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Fundamental Study of Flow Field Generated by Rotorcraft Blades Using Wide-Field Shadowgraph

S. P. Parthasarathy
Y. I. Cho
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October 1, 1985

NASA
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
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Abstract

The vortex trajectory and vortex wake generated by helicopter rotors were visualized using a wide-field shadowgraph technique. Use of a retro-reflective Scotchlite screen made it possible to investigate the flow field generated by full-scale rotors. Tip vortex trajectories were visible in shadowgraphs for a range of tip Mach number of 0.38 - 0.60. The effect of the angle of attack was substantial. At an angle of attack greater than 8 degrees, the visibility of the vortex core was significant even at relatively low tip Mach numbers. The theoretical analysis of the sensitivity was carried out for a rotating blade. This analysis demonstrated that the sensitivity decreases with increasing dimensionless core radius and increases with increasing tip Mach number. The threshold value of the sensitivity was found to be 0.0015, below which the vortex core is not visible and above which it is visible. The effect of the optical path length was also discussed. Based on this investigation, it is concluded that the application of this wide-field shadowgraph technique to a large wind tunnel test should be feasible. In addition, two simultaneous shadowgraph views would allow three-dimensional reconstruction of vortex trajectories.
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is visible.
1. **INTRODUCTION**

The objective of the task was to visualize the helicopter rotor wake to determine the geometry and structure of the tip vortices using the wide-field shadowgraphy technique. The vortices should be observed for several blade passages above the rotor which is thrusting downward in the present case. An important condition in the design of the experiment was to conduct the experiment at nearly full scale (i.e., the distance between the screen and rotor blade should be in the order of 3-9 m) so that the system of measurement could apply to an actual wind tunnel test. Experiments were conducted on a tail rotor, which is considerably smaller than the main rotor, but the distances from light source to screen were kept large enough to be approximately full scale. The largest distance between the axis of the rotor and the screen was 5.4 m.

It was expected that useful shadows would result from the natural density changes in the vortex cores associated with low pressures. The sensitivity of the shadowgraphs which depends on the second derivative of the density field was not known. It was, therefore, necessary to determine the visibility experimentally.

Addition of a fluid with different density was also investigated to determine the characteristics of the resulting shadowgraphs. This was done by using a hot air gun during some of the tests.

2. **BACKGROUND OF FLOW VISUALIZATION TECHNIQUES**

2.1 **Schlieren Technique**

Fluid flows are visualized by many optical techniques, as is well known. Of these, Schlieren photography is practically restricted to a field of view of about 50 cm because of the necessity of using high quality mirrors in the technique. Interferometry which senses the density field is very delicate and has the same field of view limitation.

Schlieren photography has been used to visualize the tip vortex flow by Tangler\(^{(1)}\) using a small scale setup. The rotors were about 1 ft radius. The wake of each blade can be seen for approximately one revolution of the blade before it vanishes by diffusive interaction. Kokurek and Tangler\(^{(2)}\) developed an improved wake representation from small scale Schlieren studies.

Moiré Schlieren can be used for large field flow visualization but the method is more complicated than simple shadowgraphy.

2.2 **Shadowgraphy Technique**

Shadowgraphy is the simplest optical technique. Here, second derivatives of density are sensed as light variations on the screen. When a point source illuminates a large screen, density changes in the test section between the light source and the screen cause shadows to be cast on the screen. This shadow can be seen directly or can be photographed by a camera provided there is enough light to produce a good exposure. Usually, light is insufficient for a good exposure if the screens are ordinary, white surfaces.
However, when the screens are treated with retroreflecting Scotchlite (a 3M product), the light gathered by a camera placed as close as possible to the point source of light is sufficient for a good exposure. A stroboscope is generally used to freeze the motion during the time the camera shutter is open.

Shadowgraphy reveals naturally occurring density changes in the flow as well as those changes induced by deliberate introduction of tracers of different densities such as hot air, carbon dioxide gas, etc. In the present application, tip vortices from rotors cause enough density changes to be visible without the introduction of tracers. However, tracers can be used to examine the flow field in regions where there are no naturally occurring density changes.

2.3 Use of Smoke

In addition to the optical technique, introduction of dense smoke into the flow field is a method that has been used to examine the position of tip vortices and the location of vortex sheets which reveal their presence by the discontinuity in smoke streaks. Many photographs using this method are given in the report by Landgrebe. They reveal the shadow all along the vortex core because there is no need for a tracer. If two views of the same field are taken simultaneously, it should be possible to obtain accurately the coordinates of the spiralling tip vortex as a function of time with no assumptions on the nature of the flow field and with no disturbance to the flow.

3. EXPERIMENTAL FACILITY

3.1 Rotor Blade Assembly

To simulate flow fields generated by rotocraft blades, a tail rotor together with the gear box (Hughes Model 300) was obtained through the Sheriff’s Department, County of Los Angeles. The symmetric blade was rectangular with chord length of 0.12 m (NACA airfoil 0015). The distance from the center of rotation to the blade tip was 0.65 m. The designed-operating speed of this rotor was 2900–3100 rpm with a torque of 269 N-m. At 3100 rpm, the blade tip speed was found to be 210 m/s (i.e., Mach number 0.61) and the required electric motor power was 18.6 Hp. The schematic
diagram of the rotor blade assembly is shown in Fig. 1, including the tail rotor (2-blades), gear box, pitch angle controller, variable pulley and sheaves, 20 Hp motor (440V, 25 Amp), adjustable motor base, and reduced voltage starter. A picture of the system is also shown in Fig. 2.

The rotor test assembly was balanced with the Vibrex Track and Balance System made by the Chadwick and Helmuth Company (El Monte, CA). During the balancing test, the maximum operational speed of 3100 rpm was obtained.

3.2 Limitation of the Rotor Blade Assembly

As mentioned earlier, the designed-operating speed of the tail rotor (Hughes Model 300) was 3100 rpm (i.e., Mach number = 0.61). However, to obtain a Mach number of 0.7, the rotor would have to rotate at 3560 rpm, which may be beyond the design limit of this rotor. In addition, tail rotor blades were retired after 3000 flight hours logged by the L. A. County Sheriff's Department. Therefore, from a safety point of view, it was advisable to stay within the designed maximum limit (i.e., 3100 rpm). This limited obtaining a higher Mach number than 0.61 from the rotor blade assembly.

The limitation of keeping the tip Mach number below 0.61 would not be serious if shadowgraphical observations of the tip vortices were possible at the lower Mach numbers. This proved to be the case.

3.3 The Shadowgraph Setup

The setup with camera focused on the shadow on the Scotchlite screen is shown in Fig. 3. Stroboscopic observations were made by driving the strobe lamp from the signal from the photoprobe, thus automatically freezing the rotor blade motion at a fixed location throughout the test. In addition, the use of slip/sinc control in the Strobex System (made by the Chadwick and Helmuth Company) allowed us to observe shadowgraphs from slowly moving rotor blades. The magnetic pickup mounted near the shaft connecting the rotor clutch device to the electric motor measured the shaft rpm which was 2/3 of the rotation speed of the rotor because of the gear ratio used in the device. Scotchlite shadowgraphs were observed at two distances, viz 6.4 m between the rotor and screen and also 4.4 m. The corresponding distances between the light source and screen were 11 m and 7.8 m, respectively. These distances could be expected in applications of this technique when the strobe source is located in a large wind tunnel.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Many Shadowgraphs taken at different rpm and angles of attack are enclosed in the report (Figs. 4-16). The values of the relevant parameters are given in the figure captions. The vortices and the flow field near them, made visible by the use of hot air injection, can be seen and interpreted readily. Note that since the blades are at different rotational locations in the figures, the vortex system extends beyond the instantaneous projections of the blades.
4.1. Visibility

Figure 4 shows the shadowgraph of the rotor at $l = 4.4$ m at 3200 rpm (i.e., $M_T = 0.64$) and at 12° angle of attack. The vortex cores are seen as two thin spirals emanating from the two blade tips. On the right, hot air from a hair dryer circulates around the tip vortex and shows the circulating flow. On the left, only the density gradient occurring naturally in the core makes the vortex visible. At the extreme right and left edges, the shadows are denser because the light rays pass tangentially through the vortices. Three dark spots are visible on the left vertically showing these edges. The vortices are distorted at this condition of high angle of attack and high rpm. Figure 5 shows another phase of the rotor at the same conditions. Distortions are clearly visible on the left. It is worth noting that these shadowgraph pictures give detailed information on the entire vortex trajectory, the vortex core size and the wake around the vortex core, which can provide useful input for the computer modeling of the helicopter rotor performance (3).

Photographs taken from a larger optical path length $l = 6.4$ m are considered next. In Fig. 6 at 1920 rpm (i.e., $M_T = 0.38$) and $\alpha = 4°$, the tip vortex at the right is just visible (or very faint) above the hot air gun. There was no hot air flow from the gun except for a slight convection current from a previous hot run. In Fig. 7, at the same flow conditions as in Fig. 6, the flow near the tip when the hot air flow is on, together with the faint vortex (spot) are seen. In Figs. 8 and 9, the angle of attack is still 4° but the speed is higher viz 2763 rpm (i.e., $M_T = 0.55$). Spiralling vortices are slightly visible and one dark spot is clearly seen just above the heat gun. Therefore, the threshold value of the sensitivity was determined from the test with $\alpha = 4°$ and $M_T = 0.38$, which yielded a just visible tip vortex core as shown in Figs. 6 and 7. Of note is that the sensitivity analysis (see Appendix) resulted in the threshold value of $S = 0.00025$.

At a higher angle of attack $\alpha = 8°$, the spirals are clearer as seen in Fig. 10 with hot air injection at the right. Figs. 11 and 12 at $\alpha = 8°$, 2890 rpm (i.e., $M_T = 0.58$) show the vortices clearly. Distortions in the spirals are also seen. Figs. 13 to 16 are for $\alpha = 14°$. The visibility of these vortices is similar to those at 8°. Of note is that the values of the sensitivity corresponding to the angle of attack $\alpha = 8°, 12°$ and 14° were obviously above the threshold value of $S = 0.00025$. These details are given in the Appendix.

As mentioned earlier, two different beam lengths $l$ (i.e., distance between the rotor and screen) were used. In Figs. 4 and 5, the beam length $l$ was 4.4 m and in Figs. 6 to 16, it was 6.4 m. Although the theory shows that the sensitivity is linearly proportional to the beam length, the contribution of the beam length was not significant in these shadowgraph pictures when $l$ was changed from 4.4 to 5.4 m.

Other photographs not included in this report show similar characteristics. The table shows the experimental conditions with brief comments on the results.
4.2 Experimental Determination of Vortex Core Radius \( r_0 \)

The size of the vortex core was experimentally determined from the shadowgraph picture given in Fig. 5 (i.e., \( \alpha = 12^\circ \) and \( M_t = 0.64 \)). Since the rotor radius is 0.65 m, one can calculate the scale-up factor between the real size and shadowgraph image. This results in a value of the vortex core radius of 7.6 mm for the case shown in Fig. 5. Thus, the ratio of the vortex core radius to the chord \( r_0/c \) is 0.063.

4.3 Experimental Determination of the Axial Velocity in the Wake

Most shadowgraph pictures in Figs. 5 and 6, 10-16 show, typically, three vortex cores (for example, see three dark spots at the left side in Fig. 4). Thus, by knowing the rpm and the distance between two vortex cores, one can calculate the axial velocity due to the hovering motion of rotors. For the case of 3200 rpm and an angle of attack of 12\(^\circ\) in Fig. 4, the axial velocity was calculated to be 20.4 m/s.

Further discussion of experimental data and analysis is given in the Appendix.

5. CONCLUSIONS AND RECOMMENDATIONS

Tip vortex trajectories were visible in shadowgraphs for a range of tip Mach numbers from 0.38 to 0.6. The angles of attack ranged from 4\(^\circ\) to 14\(^\circ\). Visibility improves with speed and angle of attack. The effect of the angle of attack \( \alpha \) was substantial. At an angle of attack greater than 8 degrees, the visibility is significant even at relatively low tip Mach numbers. It can be expected that at higher tip speeds, visibility would be even better. In addition, the size of the vortex core and the axial velocity during the hovering motion could be determined experimentally.

It is therefore concluded that the application of the technique to a large wind tunnel would be successful. Simultaneous, multiple views would be the next step to get three dimensional information on the tip vortices, the vortex core radius and the axial velocity.
ACKNOWLEDGMENT

Mr. John Kendall from the County of Los Angeles, Sheriff's Department provided the rotor and its clutch box, and Mr. J. Chadwick from the Chadwick-Helmuth Company balanced the rotor with his Vibrex Track and Balance System.

The authors also express appreciation to Messrs. J. Godley, B. Green and R. Smither for their contributions in fabrication and assembly of the test facility and to Dr. Ken Harstad for his assistance in the calculation of the sensitivity function.

REFERENCES


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Fig. 1 Schematic diagram of Rotorblade Experimental Setup.
2.4 x 2.4 m SCOTCHLITE SCREEN

Fig. 2 Tail Rotor, electric motor and 2.4 m x 2.4 m Scotchlite Screen Picture
Fig. 3 Sketch of widefield shadowgraph instrumentation.
Fig. 4  Shadowgraph Photograph of the Vortex Structure for the Tail Rotor, 
$M_T = 0.64$, $3200$ rpm, $\alpha = 12^\circ$ $\ell = 4.4$ m with heat, Rotor Tip is facing 
the viewer. Vortex structure is visible.
Fig. 5 Shadowgraph Photograph of the Vortex Structure for the Tail Rotor, $M_T = 0.64$, 3200 rpm, $\alpha = 12^\circ$, $z = 4.4$ m with heat. Rotor is located normal to the viewer. Vortex structure is visible.
Fig. 6  Shadowgraph Photograph of the Vortex Structure for the Tail Rotor,
\[ M_T = 0.38, \text{ 1920 rpm, } \alpha = 4^\circ, \text{ } l = 6.4 \text{ m without heat. Vortex structure is not visible.} \]
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Fig. 8  Shadowgraph Photograph of the Vortex Structure for the Tail Rotor, $M_T = 0.55$, $2763$ rpm, $\alpha = 4^\circ$, $z = 6.4$ m without heat. Vortex structure is not visible.
Fig. 9  Shadowgraph Photograph of the Vortex Structure for the Tail Rotor, $M_T = 0.55$, $2763$ rpm, $\alpha = 4^\circ$, $l = 6.4$ m with heat. Vortex structure is not visible. Vortex structure is visible.
Fig. 10 Shadowgraph Photograph of the Vortex Structure for the Tail Rotor. $M_T = 0.38$, 1910 rpm, $\alpha = 8^\circ$, $z = 6.4$ m with heat. Vortex structure is visible.
Fig. 11 Shadowgraph Photograph of the Vortex Structure for the Tail Rotor, $M_r = 0.58$, 2890 rpm, $\alpha = 8^\circ$, $z = 6.4$ m without heat. Vortex structure is visible.
Fig. 12 Shadowgraph Photograph of the Vortex Structure for the Tail Rotor, \( M_T = 0.58 \), 2890 rpm, \( \alpha = 8^\circ \) \( z = 6.4 \) m with heat. Vortex structure is visible.
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Fig. 14 Shadowgraph Photograph of the Vortex Structure for the Tail Rotor, $M_T = 0.38$, 1908 rpm, $\alpha = 14^\circ$ $L = 6.4$ m with heat. Vortex structure is visible.
Fig. 15 Shadowgraph Photograph of the Vortex Structure for the Tail Rotor, $M_r=0.55$, 2752 rpm, $a=14^\circ$, $l=6.4\text{ m}$ without heat. Vortex structure is visible.
Fig. 16  Shadowgraph Photograph of the Vortex Structure for the Tail Rotor, $M_t=0.55$, 2762 rpm, $\alpha=14^\circ$, $l = 6.4$ m with heat. Vortex structure is visible.
APPENDIX

In the Appendix, further data analysis is carried out. Also, an analysis of the visibility function is given.
Abstract

The vortex trajectory and vortex wake generated by helicopter rotors were visualized using a wide-field shadowgraph technique. Use of a retro-reflective Scotchlite screen made it possible to investigate the flow field generated by full-scale tail rotors. Tip vortex trajectories were visible in shadowgraphs for a range of tip Mach number of 0.38 - 0.60. The effect of the angle of attack was substantial. At an angle of attack greater than 8 degrees, the visibility of the vortex core was significant even at relatively low tip Mach numbers. The theoretical analysis of the visibility was carried out for a rotating blade. This analysis demonstrates that the visibility decreases with increasing dimensionless core radius \( r_0/2r \) and increases with increasing tip Mach number. Based on this investigation, it is concluded that the wide-field shadowgraph flow visualization technique should be feasible to study the flow field generated by a large main rotor in a wind tunnel and in an outdoor full-scale test stand. Of note is that the shadowgraph technique could easily be used with other ongoing tests such as aerodynamic performance study, noise measurements, velocity measurements with LDV or hot wire anemometer, local pressure measurement on the rotor surface, etc.

Nomenclature

- \( A \): area of disk
- \( AR \): Blade aspect ratio, \( RT/c \)
- \( a_0 \): ambient speed of sound
- \( b \): number of blades
- \( B \): factor less than 1 in \( v = RB/2\pi \)
- \( c \): blade chord
- \( C_{x} \): section lift coefficient, \( L/\rho U^2 \)
- \( C_T \): rotor thrust coefficient, \( T/\rho R^2 \)
- \( I \): intensity
- \( L \): lift per unit span (=\( \rho V \))
- \( E \): beam lengths, distance between rotor and screen
- \( M \): Mach number
- \( M_T \): tip Mach number
- \( m \): refractive index
- \( r \): radius measured from the tip vortex center
- \( r_0 \): core radius of tip vortex
- \( R \): radial coordinate along rotor blade
- \( R_T \): blade tip radius measured from the hub center
- \( t \): time
- \( T \): rotor thrust
- \( S \): visibility function defined in Eq. (28)
- \( U \): free stream velocity in a rectilinear motion or \( RT \) for rotor blade
- \( U_{max} \): maximum free stream velocity in a rectilinear motion
- \( v \): circumferential velocity in vortex
- \( w \): axial velocity in the far wake
- \( x \): coordinate
- \( y \): coordinate
- \( \alpha \): angle of attack
- \( \beta \): dimensionless constant in Eq. (22), 0.000292 for air
- \( \delta \): velocity factor that changes from 0.5 to 1 from the disk to downstream infinity
- \( \gamma \): ratio of specific heats (1.4 for air)
- \( \rho \): kinematic viscosity
- \( \rho \): density
- \( \Omega \): rotor solidity, ratio of blade area to rotor disc area \( (bc/R^2) \)
- \( \phi \): wake azimuth angle
- \( \Omega \): rotor rotational speed
- \( \omega \): rotational speed in vortex core

1. Introduction

Accurate prediction of the instantaneous flow field and associated performance of a lifting rotor is the key to improve blade designs for helicopters. Over the past thirty years, numerous investigators have attempted to determine rotary-wing inflow and performance using various mathematical methods. Landgrebe and Cheney\(^1\) made an extensive survey of these earlier rotor inflow studies. They divided about eighty references into four categories. These are inflow methods based on 1) momentum theory assuming a uniformly loaded actuator disc without tip loss, 2) undistorted wake geometry neglecting wake contraction, 3) a theoretical distorted wake geometry and 4) prescribed empirical wake geometry.

Concurrent with these analytical and semi-analytical studies, a number of investigators have carried out experiments to better understand wake geometry and corresponding airload of rotors. Detailed blade loading was obtained using hub-mounted pressure transducers\(^2\), hot-wire anemometer\(^3\), and laser doppler velocimetry\(^4-8\). Of note is that as pointed out by Yu and Kittleson\(^9\), pressure transducer instrumented airfoils are expensive and difficult to fabricate, and measurements can be made only on the blade surface. Hot-wire anemometry is located within the flowfield, thus disturbing the flow. Furthermore,
both hot-wire anemometry and laser doppler velocimetry are time-consuming point measurements for the complex three-dimensional flow field generated by helicopter rotors. In spite of these difficulties, these methods provided excellent quantitative data on the detailed structure of the flow field of a rotor. Recently, Yu and Kittleson used holographic interferometry and computer assisted tomography to determine the transonic velocity field of a model rotor blade in hover at a tip Mach number of 0.90.

Wake geometry was observed using smoke photography, direct observation using the condensation of moisture in the low pressure vortex core, etc. The smoke injection technique, one of the simplest methods, provided three or four dark vortex cores, thus indicating the wake contraction boundary distinctively. Also, it revealed the presence of the vortex sheet by the discontinuity in smoke streaks. However, this does not provide the vortex spiral trajectory. In addition, the rapid diffusive and the excessive quantity of smoke required pose significant problems in the use of smoke photography for a full scale main rotor test. Schlieren photography is practically restricted to a field of view of about 50 cm because of the necessity of using high quality mirrors in the technique. For this reason, it has been used to visualize the tip vortex trajectory produced by a relatively small model rotor. Direct observation using condensation of moisture is only possible when the humidity and temperature conditions are appropriate and the rotor tip speed is relatively high such that vapor trails are visible. Of note is that these flow visualization techniques provide qualitative two-dimensional views of three-dimensional flow.

However, these techniques produced valuable information on wake geometry such as wake contraction, distortion of wake, nonsymmetry of wake, radial and axial movement of vortex core, which are needed in the analytical prediction of the performance of a lifting rotor. Most investigators studied the wake of a hovering helicopter rotor because of the importance of hovering performance. Also, the hovering condition is the simplest one for experimental set-up.

The objective of the present investigation was to develop a new experimental technique to visualize the helicopter rotor wake to determine the geometry and structure of the tip vortices of a full-scale rotor. The vortices should be observed for several blade passages above the rotor. An important condition in the design of the experiment was to conduct the experiment at nearly full scale (i.e., the distance between the screen and rotor blade should be the order of 3'-9") so that the system of measurement could apply to a large wind tunnel test.

It was expected that useful shadows would result from the natural density changes in the vortex cores associated with low pressures. However, it was necessary to determine the visibility experimentally since the sensitivity of the shadowgraphs depends on the second derivative of the unknown density field.

Addition of a fluid with different density was also investigated to determine the characteristics of the resulting shadowgraphs. This was done by using a hot air gun during some of the tests.

II. Method of Experiment

Shadowgraphy is the simplest optical technique. Here, second derivatives of density are sensed as light variations on the screen. When a point source illuminates a large screen, density changes in the test section between the light source and the screen cause shadows to be cast on the screen. This shadow can be seen directly or can be photographed by a camera provided there is enough light to produce a good exposure. Usually, light is insufficient for a good exposure if the screens are ordinary, white surfaces.

However, when the screens are treated with retroreflecting material such as Scotchlite (made by 3M company), the light gathered by a camera placed as close as possible to the point source of light is sufficient for a good exposure. A stroboscope is generally used to freeze the motion during the time the camera shutter is open.

Shadowgraphy reveals naturally occurring density changes in the flow as well as those changes induced by deliberate introduction of tracers of different densities such as hot air, carbon dioxide gas, etc. In the present application, tip vortices from rotors cause enough density changes to be visible without the introduction of tracers. However, tracers can be used to examine the flow field in regions where there are no naturally occurring density changes.

To simulate flow fields generated by rotorcraft blades, a tail rotor together with the gear box (Hughes Model 300) was obtained through the Sheriff's Department, County of Los Angeles. The symmetric blade was rectangular with chord length of 0.122 m (NACA airfoil 0015). The distance from the center of rotation to the blade tip was 0.65 m giving the blade aspect ratio (AR) of 5.3 and the rotor solidity (c) of 0.120. The designed-operating speed of this rotor was 2900-3100 rpm with a torque of 269 N-m. At 3100 rpm, the blade tip speed was 210 m/s (i.e., Mach number 0.61) and the required electric motor power to rotate the rotor was 18.6 Hp.

The rotor test assembly was balanced with the Vibrex Track and Balance System made by the

![Fig. 1 Sketch of widefield shadowgraph instrumentation.](image-url)
Chadwick and Helmuth Company (El Monte, CA). During the balancing test, the maximum operational speed of 3100 rpm was obtained.

The setup with camera focused on the shadow on the Scotchlite screen is shown in Fig. 1. The aperture (f) of 5.6 and shutter speed of 1/15 sec. were used to take the shadow photographs with Kodak film (Tri-X PAN 120, ASA 400). Stroboscopic observations were made by synchronizing the xenon point-source strobe lamp with the signal from the photoprobe, thus automatically freezing the rotor blade motion at a fixed location throughout the test. A typical flash rate during photography was 25 flash/sec with a pulse power of 2.48 J/flash. Each flash duration was 21 us. In addition, the use of slip/sinc control in the Strobex System (made by the Chadwick and Helmuth Company) allowed us to observe transient shadowgraphs from slowly moving rotor blades. The magnetic pickup probe mounted near the shaft connecting the rotor clutch device to the electric motor measured the shaft rpm which was 2/3 of the rotation speed of the rotor because of the gear ratio used in the device. The rpm measured using the magnetic sensor was the same as the stroboscopically measured data within five percent. Scotchlite shadowgraphs were observed at two distances, viz \( z = 4.4 \) m between the rotor and screen and also \( z = 6.4 \) m. The corresponding distances between the light source and screen were 7.8 m and 11.0 m, respectively. These distances could be expected in applications of this technique when the strobe source is located in a large wind tunnel.

III. Experimental Results and Discussion

Figure 2 shows the shadowgraph of the rotor at \( z = 4.4 \) m at 3200 rpm (i.e., \( M_r = 0.64 \)) and at 12° angle of attack. Of note is that the rotor tip is facing toward the viewer. The vortex cores are seen as two thin spirals emanating from the two blade tips. On the left, only the density gradient occurring naturally in the core makes the vortex visible. On the right, hot air from a hair dryer circulates around the tip vortex and shows the circulating flow. At the extreme right and left edges, the shadows are denser because the light rays pass tangentially through the vortices. Three dark spots are visible on the left vertically showing these edges. The vortices are distorted at this condition of high angle of attack and high rpm.

Figure 3 shows another phase of the rotor at the same conditions. Distortions are clearly visible on the left. It is worth noting that these shadowgraph pictures give detailed information on the entire vortex trajectory, the vortex core size and the wake around the vortex core, which can provide useful input for the computer modeling of the helicopter rotor performance.

Figure 4 shows the shadowgraph of the rotor at \( z = 6.4 \) m, 2890 rpm (i.e., \( M_r = 0.58 \)) and at 8° angle of attack. Spiralling vortices are distinctly visible and the flow field around two tip vortex cores is dramatically shown with the help of hot air introduced below the rotor tip. By comparing Fig. 4 with Figs. 2 and 3, the shadowgraph picture taken at \( z = 6.4 \) m was found to be equally good as (or no better than) those taken at \( z = 4.4 \) m, when \( z \) is the order of 4 to 6 m.

Other shadow photographs taken at different Mach numbers and different angle of attacks are given in our earlier report. Of note is that for \( \alpha = 4° \) and \( z = 6.4 \) m, a just visible tip vortex core was observed at \( M_r = 0.38 \), a slightly visible spiralling vortex trajectories together with distinctively visible one dark vortex core spot.
were seen at \( M_r \) of 0.55. Therefore, the threshold values of \( \alpha \) and \( M_r \) for the shadowgraph technique to yield useful information were found to be 4° and 0.36, respectively. In general, visibility significantly improved with the tip speed and angle of attack. However, the effect of the angle of attack \( \alpha \) was found to be more important than the tip speed. At an angle of attack greater than 8°, the visibility was significant even at relatively low tip Mach numbers of 0.38 (see shadowgraph pictures in Ref. 16). In the following, it will be demonstrated that three important quantitative data such as vortex core radius \( r_0 \), axial velocity in the wake \( W \), and tip vortex axial and radial coordinates, can be obtained from a qualitative shadowgraph flow visualization picture.

a. Vortex Core Radius \( r_0 \)

The size of the vortex core was experimentally determined from the shadowgraph picture given in Fig. 3 (i.e., \( \alpha = 12° \) and \( M_r = 0.64 \)). Since the rotor radius is 0.65 m, one can calculate the scale-up factor between the real size and shadowgraph image. This results in a value of the vortex core radius of 7.6 mm for the case shown in Fig. 3. Thus, the ratio of the vortex core radius to the chord \( r_0/c \) is 0.063.

b. Axial Velocity in the Wake

Shadowgraph pictures in Figs. 2–4 show, typically, two or three vortex cores (for example, see three dark spots at the left side in Fig. 2). Thus, by knowing the rpm and the distance between two vortex cores, one can calculate the axial velocity due to the hovering motion of rotors. For the case of 8200 rpm and an angle of attack of 12° in Fig. 2, the axial velocity was calculated to be 20.4 m/s.

c. Tip Vortex Coordinates

Axial and radial movements of tip vortices are calculated from the shadowgraph picture given in Fig. 2. In Fig. 2, the angle of attack was 12° at 8200 rpm (i.e., \( M_r = 0.64 \)). The data reduction procedure was similar to those used by Landgrebe12,17 and Kocurek and Tangier15 and results are given in Fig. 5, which also shows earlier results obtained by other investigators. Table 1 gives pertinent information on these investigations. Of note is that Landgrebe12,17 used smoke photography, Kocurek and Tangier15 Schlieren method, and Cardona and Tung's hot-wire anemometer probe to obtain the tip vortex coordinates. In addition, Landgrebe's, and Kocurek and Tangier's data were read from their wake-fitting formula correlated in terms of \( C_L/\alpha \) and \( C_L \) respectively, while Cardona and Tung's data were read at a given pitch angle. Of note is that all the above-mentioned investigators used an airfoil type NACA 0012. In the present study, \( C_L \) was not measured experimentally. However, by knowing the blade shape (i.e., NACA 0015) and angle of attack (i.e., 12°), one can calculate the average lift coefficient \( C_L \) and accordingly the thrust coefficient \( C_T \) from \( C_T = \delta C_L/(6\pi AR) \). Values of \( C_L \) and \( C_T \) were 0.45 (i.e., see Ref. 4) and 0.0090 respectively, for the present case given in Fig. 2.
The results of Kocurek and Tangler who used a Schlieren method are in relatively good agreement with our shadowgraph technique at wake azimuthal angles to about 100 deg, but at larger angles do indicate smaller axial displacement of the tip vortex. The other techniques of Caradona and Tung, and Landgrebe give progressively smaller axial displacements. Kocurek and Tangler have pointed out differences between their results and those of Landgrebe for tip vortex axial position in terms of the blade aspect ratio AR and number of blades b. Our results for one aspect ratio AR = 5.3 and 2 blades appear to be similar to those of Kocurek and Tangler with 2 blades, although somewhat larger tip vortex axial locations are indicated than for the similar rotor results of Caradona and Tung (AR = 6 and b = 2).

Figure 5 clearly demonstrates that the shadowgraph technique can be used to measure tip vortex axial and radial coordinates. The present data reveals non-linearity of the axial coordinate of tip vortices.

**IV. ANALYSIS**

**a. Visibility of a Vortex Wake**

A simplified analysis is developed to estimate the influence of angle of attack, and tip speed on the visibility of vortices in the shadowgraphs. More elaborate treatments of trailing vortices have been conducted by many investigators for fixed wings. Large scale vortices from aircraft have been studied by McCormick et al. Simulation of the wake of a large aircraft by a small scale model is discussed by Bate. Growth of vortices in turbulent flow was discussed by Squire by using a suitable eddy viscosity model. Wind tunnel investigations of the far-field wake structure were conducted by Mason and Marchman and the structure of the vortex was related to the circulation distribution on the wing.

**b. Rectilinear Motion**

Consider first an airfoil in rectilinear motion with velocity \( U \). The airfoil is considered as a lifting line. The vortex has a region of linearly increasing circumferential velocity near the center reaching a maximum value in a transition region followed by a decay as \( r^{-1} \) at large distances corresponding to free vortex behavior. The sketch in Fig. 6 shows this distribution.

In Fig. 6, the maximum circumferential velocity is given by

\[
Y_{\text{max}} = \frac{B \rho}{2\pi r_0}
\]

(1)

where the quantity \( B \) is to be obtained from vortex theory or from experiments of Corsiglia et al. For a laminar vortex, diffusion of vorticity from a line source gives the solution of the circumferential velocity \( v \) (see Lamb):

\[
v = \frac{\Gamma}{2\pi r} \left( 1 - e^{-r^2/4Ut} \right)
\]

(2)

which has a maximum at \( r = r_0 \) where \( dv/dr = 0 \).

From this, we have \( r_0/4Ut = 1.256 \). The core radius \( r_0 \) increases as the square root of \( ut \) in all diffusion problems. In a steady flow problem, \( t \) is replaced by \( x/U \) by Taylor's hypothesis. The maximum circumferential velocity is given by

\[
Y_{\text{max}} = \frac{\Gamma}{2\pi r_0} \left( 1 - e^{-1.256} \right)
\]

(3)

\[
Y_{\text{max}} = 0.715 \left( \frac{\rho}{2\pi} \right)
\]

(4)

therefore, for a laminar vortex, the corresponding factor \( B \) in Eq. (1) is 0.715.

**Fig. 6 Velocity distribution in the tip vortex**

Flow in a turbulent trailing vortex is discussed by Govindaraju and Saffman where it is shown that the circulation must develop an overshoot. The logarithmic profile of Hoffman and Joubert is explained and previous results of model and flight tests are discussed.

Turbulent vortices, described in terms of core, log region and outer defect region, in analogy with turbulent boundary layers by Hoffman and Joubert, have been further discussed by Corsiglia et al. who made measurements with a rapid scanning flying hot wire. From these measurements, the factor \( B \), corresponding to the turbulent trailing vortex, is found to be about 0.42. Thus, the uncertainty involving the constant \( B \) in Eq. (1) varies from 0.715 for the laminar vortex to 0.42 for the turbulent one.

Now, for the analysis of the visibility of a vortex wake, a relationship will be developed in the following, which includes the maximum circumferential vortex velocity \( Y_{\text{max}} \) and velocity \( U \). This relation will be used in the calculation of the density changes due to the flow velocities.

First, the ratio of the circumferential vortex velocity to the free stream velocity, \( v/U \) can be given in terms of the circulation \( \Gamma \) by

\[
\frac{v}{U} = \left( \frac{\Gamma B}{2\pi} \right) \left( \frac{1}{U} \right)
\]

(5)

Since the lift per unit span \( L = \rho U \), we have
Introducing the lift coefficient $C_\ell$, becomes

$$v = \frac{B \cdot C_\ell}{4\pi r_0/c} \quad \text{(7)}$$

where $C_\ell = \frac{L}{\frac{1}{2} \rho U'^2 c}$

and $c$ is the chord length of the blade.

Since the maximum circumferential velocity occurs at $r = r_0$, Eq. (7) becomes

$$v_{\text{max}} = \frac{B \cdot C_\ell}{4\pi r_0/c} \quad \text{(9)}$$

Applying the $B$ value corresponding to the turbulent trailing vortex, i.e., $B = 0.42$, we have

$$v_{\text{max}} = \frac{0.42 \cdot C_\ell}{4\pi r_0/c} \quad \text{(10)}$$

For the NACA airfoil 0015 with 12 degree angle of attack in rectilinear motion, $C_\ell = 1.11$. Thus, using $r_0/c = 0.063$ which was obtained from our flow visualization pictures, Eq. (10) becomes

$$v_{\text{max}} = \frac{0.54}{4\pi r_0/c} \quad \text{(11)}$$

Of note is that the ratio of the vortex core radius to the chord, $r_0/c$ was experimentally found to be 0.035 by Corsigilia et al., who used two geometrically similar fixed wing models (NACA airfoil 0015) with a span of 0.61 and 2.43 m and an aspect ratio of 5.33. Also note that for a laminar vortex (i.e., $B = 0.715$), the value of $v_{\text{max}}/U$ in Eq. (11) becomes 1.002.

Equation (11) demonstrates that the maximum circumferential velocity $v_{\text{max}}$ is approximately half the airfoil velocity. Such velocity changes are accompanied by significant density changes as will be shown later.

### c. Rotating Blade

For a rotor, the flow field is different in the wake because the tip vortices caused by a hovering rotor are surrounded by a smaller axial jet flow. This flow can be calculated following the actuator disk theory as described in Prandtl.\textsuperscript{28} The rotor disk increases the velocity of the fluid at the disk by one-half the axial jet velocity far downstream.

The thrust of the rotor $T$ is given in Prandtl\textsuperscript{28} which for a hovering rotor is

$$T = \frac{\rho \cdot u^2}{2} \cdot (a k^2) \quad \text{(12)}$$

where $\rho$ is the axial velocity in the far wake, and the disc area is $(\pi k^2)$ (see Fig. 7).

However, the thrust of the rotor blade can be also expressed by the integration of the differential lift over the entire span of the blade.

$$T = b \int_0^{RT} L \, dR \quad \text{(13)}$$

Substituting Eq. (8) for $L$ and using $U = aR$, we have

$$T = b \int_0^{RT} \frac{C_L}{4\pi} \, aR \, dR$$

Fig. 7 Sketch of top and side views of two rotors and vortex trajectory for a hovering helicopter.

$$T = b \int_0^{RT} \frac{C_L}{4\pi} \, aR \, dR \quad \text{(14)}$$

For an average $C_L$, this becomes,

$$T = c \frac{\rho}{k} \int_0^{RT} \frac{C_L}{4\pi} \, aR \, dR \quad \text{(15)}$$

Therefore, combining Eqs. (12) and (15), we have

$$W = \frac{\pi k \cdot D}{3} \sqrt{\frac{\rho C_L}{4\pi}} \quad \text{(16)}$$

For $C_L = 0.45$ (Ref. 4) and $R_T/c = 5.33$, which is obtained from our rotor blade geometry, we obtain

$$W = 0.134 \quad \text{(17)}$$

For the case given in Fig. 2 (i.e., 3200 rpm with
\( \alpha = 12^\circ \), Eq. (17) gives the upward jet velocity \( W \) of 29.2 m/s. This value of \( W \) in the far wake is consistent with rotor thrust theory since the ratio of the experimentally determined axial velocity of the tip vortex in the near wake to \( W \) gives a value of \( \beta = 20.4/29.2 = 0.70 \).

Equation (17) shows that the upward jet velocity is about 13\% of the rotating blade tip velocity, \( cR \). Therefore, one may neglect the effect of the upward jet velocity \( W \) on the calculation of the circumferential vortex velocity. Accordingly, the maximum velocity in the vortex core is approximately given by Eq. (9):

\[
V_{\text{max}} = \frac{cR \cdot \beta}{4W} \quad (18)
\]

However, the complete expression for the maximum velocity in the vortex core \( V_{\text{max}} \) is also simple enough to use.

\[
V_{\text{max}} = \sqrt{V_{\text{max}}^2 + (6W)^2} \quad (19)
\]

where \( V_{\text{max}} \) and \( W \) are given in Eqs. (18) and (16) respectively.

Of note is that \( \beta \) the correction factor in \( W \), has the value 0.5 just downstream of the rotor disk and increases to 1 at downstream infinity, which is the so-called half-body theorem.\(^{28}\) As mentioned earlier, the shadowgraph experiment resulted in the value of \( \beta = 0.70 \).

The density changes accompanying the flow velocities can be calculated by assuming that the flow outside the core remains isentropic from infinity to \( r_0 \). In isentropic flow,

\[
\frac{\rho_{\text{min}}}{\rho_s} = \left[ 1 + \gamma \frac{1}{2} M_{\text{max}}^2 \right]^{-\frac{1}{\gamma - 1}} \quad (20)
\]

where \( M_{\text{max}} \) is the maximum Mach number based on \( V_{\text{max}} \) (i.e., \( V_{\text{max}}/a_0 \)). In addition, \( \rho_{\text{min}} \) and \( \rho_s \) are the densities corresponding to \( V_{\text{max}} \) and stagnation values, respectively.

Of note is that \( V_{\text{max}} \) depends on \( (r_0/c) \) and \( cR \) as shown in Eq. (18), as does \( \rho_{\text{min}}/\rho_s \).

d. Sensitivity of Shadowgraphs

A shadowgraph is sensitive to the second derivative of the refractive index, \( n \). The change in intensity, \( I \), at a screen located at a distance \( z \) is given by Goldstein\(^{42}\):

\[
\frac{dI}{I} = -\frac{1}{\rho_s} \int_0^{r_0} \frac{\partial^2 n}{\partial y^2} r \, dr \quad (21)
\]

where \( n \) is the refractive index, and \( \rho_s \) is that for surrounding air. The integral in Eq. (21) represents the total change due to the passage of light through a characteristic length \( r_0 \). In Eq. (21), \( y \) represents a coordinate normal to \( r \) along which \( n \) is changing. The refractive index \( n \) depends upon density and is given in Liepmann and Roshko\(^{40}\) by

\[
n = 1 + \beta \left( \frac{\rho}{\rho_s} \right) \quad (22)
\]

where \( \beta \) for air at standard conditions is 0.000292.

Of note is that \( \rho_s \) in Eq. (21) becomes

\[
\rho_s = 1 + \beta = 1 \quad (23)
\]

Substituting Eq. (22) into Eq. (21), it can be seen that

\[
\frac{dI}{I} = -\frac{\rho_s}{\rho} \int_0^{r_0} \frac{\partial^2 n}{\partial y^2} r \, dr \quad (24)
\]

Assuming that

\[
\frac{\partial^2 n}{\partial y^2} = \frac{\Delta n}{(\Delta r)^2} \quad (25)
\]

we have

\[
\frac{dI}{I} = \frac{\Delta n}{(\Delta r)^2} \int_0^{r_0} \frac{r}{\rho_s} \, dr \quad (26)
\]

Replacing \( \Delta n \) with \( (\rho_{\text{min}} - \rho_s) \), and \( \Delta r \) with \( r_0 \), respectively, we obtain

\[
\frac{dI}{I} = \frac{\Delta n}{(\Delta r)^2} \int_0^{r_0} \frac{r}{\rho_s} \, dr \quad (27)
\]

If we introduce a visibility function \( S \) which is proportional to \( dI/I \), we can write \( S \) as

\[
S = \beta \frac{\Delta n}{(\Delta r)^2} \frac{1}{\rho_s} \left( \frac{r_0}{c} \right) \quad (28)
\]

where \( \rho_{\text{min}}/\rho_s \) is given in Eq. (20), \( r_0 \) is the vortex core radius corresponding to \( V_{\text{max}} \), and \( c/4 \) is the distance between the rotor blade and the screen.

e. Calculation of the Visibility Function

The visibility function \( S \) varies with the tip Mach number \( M_t \), \( r_0/c \) and BC\( _4 \) for a given \( c/4 \).

As mentioned earlier, the correction factor \( B \) in \( V_{\text{max}} \) (i.e., see Eq. (18)) ranged from 0.42 for the turbulent trailing vortex to 0.715 for the laminar one. As an average, the value of 0.5 was used for the correction factor \( B \). The visibility function \( S \) was calculated over the range of the tip Mach number \( M_t \) and dimensionless vortex core radius \( r_0/c \) and is shown in Fig. 8. Other quantities used are given in the following:

\begin{align*}
\alpha &= 12^\circ \\
C_4 &= 0.45 \\
\rho_0 &= 350 \text{ m/s} \\
1 &= 4.4 \text{ m} \\
K_t &= 0.65 \text{ m} \\
c &= 0.122 \text{ m} \\
\gamma &= 1.4
\end{align*}
Figure 8 demonstrates that the visibility function $S$ decreases with increasing dimensionless core radius, $r_0/c$. The typical value of $r_0/c$ was experimentally observed to be 0.063, which is indicated by the vertical line noted as "Range of Experiments" in Fig. 8. In addition, the sensitivity function $S$ increases with the tip Mach number $M_t$.

The threshold value of $S$ for the vortex to be just visible can be determined somewhat approximately by using the results shown in Fig. 9. This is a case for $\alpha = 4^\circ$ and a tip Mach number equal to 0.4 where a vortex was just observed. The core radius ratio was 0.063. Because $C_L$ was not measured directly, there is some uncertainty in its value. Comparing our data to that of Caradona et al. who used an airfoil close to this, the average $C_L$ may be estimated to be 0.085. The peak values could be as high as 1.5 times this value. The strength of the tip vortex may relate to either the mean $C_L$ or the maximum. The quantity $B$, which determines the maximum velocity in the vortex ranges from 0.5 to 0.7 as indicated previously. Therefore, the value of $BC$ which governs the vortex visibility can take values between 0.0425 to 0.065 as shown in Fig. 9. Thus, the spread in the cases of $S$ vs $(r_0/c)$ is substantial. The value of $S$ for a vortex to be just visible is between 0.00013 and 0.00004.

V. Summary and Conclusions

A new experimental shadowgraphy technique using a retro-reflecting screen was developed to observe tip vortices in a full-scale test. Tip vortex trajectories were visible in shadowgraphs for a range of tip Mach numbers from 0.38 to 0.6. The angles of attack ranged from 4° to 14°. Visibility improves with speed and angle of attack. The effect of the angle of attack $\alpha$ was substantial. At an angle of attack greater than 8 degrees, the visibility is significant even at relatively low tip Mach numbers. It can be expected that at higher tip speeds, visibility would be even better. In addition, the size of the vortex core, the axial velocity, and axial and radial vortex core coordinates during the hovering motion could be determined experimentally.

A simplified analysis was developed to estimate the influence of angle of attack and tip speed on the visibility of vortices in the shadowgraphs. The circumferential velocity at the vortex core depends on the strength of the tip vortex, and hence on the lift coefficient $C_L$. The magnitude of velocity in the wake is the resultant of this velocity and the axial jet velocity from the rotor. Assuming isentropic flow outside the tip vortex from the core radius to infinity, the local density change was calculated. The second derivative of the density field integrated along the optical path leads to a measure of visibility of shadowgraphs defined by $S$. This was calculated as a function of $C_L$, tip Mach number $M_t$, vortex core to chord ratio, $r_0/c$, and optical path length. The threshold value of $S$ was found to be approximately 0.00025, above which the vortex core should be visible and below which it may not be.

The present investigation demonstrated that the application of the wide-field shadowgraphy technique to a large wind tunnel or to a full-scale test stand could be made. In addition, the simplicity of this technique should allow use concurrently in other ongoing test programs.
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Table 1 Summary of Various Experimental Methods and Test Conditions

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Method</th>
<th>MCA Airfoil</th>
<th>AR</th>
<th>AR</th>
<th>Tip Mach</th>
<th>Pitch Angle</th>
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<tr>
<td>Landgrebe12</td>
<td>smoke photographs</td>
<td>0012</td>
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<td>0.46-0.61</td>
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<tr>
<td>Kocurek and Tangler15</td>
<td>Schlieren</td>
<td>0012</td>
<td>7.1</td>
<td>1,2,3,4</td>
<td>0.46</td>
<td>0,4,6,12</td>
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<tr>
<td>Caradona and Tung</td>
<td>hot-wire anemometer pressure transducers</td>
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<td>6.0</td>
<td>2</td>
<td>0.43-0.79</td>
<td>5,8,12</td>
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REFERENCES


