[2] or tail rotor[3] and are known to be a secondary source of wake distortion that affects rotor performance and blade loads.[4] In addition, the unsteady pressure loads induced on the airframe[5] may lead to significant aerodynamic excitation of the structure and can be an elusive source of airframe vibrations and buffeting.[2,6,7] Although these rotor wake and vortex related phenomena have been the subject of much research, they are still poorly understood because they are both difficult to measure as well as to predict.

The objectives of this paper are to describe and summarize some of the challenges that are encountered when experimentally investigating and measuring the dynamics of helicopter rotor wakes and blade tip vortices. A longer conference version of this paper is given in Ref. 8. Particular emphasis is placed on understanding the physical features of the blade tip vortices. In many cases the problems are very complicated, and the experimental challenges posed are rather daunting. It will become clear, however, that, although significant progress has been made toward an improved understanding of the various vortex dynamic phenomena found on helicopters, they will continue to require further study by a variety of complementary experimental techniques. Some of the parallel computational challenges associated with helicopter rotor wakes have been described in a recent review paper by McCroskey.[9]

## Discussion

The vortex wake structure generated by a helicopter can take on several significantly different forms that depend on the flight condition. In hover, the tip vortices follow nominally helical trajectories below the rotor. However, various forms of disturbances and instabilities of the vortices have been observed.[10,11] Some of the first detailed systematic studies of the rotor wake structure during simulated hovering flight are reported in Refs. 12–14. These experiments have formed the basis for several semiempirical rotor wake models, as well as for the validation of more fundamental free-vortex wake approaches.

During forward flight, the rotor wake is skewed back behind the rotor by the oncoming flow, and a series of more complex interlocking epicycloidal tip vortex trajectories are produced; see, for example, Refs. 15 and 16 and Fig. 1. The increased mutual proximity of portions of the vortex filaments results in stronger vortex/vortex interactions and complicated distortions. Experiments in forward flight have shown that the rotor wake appears mostly free from the aperiodic disturbances and instabilities often found in hover. In high-speed forward flight, the wake is known to roll up into a pair of merging vortex bundles,[17–19] which, in the Trefftz plane, looks very much like those generated from the tips of a low aspect ratio wing.

### Flow Visualization

Flow visualization is the primary method used to understand the complicated vortex dynamics of helicopter rotor wakes. Techniques have included: balsa dust,[12,20] smoke seeding,[19,21–25] cavitation,[26] natural condensation,[27] hydrogen or helium bubbles,[28,29] projected smoke filaments,[30,31] schlieren,[11,32] shadowgraphy,[25,33–37] and interferometry.[38] The multitude of phenomena that have been observed and studied include tip vortex formation, shock waves, acoustic waves, BVI, vortex/airframe surface interaction phenomena, main rotor wake/tail rotor interactions, ground interference, multirotor flows, and the wake rollup in forward flight. Whereas mostly used qualitatively, flow visualization can also allow spatial measurements of the tip vortex locations.[15,19,22,34–36]

#### *Smoke Flow*

Rotor experiments using smoke with light sheet visualization have been performed by Ghee and Elliott,[19] Mercker and Pengel,[23]

Presented as Paper 96-1957 at the AIAA 27th Fluid Dynamics Conference, New Orleans, LA, June 17–20, 1996; received Sept. 26, 1996; revision received March 1, 1998; accepted for publication March 9, 1998. 

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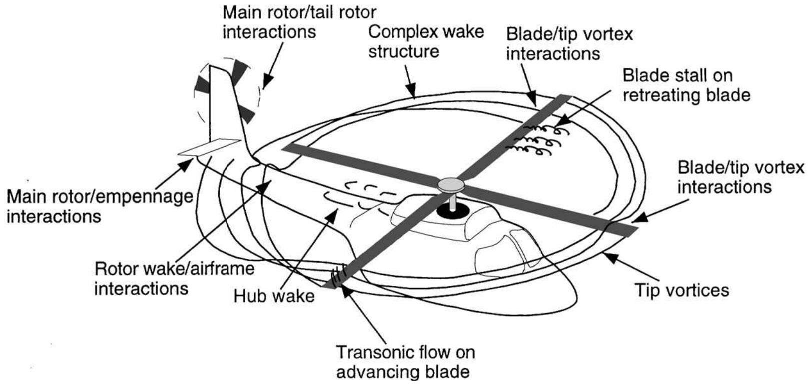



**Fig. 1 Typical flow phenomena found on a helicopter in forward flight.**

Gray,[13] Piziali and Trenka,[39] and Brand et al.,[40] among many others. The principle is straightforward; a dense white smoke is entrained into the rotor wake and tip vortices. When illuminated with a thin plane of light, preferably using a laser, the smoke particles reflect the light, allowing a photograph of the flow structure to be recorded. The illumination must be precisely strobed to the rotor position. Also, considerable light energy must be produced over a short time to avoid blurring of the results. Although very time consuming to use in forward flight, the technique can allow the spatial locations of the tip vortices to be mapped out over the rotor disk with precision.[19,23]

One challenge with the planar light sheet method is to successfully entrain smoke particles into the rotor wake and tip vortices. Because of the complex velocity field near the rotor and in its wake, the smoke (or seed) must often be introduced at locations that may be surprisingly remote from the region of interest. Furthermore, on one hand the seed particles must be large enough and in sufficient concentration to reflect light and allow an adequate photographic exposure. On the other hand, they must be small enough to accurately follow the flow. Similar conflicting requirements also exist with particle image velocimetry (PIV) and laser Doppler velocimetry (LDV). Because of the significant centripetal and Coriolis accelerations on particles entrained inside vortical flows, they spiral out of the vortex cores and become dispersed quickly throughout the wake.

Locally, the centrifugal forces produced on seed particles inside the tip vortices create voids. This is a well-known result, with a typical example shown in Fig. 2, which is a strobed image of a cross section of the rotor wake in hover taken in a radial plane extending from the rotational axis. This plane intersects the helical vortex filaments, essentially perpendicular to their axes. The entrainment of seed particles into the general locations of the tip vortices is apparent, but the dark regions in the centers are almost completely depleted of seed. As the vortex ages (top to bottom in Fig. 2), the reduced tangential velocities allow the core region to become progressively filled with seed. Further details of this type of flow are shown in the inset of Fig. 2, where the seed void is particularly vivid.

The dimension of the vortex core is important because it governs the peak swirl velocities and, therefore, the strengths of vortex interactions. The seed particle void is sometimes assumed to equate to the size of the viscous core. However, this is an incorrect and misleading assumption. To simulate the physics of the smoke redistribution process, the particle behavior can be examined numerically. Assuming Stokes drag law and following Fuchs[41] and Leishman,[42] the coupled differential equations describing the motion of a seed particle can be established. For a simple two-dimensional forced vortex, the equations can be integrated exactly and lead to spiral particle trajectories.[43] For more general vortex velocity fields, the integration must be performed numerically.

In Ref. 42, the seed particle density distribution has been computed for different particle diameters using an assumed velocity profile and a tip vortex strength typical of a Mach-scaled model helicopter rotor. This gives a good quantifiable measure of the expected particle void. Calculations show that a higher overall seed particle density is obtained in a region just outside the core where

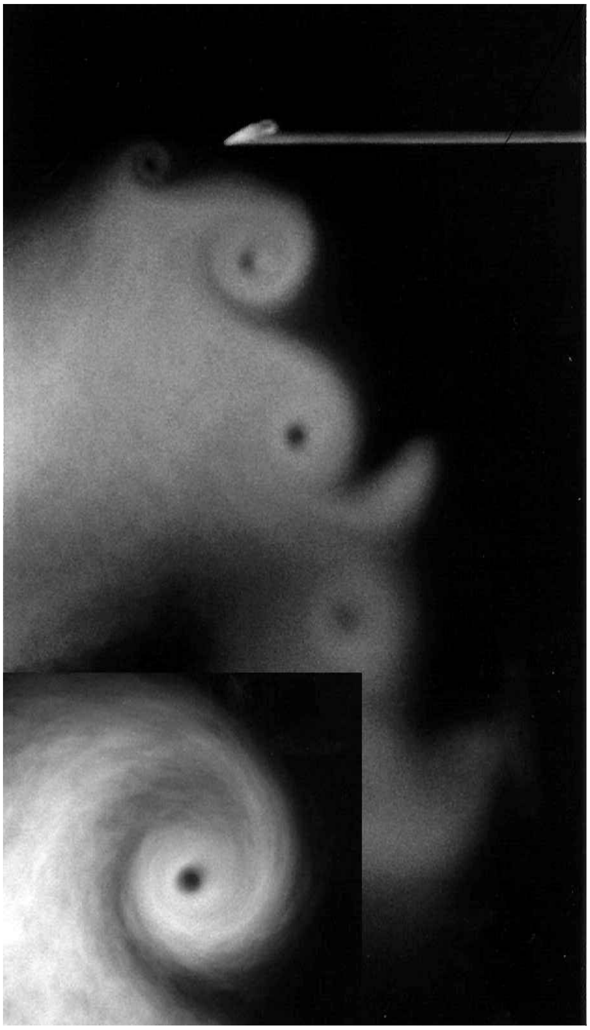


**Fig. 2 Flow visualization image of a plane through the wake of a two-bladed rotor in hover where the tip vortices are rendered visible by smoke. Inset: detail of a rotor tip vortex; note the smoke voids in the center of the vortices.**

particles reach a state of radial force equilibrium. The radial position and magnitude of this density peak is strongly dependent on particle size and mass, as well as on the tip vortex circulation. With typical smoke particles, the size of the void can be several times the size of the actual viscous core. However, if the net circulation about the vortex remains nominally constant, then the size of the seed void becomes closely proportional to the peak tangential velocities. Under some circumstances, therefore, the seed void is proportional (but not equal) to the viscous core size and can be used as an indicator for viscous diffusion effects.

Another form of smoke visualization is to eject smoke seed from the blade tip directly into the tip vortices. Smoke entrained this way renders the vortices visible as three-dimensional tubular trails with central voids. Such methods have been previously used primarily on model rotors to visualize the tip vortex geometries in hover[10,13] and forward flight.[22] The approach is prone to the same difficulties as planar light sheet visualization. Also, the relatively larger seed particles used with this technique, such as obtained by burning a glycol mixture, rapidly diffuse out from the vortex cores with increasing wake age, making the individual vortices much less identifiable in the far wake. For detailed quantitative measurements, such as using LDV, the ejection of seed particles out of the blade tip must be approached with caution to avoid the introduction of artificial velocities or turbulence into the vortex core.

Whereas the application of smoke visualization techniques has had good success when applied to subscale models, experiments on full-scale rotors are more rare. However, the method has been successfully used to visualize part of the wake of a tandem rotor helicopter.[44,45] In Ref. 46 measurements of the vertical and horizontal locations of the tip vortices were made at the longitudinal centerline of a coaxial rotor. Note that for a coaxial rotor, the vortical wake from the upper rotor is ingested by the lower rotor thereby creating locations with powerful BVIs. Once again, however, a limitation of smoke flow is that after the wake from the upper rotor has been ingested by the lower rotor, the smoke particles are quickly dispersed, and the positions of the tip vortices are harder to discern. Nevertheless, such wake data, albeit limited, are very valuable for the purposes of validating free-vortex predictions of rotor wakes.[47]

*Density Gradient Methods*

Strobed shadowgraphy and schlieren have been used very successfully to visualize and understand the vortex dynamics of rotor wakes. Because the refractive index of air is directly proportional to its density, planes with density variations in the flowfield cause incident light rays normal to these planes to be refracted. The angular deflection of the light rays is a measure of the first derivative of density with respect to distance, i.e., a schlieren effect. If the refractive index also varies in the plane, then this will produce diverging or converging light rays, and if cast onto a projection screen, will result in a shadowgram.

A fundamental requirement for the successful application of density gradient methods such as schlieren or shadowgraphy is that the flow contain significant regions with density inhomogeneities. Unfortunately, this is not always the case with helicopter rotors, unless the rotor tip speeds are close to full scale and the rotor operates at relatively high thrust levels. Early work with shadowgraphy on an aircraft propeller was conducted by Hilton.[48] This work concentrated on the sound pressure waves generated at the blade tip at near sonic tip speeds, but the blade tip vortices were also visible. Tangler[11] has used strobed schlieren with great success to observe the tip vortices and acoustic wave phenomena generated by subscale rotors. Parthasarthy et al.,[33] Norman and Light,[34] Leishman and Bagai,[35] Bagai and Leishman,[36] and Lorber et al.[25] have used strobed shadowgraphy to help understand tip vortex formation, BVIs, and rotor wake/airframe interaction phenomena. By taking advantage of axial symmetry in hover, the tip vortex displacements can be obtained as a function of rotor position.[35,49] Equivalent information can be obtained for the position of the longitudinal wake boundary in forward flight.[36] However, a challenge with the technique is the need to take simultaneous shadowgraph images from two separate directions to define the precise three-dimensional spatial locations of the tip vortex cores.

Figure 3 shows a strobed shadowgraph, where the rotor blade has trailed a typical curved tip vortex filament. This image was captured using a modified wide-field-of-view shadowgraph system incorporating a beam splitter arrangement[50] that allows on-axis viewing and that maximizes the efficiency of the retroreflective projection screen.[51] The angle of view at the extreme right of the image is almost parallel to the vortex axis, where a dark circular nucleus can be seen in the center of the vortex. This nucleus is surrounded by a very bright and almost circular ring or halo. It will be seen that similar

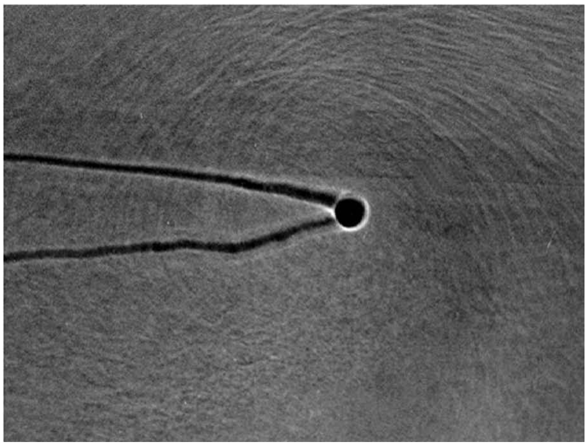


**Fig. 3 Shadowgraph of a rotor tip vortex detailing the core region.**

dark and bright regions are also observed for parts of the vortex that are trailed at an angle to the direction of the light rays; however, the contrast is weaker here because of a shorter light path through the density variation. Outside this region, the various striations indicate significant bands of turbulence and flow entrainment surrounding the vortex core.

It is possible to extract some additional information about the vortex structure from schlieren or shadowgraph images. The dimensions of the dark nucleus seen in the shadowgraphic image can, under justifiable assumptions, be related to the flow density and tangential velocity.[33,34,52] Bagai and Leishman[52] have shown that such schlieren and shadowgraphic effects obtained with tip vortices can be computed analytically. If an algebraic form of the velocity field is assumed along with isentropic flow, this can be used to find the first two density derivatives. Therefore, one can obtain an exact solution for the schlieren effect or the shadowgraphic contrast and so determine its relationship to the velocity field. Generally, it is found that the dimensions of the peak brightness (halo) or minimum (dark nucleus) in the contrast profile do not equate to the peak peripheral velocity (or viscous core radius) of the vortex.

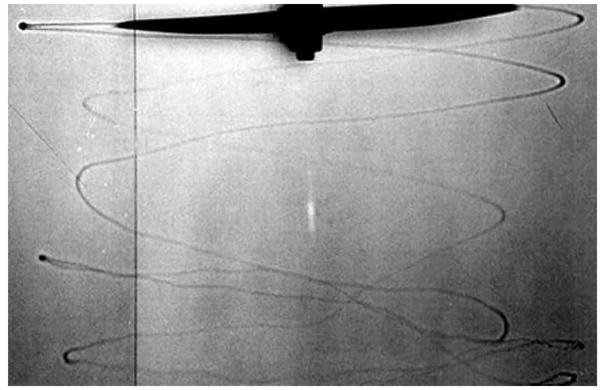
*Natural Condensation*

Natural condensation of water vapor inside vortices also produces clear evidence of rotor wakes.[27,53,54] The results often appear similar to smoke visualization, with characteristic tubular vortex trails with large voids being formed. However, in this case the physics of formation are quite different because the visibility is rendered by thermodynamic means and the two-phase nature of the fluid.[54,55] Whereas condensation flow visualization has been achieved in the environs of a wind-tunnel (unpublished photographs from model tests performed in the 20 × 20 ft tunnel at Boeing Helicopters, Philadelphia, Pennsylvania, in 1974), it is usually only outdoors that the correct combination of atmospheric conditions exists, that is, when the air temperature and dew-point spread is small. These conditions tend to exist in the early morning or just before sunset. Even then, however, a challenge is to have the right lighting conditions and background contrast to give a good photographic exposure.

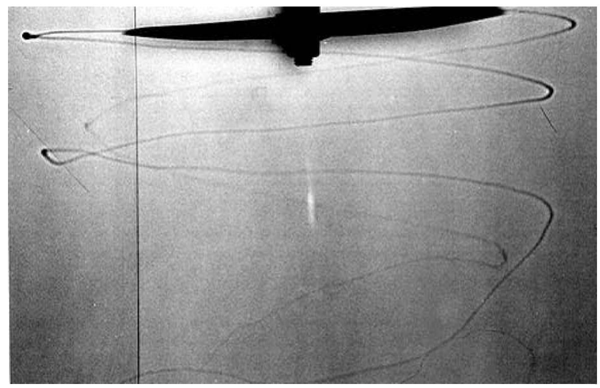
A good example of vortex condensation trails generated by a helicopter rotor is shown in Fig. 4. These trails were visible for nearly two complete rotor revolutions, which gives some idea as to the persistence of rotor blade vortices, in general. Note that the vapor trails acquire a tubular rather than a solid cylindrical structure. This is because both centripetal accelerations on the vapor particles and the thermodynamic behavior of the fluid manifest as voids similar to the effect on smoke particles. Therefore, for reasons similar to smoke visualization, the resulting void in the vapor trail cannot be equated to the viscous core radius. Other vortex dynamic phenomena that were visually observed during the flight shown in Fig. 4 included main rotor/tail rotor wake interactions and rotor wake/airframe interactions.

It appears that natural condensation has not yet been used as a tool to obtain quantitative measurements of the tip vortex locations.

**Fig. 4 Natural condensation inside the tip vortices generated by a hovering helicopter.**



**a) Regular state**



**b) Chaotic state**

**Fig. 5 Bistable vortex wake system obtained with a two-bladed propeller operating under static thrust conditions.**

Yet this might be an area that may prove fruitful in understanding some of the more complex dynamics of the rotor wake that are difficult to simulate in tests with subscale rotors. Examples may include studying the rotor wake dynamics under maneuvering flight conditions, which are known to be difficult to predict despite their importance in determining the handling qualities of the helicopter,[56] or understanding the complex problems associated with main rotor/tail rotor/empennage interactions.[6,7]

**Periodicity of Rotor Wakes**

Because the flow properties at a point vary with blade position even in hover, quantitative measurements of the velocity field must be properly phase resolved. In most cases this also requires that the flow be periodic at the rotor frequency. Unfortunately, this behavior cannot always be guaranteed, and under certain conditions the spatial locations of the tip vortices may vary quite significantly in an aperiodic manner. If this occurs to any significant degree, measurement statistics that require periodicity will become biased. In fixed-wing terminology, this phenomenon is referred to as vortex wandering or meandering. Wandering can be defined as a random movement of the vortex core transverse to its axis about a mean position. For a fixed-measurement location, the phenomenon essentially averages the flowfield properties at that point. Significant wandering, therefore, can obscure important details of the flow and can provide misleading results.[57]

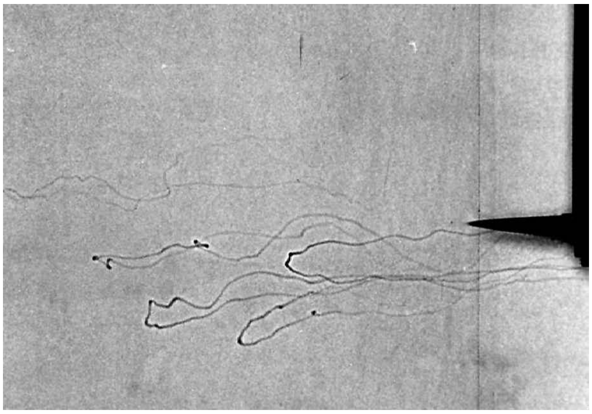
For helicopter rotors, wandering can be viewed as the aperiodic deviations of the tip vortex locations with respect to a reference blade azimuth position.[58] Under ideal circumstances, the curved tip vortices generated by each blade follow smooth curved helical or epicyclical paths, and their spatial locations relative to the rotor are periodic at the rotor rotational frequency. Therefore, measurements of the tip vortex flow properties made with a fixed hot-wire probe or with LDV can, at least in theory, be conducted if the measurements are properly phase resolved with respect to blade position. As in the case of wandering, however, if any aperiodicity of the rotor wake occurs above some acceptable amplitude threshold, then the flow velocity measurements may be substantially in error.

For rotors the available evidence suggests that wake aperiodicity is a characteristic that is, in part, related to the nature of the rotor operating state. For example, measurements of the tip vortex locations in hover that are reconstructed on the basis of a series of still images of the wake at different rotor positions (wake ages) may take the appearance of significant scatter or two possible geometries. Such a behavior can be traced to aperiodic flow effects and has been observed in several experiments including those in Refs. 36, 49, and 58. Yet most of the available experimental evidence with rotors shows that aperiodicity is pronounced only at older wake ages (older than one complete rotor revolution), at low thrust coefficients (where the slipstream convection velocities are low and the tip vortices remain close to the rotor plane), or after the first blade passage. At a minimum, appropriate allowance can be made when quoting the measurement uncertainties[58] and when comparing with computations. However, from an experimental perspective, the challenge is to understand whether aperiodicity is always an inherent physical characteristic of rotor wakes or if contributions also arise from small external flow disturbances or flow recirculation in the test facility.

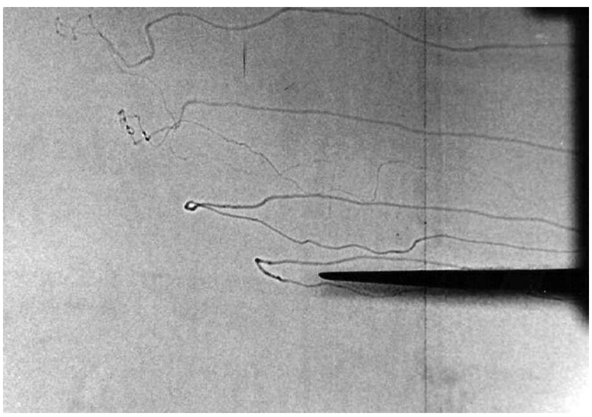
More dramatic examples of wake aperiodicity have also been observed with rotors, particularly with highly loaded rotors such as tilt rotors or aircraft propellers.[59] Figure 5 shows an example of this, where the wake of a two-bladed propeller was rendered visible by means of shadowgraphy. In this case, the vortex wake was found to alternate between two quasistable flow states and with a very slow but regular period of about 0.025 per revolution. In one quasistable state, the tip vortices formed a series of reasonably regular helical trajectories. In the other state, there was considerably more chaos and pairing of the vortex filaments in the far wake. This type of result reinforces the need to make careful flow visualization experiments to confirm the physical nature of any rotor flow before embarking on a program of quantitative measurements.

Descending flight is included among other rotor operating conditions that produce mostly aperiodic wakes. In axial flight, the flow through a rotor is characterized by three basic working states as determined by the relationship of the average rotor-induced velocity to the axial velocity of the rotor.[60] Both the normal working state and the windmill brake states are normally smooth and exhibit almost completely periodic flows. Between these states, such as during mild rates of descent, the rotor can operate in a more complex regime known as the vortex ring state. Here, the rotor can experience highly unsteady flow and large amounts of blade flapping. These flow states appear to have been first visualized by Lock et al.[61] and were later confirmed by Drees and Hendal.[62]

Figure 6 shows strobed shadowgraphs of the vortex wake recorded for a rotor in axial flight at various descent velocities.[59] For low rates of descent, the tip vortex filaments remained closer to the plane of the rotor than for the hover case, but were also convected radially outward away from the rotor. At slightly higher descent rates, the tip vortices remained almost in the plane of the rotor, and considerable aperiodicity was apparent. This can be seen in the shadowgraphs by the considerable distortion to the tip vortices and by the lack of

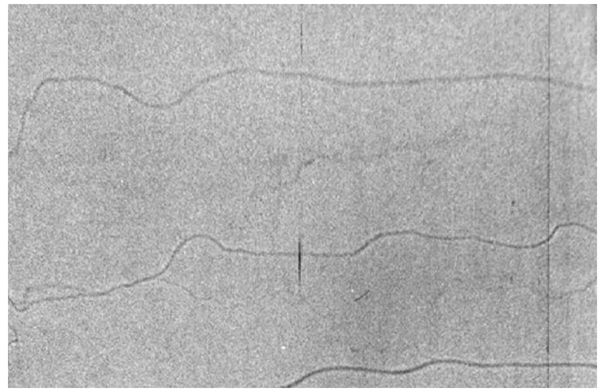


**a) Vortex ring state**

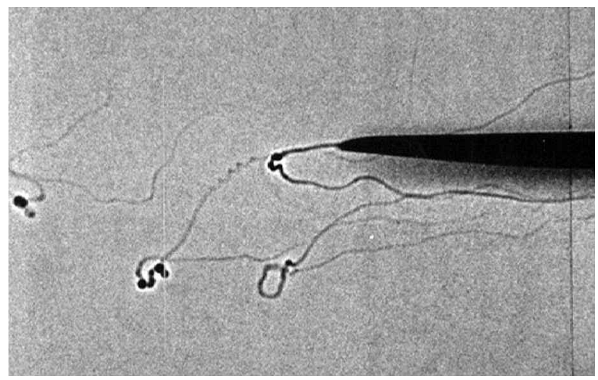


**b) Approaching windmill brake state**

**Fig. 6 Sample shadowgraphs of rotor wake under axial descent conditions; external flow from bottom to top of page.**



**a) Smooth sinuous type**



**b) Helical or corkscrew type**

**Fig. 7 Typical types of tip vortex perturbations observed in the wake of a rotor.**

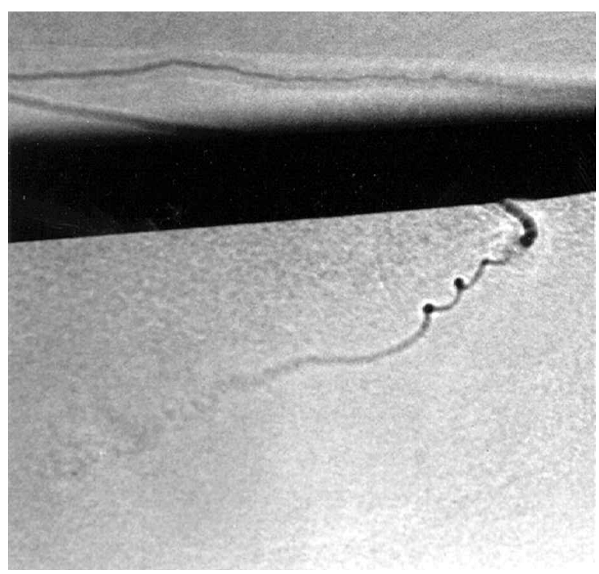


**Fig. 8 Formation of a helical type of tip vortex perturbation after the first blade passage followed by vortex bursting.**

any distinct slipstream boundary. This is consistent with the flight conditions known to cause the vortex-ring state.[60] By increasing the descent velocity further, the wake was observed to develop a more definite slipstream boundary that expanded downstream of (above) the rotor, as is typical of the windmill brake state. When in this state, the tip vortex structure was found to return to a more regular periodic and helical structure.

### Vortex Perturbations

Several types of vortex perturbations and instabilities have been observed in rotor wakes, and some of these can be seen in the descending flight images shown earlier. One common type of perturbation is of the smooth sinuous wave type observed by Sullivan[10] and analyzed theoretically by Widnall[63] and Gupta and Loewy.[64] An example is shown in Fig. 7a. These wave types of perturbations are usually neutrally stable, but become quite pronounced in amplitude at older wake ages. Based on various experimental observations, the onset of these disturbances seems to be affected by the number of blades, rotor thrust, and operating conditions.[11,59] Again, because this phenomenon results in an aperiodic behavior of the wake, albeit locally, it causes considerable challenges if quantitative measurements of the tip vortex properties are an objective. Forward flight experiments with helicopter rotors in wind tunnels have shown that the tip vortices in the rotor wake appear much more periodic,[35] suggesting that this kind of testing may be a better option for baseline measurements of the tip vortex properties.

Another type of perturbation sometimes found in rotor wakes is referred to as the short-wave corkscrew or helical type, with an example shown in Fig. 7b. Here, the vortex filament tightly twists around on itself forming a very pronounced helix. These perturbations appear to be quite common in the wakes of highly loaded propellers or tilt rotors[34] rather than helicopter rotors, but they have been observed in both. In some cases, the disturbance travels quickly down the vortex filament. In other cases, it is damped out, and the vortex returns to its regular (undistorted) form. Depending on the sign of the helical pitch, the disturbance may cause the vortex to become unstable, and it may breakdown or burst. An example of this latter phenomenon is shown in Fig. 8, where the vortex bursting originates from the formation of a helical disturbance downstream of the blade. Further details on the known parameters that affect vortex bursting are summarized by Hall.[65]

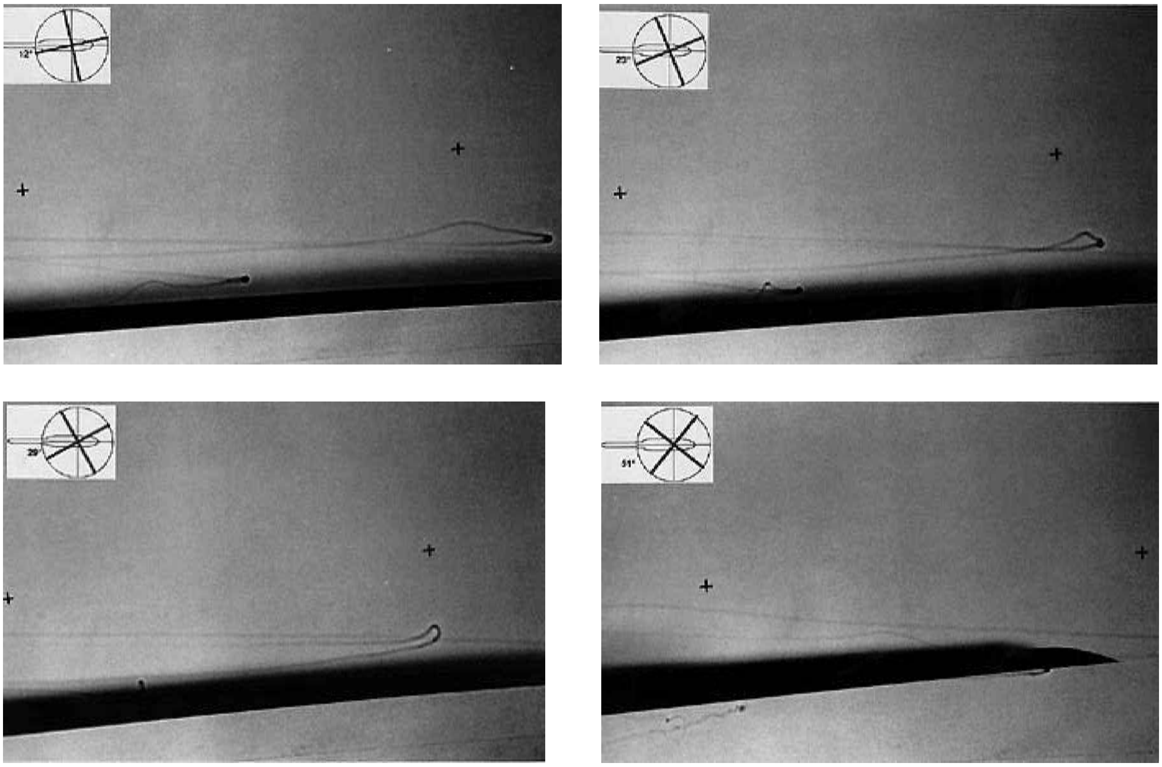



**Fig. 9 Shadowgraphs showing perpendicular blade/vortex interactions at various blade azimuth angles over the front of the rotor disk in low-speed forward flight.**

**Blade/Vortex Interactions**

The interactions of tip vortices with rotor blades can occur at many different locations and orientations over the rotor disk. BVI is known to produce locally high airloads and can be a significant source of obtrusive noise, particularly if it occurs on the advancing side of the rotor disk, where the blade and vortex axes can be nearly parallel to each other. The other type of BVI occurs when the blade and vortex axes are almost perpendicular. Whereas the former tends to produce the largest unsteady airloads and high-frequency noise generation, the latter tends to result in more highly three-dimensional airloads and broadband noise. In addition, BVIs are liable to occur on multirotor configurations comprising two or more overlapping rotors such as tandems or coaxial systems. For such helicopters, the wake from one rotor may be partially or completely ingested by the other rotor, enhancing the possibility of BVI.

Figure 9 shows a sequence of shadowgraph images that detail the blades encountering a perpendicular type of BVI over the leading edge of the rotor disk during low-speed forward flight. It can be seen that as the older wake vortices move downstream (to the left) they move up and over the top of the following blades. A wavelike disturbance is produced on the older vortices as following blades pass underneath. After the blade passes, the tip vortex usually returns to its original undisturbed shape. This suggests that the orientations of the vortex filaments to each other produce weak interactions compared to that found in the hover state, where vortex pairing and susceptibility to aperiodicity tends to be more evident. For progressively greater wake ages, the wake was convected farther downstream and downward through the tip-path plane, and the blade intersected and cut the vortex filament. In some cases it has been noted that perpendicular BVI leads to the development of a helical type of vortex instability and/or vortex bursting and, therefore, an increase in the effective diffusion rate of the tip vortex.

Despite its importance to helicopter noise and vibration, clear experimental studies of the parallel BVI problem are very rare. Good, albeit idealized, quantitative measurements of BVIs and collisions are described in Refs. 66–68. Contributions to visualizing the problem have been achieved with the use of smoke[23,25] and strobed shadowgraphy.[37] However, much further work needs to be done to visualize and to measure its effects to fully understand the parallel BVI problem, especially with elastic rotors. The complexity of this problem cannot be underestimated, and the further understanding of BVI poses many challenges to the experimentalist.

**Vortex/Surface Interaction Phenomena**

In practice, the problem of understanding the vortical wake structure generated by the helicopter rotor is rather more complicated because of the effects of the airframe. Studies of simplified vortex/surface interactions[69,70] have revealed much insight into the physics, and many of the results are directly applicable to an improved understanding of the real problems found on rotorcraft. Interactional problems are significant for helicopters and tilt rotors alike, and these vary in location and intensity as a function of flight condition. The interactions range from almost benign glancing type interactions with the airframe or empennage surfaces to direct impingement and associated large-scale reorganization of the flow structure. However, even though the encounter may vary in terms of its severity, in almost all cases the vortices induce large unsteady airloads on the airframe surface.[7,71–73] This can be a source of significant airframe vibrations and buffeting problems. In addition, the airframe or empennage surfaces can alter the tip vortex trajectories,[7,35] which can lead to a change in the induced velocity field and can influence the distribution of loads over the rotor disk.[4]

Figure 10 shows a shadowgraph visualization of the tip vortices at the rear the rotor wake in low-speed forward flight. The freestream is from right to left. The airframe in this case was a simple body of revolution that had a constant circular cross section in the region where the vortex/surface interactions occured.[5,35] The results showed both large-scale and local deformations to the rotor wake. At a local level, it was found that as the vortex filaments came close to the body surface they began to convect downstream more quickly under the influence of the surface, and the tip vortices traveled parallel to the airframe surface. This resulted in the formation of a loop or hairpin vortex structure over the airframe. Although a complex problem in vortex dynamics, these vortex/surface interactions seem to have been fairly successfully modeled by numerical means.[73,74] The main impact of an improved understanding of rotor/airframe

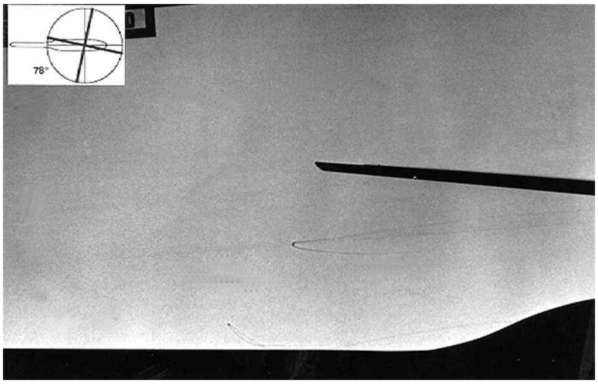
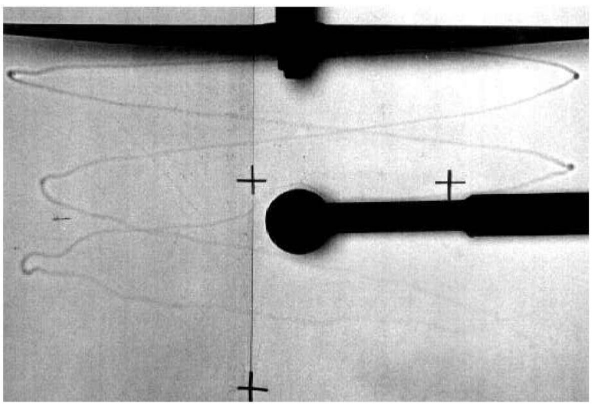
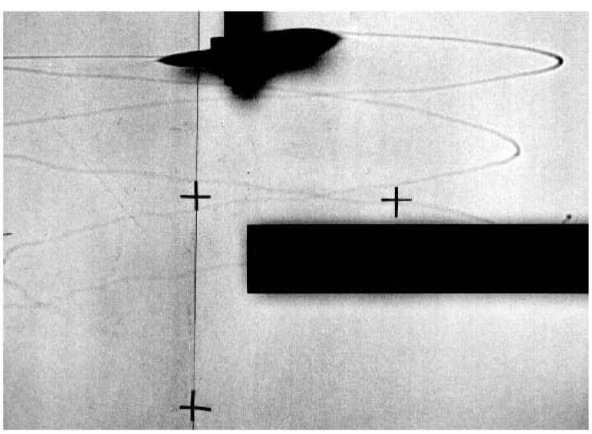



**Fig. 10 Shadowgraph showing the interaction of the rotor tip vortices with the tailboom of a helicopter fuselage in low-speed forward flight.**



**a) View along longitudinal axis of body; note vortex stretching**



**b) Side view of process**

**Fig. 11 Shadowgraph of rotor tip vortex/body interaction.**

interactions is toward successfully predicting the effects on rotor blade airloads and performance as a result of the distortion to the rotor wake structure.

From an experimental perspective, it is extremely challenging to study vortex/surface interaction problems in a wind tunnel because lack of optical access limits multiple viewing directions.[25] Figure 11 shows shadowgraphs that document the tip vortices in the wake of a hovering rotor as they interact with a circular body.[59] The horizontal image in Fig. 11a is the shadow of the support, and this is outside of the immediate flowfield. As described before, as the vortex approaches the top of the body a loop or hairpin type of deformation is formed. Images viewed along the longitudinal axis of the body showed the vortex filament to be stretched around the circular contour of the body. As the wake was convected farther and the vortex filament became significantly strained, two ends of the vortex filament, one on each side of the body, could be seen to quickly diffuse. This process was particularly vivid when recorded on video. A schematic detailing the full dynamics of the vortex/body interaction process is shown in Ref. 59.

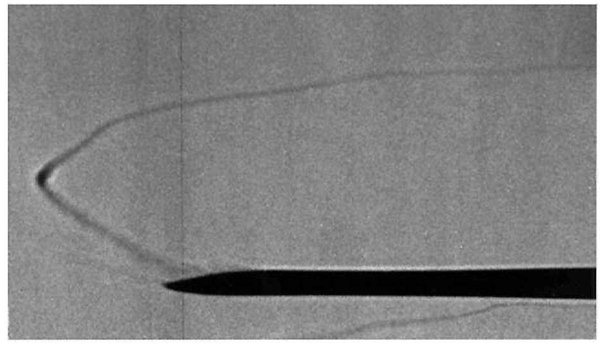


**Fig. 12 Shadowgraph of tip vortex formation on a rectangular blade tip.**

### Tip Vortex Formation

The rollup of the tip vortex defines the initial conditions for the subsequent behavior of the rotor wake and also defines the conditions for BVI. Tip vortex formation is a complex problem involving high velocities with shear, flow separation, pressure equalization, and turbulence production. Because rotor blades have very large-pressure differences concentrated over the tip regions, the resulting tip vortices are intense with high-swirl velocities and small-viscous cores. The effect of the tip shape is known to affect the strength and location of the tip vortex trailed into the wake.[22,75] For some tips, multiple vortices may be produced, although one of these is usually stronger and tends to dominate the flow. Depending on the sign of the other vortex, it may roll up into the primary vortex or may convect through the wake with the primary vortex as a parallel pair.

On rectangular or mildly tapered blade tips, the vortex is known to form immediately at the blade tip, e.g., Fig. 12. This strobed shadowgraph shows the entire tip region to be enveloped in a turbulent vortical flow, but immediately behind the blade the vorticity rolls up into a single vortex. Depending on the angle of view, these types of images sometimes show other density gradients near the tip, such as turbulence and acoustic waves.[48] The tip vortex location and overall flow structure behind the blade is, however, difficult to predict with existing models. Based on classical Betz-type centroid of vorticity approaches,[76] as used in some rotor analyses, the predicted vortex release locations always tend to appear radially much farther inward toward the hub than is observed in practice. Recent work by Rule and Bliss[77] has reinforced the complexity of the problem. Modern finite difference methods[9] have achieved greater success in predicting the point of origination, but numerical diffusion tends to produce significant errors in the subsequent vortex behavior. A challenge in the future is to fully correlate numerical predictions with experimental measurements of the tip vortex structure and its location behind the blade.

### Velocity Field

Proper quantification of the tip vortex strength, viscous core radius, and induced velocity field and how these properties change as the vortex ages pose considerable challenges to the experimentalist. The accurate determination of these properties has important consequences in terms of predicting many rotor problems, including phenomena such as BVI and vortex/surface interactions. The vortex core size is approximately inversely proportional to the peak tangential (swirl) velocities in the vortex, and so the intensity of these interactional phenomena is, in part, related to an understanding and prediction of viscous diffusion, turbulence production, and dissipation. Most engineering models used for rotor loads, performance, and acoustics tend to have simple empirical or semiempirical representations of these important physical effects based mostly on experimental data from fixed-wing experiments. However, because of the close blade/vortex proximities and powerful mutual interactions between rotor tip vortices, there is little reason to expect that the evolutionary trends of helicopter vortices can be simply extrapolated from fixed-wing studies.

There have been several experiments conducted to quantify the overall magnitude and distribution of the induced velocity field inside the wake generated by helicopter rotors. Various experimental techniques used include multihole pressure probes,[18,78] HWA,[79,80] and LDV.[81,82] Whereas global measurements are useful, obtaining flow details inside the tip vortices is much more difficult. Details of the rotor tip vortex structure have been attempted using hot-wire anemometry (HWA),[82–86] LDV,[81,87–92] and, to a more limited extent, PIV.[91] An advantage of LDV (or PIV) is that it is nonintrusive, so unlike a probe it will not disturb the flow and alter the evolutionary physics of the vortex. Also, whereas the turbulent structure of tip vortices has been examined for fixed-wings using LDV,[93] there is a dearth of corresponding measurements for rotating wings.

In recent work by Leishman et al.,[88] Han et al.,[92] McAlister et al.,[89] and McAlister,[90] temporal phase-resolved measurements have been made using three-component LDV to determine the tangential and axial velocity fields, as well as turbulence structure surrounding convecting rotor tip vortices. Such measurements are difficult and time consuming partly because of the unsteady periodic nature of the problem that requires the measurements to be performed in a fully phase-resolved sense. In addition, as already mentioned, the high rotational velocities found in rotor tip vortices make the entrainment of seed particles relatively difficult. Nevertheless, LDV offers one of the best available techniques of quantifying detailed evolutionary trends of the tip vortices generated by rotors.

Typical results from Ref. 88 are shown in Fig. 13 for several wake ages ($\zeta$), where the phase-resolved tangential component of velocity has been nondimensionalized by the rotor tip speed and the distance from the rotational axis is nondimensionalized by the rotor radius $R$. In this experiment, it was found possible to track the tip vortex for about two rotor revolutions. For increasing $\zeta$, the tip vortex was convected downward below the rotor and radially inward, so that the velocity signatures move to the left of the graph shown in Fig. 13. Note that the results presented in Fig. 13 show that tangential velocity signatures are significantly asymmetric and the larger velocities are biased toward the slipstream (inner) side of the rotor wake. This is because the vortices lie at the edge of a jetlike boundary, and so they convect in a nonuniform flow. One further cause of the asymmetry is the curved helical nature of the tip vortex that produces a self-induced effect.

The results shown in Fig. 13 are significant in that, in addition to viscous diffusion, they also show that the measurements made just after the first blade passage ($\zeta = 360$ deg for the one-bladed rotor and $\zeta = 180$ deg for the two-bladed rotor) indicate an apparent increase in peak tangential velocity and decrease in core diameter. To understand why, it is significant to note that the blade passage produces two important effects. First, there is an increase in the axial settling rate of the wake in hover because of the downwash produced by the blade. Second, there is an additional increment to the axial settling because of the introduction of another turn in the vortex spiral. In the latter case, the older tip vortices lie below and radially inward of this new turn in the vortex spiral, so that they are subjected to an axial increment in slipstream velocity. This effect is more pronounced for the vortices at the first blade passage, although the effects have also been noted in Ref. 36 for the second and third blade passages. Therefore, these steep velocity gradients associated with a blade passage produce three-dimensional vortex stretching, thereby inducing vorticity intensification.[94] It is likely that a similar phenomenon occurs during forward flight. Although poorly documented, some encouraging progress on this problem using LDV is reported by Berenger et al.[82]

*Vortex Core Size*

Physically, the average core size of the tip vortex generated by helicopter rotors has been measured to be of the order of the blade thickness, which is typically 10–15% of mean blade chord. On a multibladed rotor, the tip vortices generated by each individual blade interact with each other, and substantial modifications to the growth of the tip vortices may occur. This behavior will be a complex function of each individual rotor and its operating state. A simple quantitative estimate of the growth in core radius with time can be based on the Lamb[95] result for laminar flows, which shows that without external velocity gradients the core radius varies with the square-root of age.[96,97] In practice, the actual diffusion of vortices is known to be much quicker because of turbulence generation. These effects can be incorporated into a model growth equation using an average turbulent viscosity coefficient (see Ref. 97 or 98). This coefficient is not known a priori and must be estimated from vortex core structure measurements. In addition, because it is known that the vortex is already in some stage of decay immediately after its formation,[99] the growth curve can be originated at a virtual time.

The measured growth of the vortex core with wake age ($\zeta$) for hovering one- and two-bladed rotors[88] is shown in Fig. 14. The results are presented as a fraction of the blade chord $c$. Note that the initial core growth is rapid, and seems to follow a Lamb-like logarithmic result. Although vortex core growth measurements from rotors are rare, the logarithmic trend shown appears consistent with the work of Sullivan[10] and Thomson et al.[100] In these latter cases, the core was estimated from the size of the particle void. Whereas this does not give the correct quantitative size of the viscous core, an analysis of the seed particle dynamics shows that the void growth trends mimic the actual core growth. What is apparent from these results, however, is that there is a fairly rapid but asymptotic-like growth in the core, at least up to the first blade passage. It is acknowledged that these trends may well be different for full-scale rotors, which will have blade and vortex Reynolds numbers that are at least one order of magnitude greater than for the data presented

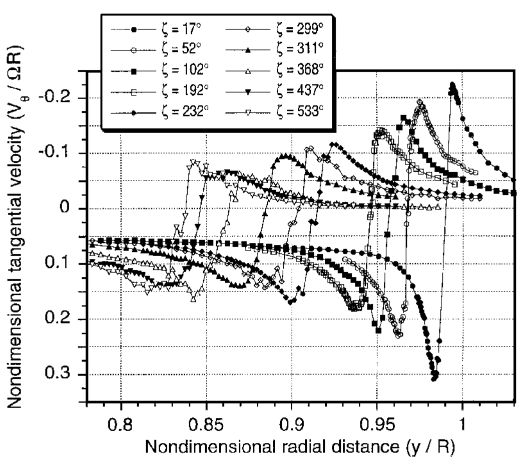



**Fig. 13 Phase-resolved tangential velocities in the tip vortex as measured at different wake ages after generation.**

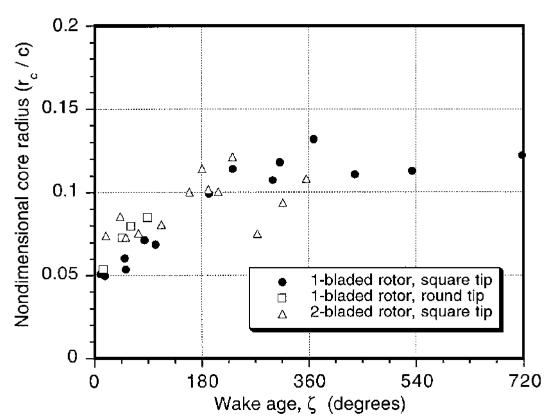



**Fig. 14 Estimated growth in the tip vortex core with wake age for one- and two-bladed hovering rotors.**

here. In addition, on multibladed rotors the presence of other tip vortices and the closeness of following blades to the tip vortex trailed from a previous blade mean that the viscous diffusion process may be extremely complicated. Such issues are currently poorly understood and pose many challenges to the experimentalist to obtain measurements at full-scale blade and vortex Reynolds numbers.

*Turbulence in the Tip Vortex*

The rate of development of the vortex turbulent structure will alter diffusive and dissipative features of the vortex.[101] This, in turn, will affect the intensity of problems, such as BVI, and also the physics of the vortex flow after BVI, i.e., whether the vortex remains coherent, develops waves or instabilities, or bursts. Whereas the turbulence structure of a tip vortex has been measured for fixed wings,[57,93] there is a dearth of corresponding measurements for rotating wings, especially using LDV. This is partly because of the need to acquire very large numbers of statistically valid samples to allow satisfactory phase averaging. In addition, there is a need to ensure flow periodicity to avoid biasing the statistics. It can be expected that the tip vortex initially exhibits a laminar behavior. This will be accompanied by a maximum in kinetic energy, and thereafter the vortex progressively becomes turbulent. The timescales over which this degeneration to turbulence occurs are related to the vortex Reynolds number, among other factors. The vortex is known to become enveloped by a mixing layer that transfers the turbulent kinetic energy contained in the vortex core into smaller eddies downstream. In these smaller eddies, the turbulent kinetic energy is ultimately dissipated by viscosity.[102]

In Ref. 92, the tangential, radial, and axial turbulence components were measured inside a rotor tip vortex using LDV. At early wake ages, distinct double peaks were observed in all three turbulence components inside the vortex core radius. This confirms that turbulence is generated mostly by shear just inside the core. The turbulence is then diffused radially outward. The radial component of turbulence was measured to be the most dominant. Within the assumptions of incompressible quasisteady flow and by comparisons of orders of magnitude, the equation for turbulence production can be derived. The resultant sign changes in the production equation can be deduced from the signs of both Reynolds' shear stress and the gradient of mean velocity inside the tip vortex. Because the tip vortex has a substantial tangential velocity gradient at the core boundary, it must produce most of the turbulence inside the vortex core. Substantial amounts of turbulent kinetic energy (TKE) are also produced near the edge of the viscous region just outside the core region. Although LDV statistics are hard to acquire inside the vortex core because of seeding difficulties, the TKE production has been found to quickly decrease with increasing wake age. This confirms that the mean velocity field creates significant turbulence at the earliest wake age, and diffusive action follows rather quickly within half a rotor revolution. Clearly, however, further work must be undertaken to more fully understand the turbulent diffusive and dissipative behavior of the blade tip vortices.

## Concluding Remarks

The examples discussed illustrate some of the complex problems in forming a more complete understanding of the vortex dynamics of helicopter rotor wakes. Although the deeper understanding of these problems poses many challenges to the experimentalist, considerable progress has been made in many areas over the past decade. Problems such as tip vortex formation, BVI, and rotor/airframe interference are better understood, and recent systematic experimental measurements have provided significant amounts of data that will help validate numerical predictions of the various phenomena. The fruits of some of this research are already fostering new ideas for rotor design, particularly using active control, that will have an impact on new helicopter designs well into the next century. However, one of the biggest challenges still remaining in rotor analysis is to reveal more completely the intricate structure of the blade tip vortices. This research may result in new ideas for tip vortex control and the alleviation of several of the complex problems involving vortex dynamics that hinder the development of quieter helicopters with better performance and lower vibrations.

## Acknowledgments

Some of the work reported in this paper was supported by the U.S. Army Research Office under the Rotorcraft Centers of Excellence Program during the period 1988–1995. Thomas Doligalski was the Technical Monitor. Other support has been provided by the Minta Martin Fund for Aeronautical Research, NASA Ames Research Center, and Boeing Helicopters. The contributions of Nai-pei Bi, Erwin Moedersheim, Mark Daghir, Alan Coyne and Andrew Baker to the results reported in this paper are much appreciated. Figure 4 is by courtesy of Rotary Wing Aircraft Test Directorate, U.S. Naval Air Warfare Center, Patuxent River, Maryland. A short videotape documenting many of the vortex dynamic phenomena discussed in this paper is available from the authors on request.

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