Physics of Reverse Flow on Rotors at High Advance Ratios

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When a rotor blade encounters reverse flow in edgewise flight at high advance ratio, a strong vortical structure forms on the leeside of the sharp blade edge. This has unexpected effects on blade aerodynamics. A differential onset velocity gradient due to rotor rotation creates an envelope of reverse flow extending from the hub. A Sharp Edge Vortex (SEV) is observed at the geometric trailing edge, forming soon after the blade enters the retreating-blade side. The SEV grows radially inwards in size and strength as the blade retreats. The SEV convects and evolves along with the rotor blade until dissipation. In this paper, a coherent vortex is observed at 240 degrees azimuth. Vortex size and strength increase as the blade retreats, ceasing to grow before 270 degrees. The reverse flow envelope increases at higher advance ratios with increased vortical strength. The solid-body rotation core of the vortex stretches at lower advance ratios, and shows the signs of a burst vortex in the dissipation phase. The proximity of the SEV to the blade causes large excursions in surface static pressures which in turn generates significant negative lift on the retreating blade. The attached, coherent sharp edge vortex shows similar morphological features as the leading edge vortex on a delta wing.

Keywords: Reverse Flow; Vortex Aerodynamics; Vortical Flow; Stereo PIV

I. INTRODUCTION

Edgewise flight at high advance ratio ($\mu$) poses strong uncertainties in rotorcraft aeromechanics. These stem primarily from the flowfield on the retreating side of the rotor. Radial flow, differential on-set velocity, centrifugal stresses, dynamic stall and reverse flow are some of the prominent features expected in this flow field. As seen from Figure 1 as advance ratio increases, the region where the blade is moving slower than the freestream increases in extent, out from the hub. Models of varying realism have been used to analyze and compute rotorcraft aeromechanics in this regime, going well beyond looking up airfoil force coefficient tables and applying static sweep corrections.

The reversed flow phenomenon can also be observed on slowed rotors, such as on an autogyro or compound helicopter, or wind-turbine blades encountering edgewise gusts. The phenomenon leads to many uncertainties. One is the chordwise movement of the airfoil center of pressure, from the quarter-chord position expected in incompressible flow to the 75% position as measured from the blunt edge. This is expected to occur in the inboard region where reverse flow occurs, whereas the outboard portion still has its center of pressure at quarter chord. In addition, the lift direction switches from up to down in the reversed flow regime. These induce both quasi-steady changes in bending and twisting moments on the blade, followed by vibratory loads caused due to the cyclic nature of the blade aerodynamic loading. The blunt edge might cause high fluctuations in drag. Some researchers have postulated the occurrence of periodic shedding from the blunt edge, based on expectations from two-dimensional airfoil aerodynamics.

FIG. 1. Extent of reverse flow region with increasing advance ratio ($\mu$)

II. PRIOR WORK

Modern vehicles such as the Sikorsky X2 and Eurocopter X3 can exceed advance ratios of 0.8 [1, 2]. At these high advance ratios, significant sections of the retreating blade experience reverse flow. Reverse flow is a major limiter in the design of high-speed rotorcraft, causing early flow separation, negative lift, and periodic vortex shedding [3]. Wheatley et al [4] measured forces on a Pitcairn PCA-2 autogyro rotor at various pitch settings and advance ratios up to $\mu = 0.7$ and found a negative correlation between lift coefficient and advance ratio.
Designs that attempt to mitigate the effects of reverse flow date back to the early 1970s. The Fairchild Republic Reverse Velocity Rotor [5] featured a negative pitch angle on the retreating blade in order to achieve a positive angle of attack in the reverse flow regime, and incorporated airfoils with blunt leading and trailing edges (with significant drag penalty). The Sikorsky X2 Technology Demonstrator [6] has coaxial rotors based on the Advancing Blade Concept [7] platform and also features blunt trailing edge airfoil sections near the blade root.

The thread running through the following survey is a search for the physical fluid dynamic phenomena that are responsible for the aeromechanics observed at high advance ratio. As the advance ratio increases, the region of reverse flow on the rotor disk expands, reaching the blade tip at 270° azimuth at an advance ratio \( \mu \approx 1 \). Prior work is summarized from [8]. The most basic method was to take airfoil data [9,12] from 2D wind tunnel tests in the region around 180 degrees angle of attack, use a trigonometric correction for yaw, and if needed, an aspect ratio correction. Uncertainties in lift, drag, pitching moment, blade bending and twist and rotor stability are cited in [13,14]. At the next level, with experiments revealing evidence of vortices in the flow field, ‘vortex shedding’ was postulated; both from the blunt edge when using NACA0012 type airfoils with blunt leading edges, and from the sharp edge as from a thin flat plate held at large negative angle of attack [3]. Karman vortex street analogues were also developed, along with modifications to include unsteady airfoil pitching effects. Other studies with unswept airfoils have modeled the sharp-edge flow as a diffused separated shear layer, with the blunt edge shedding vortices. Others have postulated a ‘reverse-chord dynamic stall’ process [2], explaining the occurrence of sharp pitching moments as well as strong vortices seen in the flow field in experiments.

Problems have become evident in computational predictions at all levels. MacCloud et al [15] observed a drop in lift coefficient at high advance ratios (up to 1.0) on a teetering rotor with NACA0012 blades. Charles et al. [16] showed that performance predictions broke down for 0.5 < \( \mu < 1.1 \) for a UH-1D rotor. They observed flapping instability and a long transient response to control input at \( \mu = 1.1 \). H. Harris et al. [17] correlated these datasets in 2008 and concluded that the 3D Navier-Stokes solver OVERFLOW-2 was not accurately predicting lift, drag and pitching moments for reverse flow over airfoils. Other recent work includes [17,23]. The survey by Quackenbush [18] captures many of the phenomena to be expected from reverse flow geometry, and even shows a sharp-edge vortex. Harris [17] summarizes high advance ratio rotorcraft flight experience. Niemiec [22] and Carter [24] describe airfoils intended for the reversed-flow regime.

Large pitch link impulsive loads on a slowed UH-60A rotor near \( \mu \) of 1 were ascribed to reverse-blade dynamics stall by [2,23,27]. Kottapalli’s efforts [28,29] to predict the blade loads on the UH-60A using CAMRAD II encountered difficulties at \( \mu > 0.8 \). Predictions by Yeo [30] using CAMRAD II showed only fair airload and structural load correlation. Potsdam’s et al [19,31] coupled CFD and comprehensive analysis predicted unconventional wake patterns and a lower surface vortex on the retreating blade. He attributed that to dynamic stall. Pitching moment predictions on the advancing and retreating sides were not encouraging. Lee et al [32] performed time-averaged force measurements and flow visualization on various airfoil sections in reverse flow and found a drag jump at \( \alpha = 180^\circ \) due to the unsteady formation and convection of a large vortex in the wake. Lind et al [3,33,36] also conducted reverse flow studies on static sharp and blunt trailing edge airfoils. They postulated that the large negative angles of attack of the inboard section of a rotor in reverse flow caused flow separation and the onset of vortex shedding. It was suggested that the use of a blunt-trailing edge airfoil with a relatively linear lift curve slope would be ideal for the reverse flow regime. Ormiston et al. [37,39] performed a computational analysis on the rotor blades at high advance ratios, and showed inconsistency with the observed experimental data due to limited knowledge of the aerodynamic model.

In summary, the past approaches to the rotor reverse flow problem have been largely based on the physics of the 2-D airfoil model. The 270-degree azimuth angle has usually been taken as the starting point for analyses, where the blade has no yawed flow. This presumes that the rest of the retreating blade sector can be analyzed as perturbations of the 270-degree case, with yaw corrections applied.

III. WORK AT OUR LABORATORY

Our publications [8,40] argued that the formation and evolution of a strong three-dimensional (helical) vortex early on the retreating blade side, would be key to the entire problem. At azimuth angles between 180 degrees and 240 degrees, the sharp edge of the blade resembles the edge of a highly forward-swept wing. This causes a strongly helical vortex to form, with significant axial flow along its core. With increasing azimuth, the yaw angle decreases. The subsequent evolution of the vortex is similar to the observed phenomena on delta wings. We explored the argument that the genesis of the aerodynamic loads was best viewed through the perspective of vortex flows occurring on sharp-edged swept wings at moderate angle of attack.

Initially, a rotor blade which is part of the 2-bladed rotor that will be discussed in this paper, was used in a fixed-wing experiment [11]. The blade of aspect ratio 3.47 was mounted vertically in a wind tunnel at settings of angle of attack around 0 (forward-facing) and 180 (reverse-facing), and yaw angles up to 60 degrees in forward-sweep fashion and backward-sweep fashion. This covered the range of attitudes encountered by a rotor in edgewise flight. Aerodynamic lift, drag and pitching moment were
measured using a 6-degree-of-freedom load cell. Woollen tufts were used to examine flow behavior. The variation of relative velocity along the span that occurs on a rotating blade could not be simulated. However, the experiment served to confirm that in the reverse-flow cases, a strong vortex did indeed form on the lee-side. The aerodynamic loads showed the clear evidence of vortex lift. Calculations using the Polhamus Suction Analogy [42] for delta wing aerodynamics, showed that the vortex lift component was quite significant in the loads on the blade. Tuft visualization confirmed the presence of the vortical structure. Subsequently, the same blade was placed back on the rotor in the wind tunnel, and held in place in the tunnel freestream. Particle Image Velocimetry was used to examine the flow below the blade at the 240 degree azimuth, at an angle of attack that roughly simulated the rotor conditions to be tested. Again, the varying relative velocity was missing from this test case, and so was the radial velocity that might be expected due to centrifugal effects. Again, the presence of the vortex below the sharp edge (the SEV) was confirmed by the velocity field results. Load measurements were not possible when attached to the rotor.

IV. PRESENT SCOPE

This paper focuses on the physical mechanisms of reverse flow on a rotor blade at high advance ratios. It examines the evolution and dissipation phases of the sharp edge vortex using stereo particle image velocimetry (SPIV). The characteristics of the SEV such as convection speed, core size, and the velocity profile are studied. The similarities of the SEV with the leading edge vortex on a delta wing at high angles of attack is described.

V. EXPERIMENTAL METHOD

A. Experimental setup

The experiments were conducted in the John Harper 2.13 m x 2.74 m closed circuit low speed wind tunnel at the Georgia Institute of Technology. The rotor was composed of two untwisted, rectangular NACA 0013 rotor blades (identical to and including the one used in the static experiments discussed by Raghav et al. [43]), attached to a teetering rotor hub actuated by a 3.73 kW motor. Figure 3 shows the rotor setup with the laser sheet and SPIV used in this work. The collective pitch angle was set at 7° and the longitudinal cyclic angle was set at 8°, which results in a 15° pitch at \( \psi = 270° \). These pitch angles created a tip path plane tilting forward, simulating a typical forward flight condition. Higher pitch angles resulted in rotor vibrations resulting from dynamic stall, and were avoided for safety reasons. There was no lateral cyclic in these experiments. A detailed analysis on the blade surface roughness is described in our prior work [43]. The rotor specifications are shown in Table I.

B. Flow and Test conditions

Phase-locked SPIV measurements on the rotating rotor blade were acquired at advance ratios of \( \mu = 0.7, 0.85, 1.0 \) and a rotor angular velocity of \( \Omega = 20.94 \text{ rad/s} \) (200 RPM). Measurements were gathered at radial locations of \( r/R = 0.4, 0.5, 0.514, 0.6, \) and 0.7 and at azimuthal angles \( \psi = 240°, 270° \) and 300°. The azimuth angle of 240 degrees covered additional refined datasets at \( r/R = 0.35, 0.45, 0.5, 0.55, \) and 0.65. Table II summarizes the test cases for the SPIV results.

| Description         | Value | Units |
|---------------------|-------|-------|
| Blade mass          | 1.747 | kg    |
| Blade span          | 0.622 | m     |
| Blade chord         | 0.178 | m     |
| Blade aspect ratio  | 3.49  | -     |
| Disk radius         | 0.889 | m     |
| Solidity            | 0.089 | -     |
| Precone             | 1.6   | degrees |
| Max. collective     | 10    | degrees |
| Cyclic              | 6.7 - 9.0 | degrees |
| Motor               | 3.73  | kW    |
| Height              | 1.575 | m     |

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TABLE II. Test matrix for SPIV measurements

| Azimuth (Ψ) | Advance ratio µ | r/R |
|-------------|----------------|-----|
| 240°        | 0.7, 0.85, 1.0 | 0.35, 0.4, 0.45, 0.5, 0.514, 0.55, 0.6, 0.65, 0.68 |
| 270°        | 0.7, 0.85, 1.0 | 0.4, 0.5, 0.514, 0.6, 0.68 |
| 290°        | 0.7, 0.85, 1.0 | 0.4, 0.5, 0.514, 0.6, 0.68 |
| 300°        | 0.7, 0.85, 1.0 | 0.4, 0.5, 0.514, 0.6, 0.68 |

TABLE III. Uncertainty estimates in SPIV measurements

| Parameter | Error |
|-----------|-------|
| In-plane random error | 0.088 - 0.281 pixels |
| In-plane velocity error (ε_u, ε_v) | 0.006 m/s - 0.02 m/s |
| Out-of-plane velocity error (ε_w) | 0.028 m/s - 0.281 m/s |
| Total measurement error | 0.75% - 3.96% |

C. Measurement uncertainties

The uncertainty in instantaneous velocity measurements is computed using methods described in [44] and [45]. The out-of-plane component error estimation due to the relative angle of the cameras is discussed in [46]. For the camera angles used in these experiments the RMS error for the out-of-plane component of displacement is between 2.8% - 6% for a laser light sheet thickness of 3-4 mm and a camera magnification of 1/16. The error in out-of-plane component of velocity varies between 0.74% to 3.95%. This amounts to an absolute error of 0.028 m/s to 0.281 m/s based on maximum out of plane velocity component. The in-plane velocity measurement error was estimated to be 0.06% to 0.2%. This amounted to an absolute error of 0.006 m/s and 0.02 m/s based on maximum in-plane velocity component. The total velocity measurement error is computed as a percentage by computing the magnitude of all the measurement errors and it amounts to 0.75% to 3.96%. The uncertainty estimates in the SPIV measurements are summarized in Table III.

VI. RESULTS AND DISCUSSION

A. Azimuthal evolution of the SEV

At an azimuth of 240 degrees, the curvature of streamlines depicted in Figure 4 shows an incipient SEV. The attached coherent vortex is observed very close to the surface originating from the sharp edge. As the rotor blade progresses azimuthally, the SEV becomes stronger, larger and detached from the surface, but still convecting along with the rotor blade. Beyond 270 degrees, the vortex becomes even larger and eventually diffuses into the freestream. Unlike the generally accepted hypothesis of vortex shedding from sharp corners, no such phenomenon was observed in the data sets. All phase-locked SPIV data sets showed a coherent tight vortex with a small core size at the sharp edge convecting with the blade. The presence of the SEV well ahead of 270 degrees azimuth invalidates the reverse dynamic stall hypothesis wherein the presence of a vortex is related to the perturbations at 270 degrees.

At 240 degrees, the near-farfield flow and the vortical flow are directed radially inwards, towards the rotor hub. At 270 degrees azimuth, the near-farfield flow is directed radially outboard and the vortical flow still directed inwards. At 270 degrees, the rotor blade is oriented perpendicular to the free stream and there is no freestream component in the radial direction. Consequently, the near-farfield flow at 270 degrees is primarily due to centrifugal forces. The radially inward vortical flow is sufficiently strong to counteract the centrifugal stresses. At 300 degrees, the vortical flow is still directed radially in-
wards but diffused in nature. In this case, the freestream component is directed radially outwards which further strengthens the centrifugal forces that counteract the vortical flow. This interaction with the previously formed vortex resulting in a diffused vortex is termed as “history effects”.

B. Advance ratio effects on the SEV

At azimuth 240 degrees, the increase in vortex strength with the increase in advance ratio is apparent from Figure 5. The curvature of streamlines become more prominent at higher advance ratios. This is primarily due to the increase in reverse flow with advance ratio. High reverse flow near the root causes a tight and strong vortex with a small core size very close to the sharp edge. There is no vortex shedding observed at this azimuth. Again, the development of the vortex at higher advance ratio is associated with a negative radial flow (towards the rotor hub). However, before the separation of the shear layer at the sharp edge, we see a predominant positive radial velocity (towards the blade tip). This positive radial velocity reverses direction right at/after the separation of the shear layer, leading to the formation of the vortex.

At 240 degrees, the strength of the vortex is evidently larger at higher advance ratios due to higher streamline curvatures. At 270 degrees azimuth (not shown), the vortex core is larger at lower advance ratios. Further, the vortex core is detached from the surface at lower advance ratios. A similar behavior of the detached vortex is observed at azimuth 300 degrees. In addition, a strong inward directed radial flow is prominently seen near the surface, but away from the vortex center. This is in contrast to the observed radial flow in the core of the vortex at 270 degrees azimuth. The detached vortex observed at azimuth angles of 270 and 300 degrees still convects along with the rotor blade and does not diffuse/convect with the freestream.

C. Radial variation of the SEV

Figure 6 shows an incipient vortex at \( r/R \) of 0.6 that grows radially inwards. There is no evidence of the vortex at \( r/R \) of 0.7 which is outside the reverse flow region for an advance ratio of 0.85. The start of the reverse flow region is the source of vortex generation.

At 270 degrees, the vortex originates at a further outboard location of \( r/R \) of 0.68. Figure 7 shows a smaller vortex core near the tip that becomes stronger and tighter as it moves radially inward. The directionality of the vortex flow can be clearly distinguished by the outward flow in the near-farfield, thereby validating a strong helical vortex. Also, it is evident that the flow inside the vortex is directed towards the root while countering the centrifugal forces at the surface.

At 300 degrees, shown in Figure 8, the vortex is detached from the surface and shows the signs of a burst vortex with the solid core extending all the way to the outer diameter. The shear layer of feeding vorticity into
the vortex shows an outward directed flow. The inward directed flow is observed much closer to the surface and away from the vortex core. A clear distinction of the vortex origin at a particular radial location is questionable at this stage due to the history effects. The aggravating centrifugal forces on a previously formed vortex need to be considered. In contrast to the 240 degrees case at \( r/R \approx 0.68 \), which clearly falls outside the reverse flow region, the presence of the vortex at 300 degrees azimuth clearly indicates a previously formed convected vortex rather than an incipient vortex.

### D. Vortex convection

From the literature [47][49] on a convecting vortex, the convection speed of a free vortex in a freestream lies between 0.4-0.6 \( U_\infty \). A validation study was performed to obtain the convective speeds and the relative position for a free shed vortex, if this were to be the case. A vortex was presumed to be shed at \( r/R \approx 0.5 \) at an azimuth of 270 degrees. The convection times for different advance ratios for a supposedly shed vortex were found to be of the order of 18-25 ms. The relative position of a shed vortex with respect to the blade at an azimuth angle of 300 degrees is thus shown in Figure [9].

The experimentally observed SEV in the velocity fields did not show such a behavior, as a shed vortex would have convected further downstream of the sharp edge. In contrast, the SEV was observed to be at a distance of 15\%c to 28\%c from the sharp edge. The presence of the SEV near the sharp edge even at 300 degrees azimuth validates our hypothesis that the SEV truly convects with the rotor blade.

### FIG. 9. Relative position of SEV vs shed vortex at \( \Psi = 300^\circ \), \( r/R = 0.5 \)

The relative position of the SEV and the sharp edge vary as one moves radially inwards for different advance ratios and azimuths. The vortex center is identified algorithmically based on the vortex core size. The vortex position is characterized by the orientation angle \( \theta \) of the position vector, with its magnitude denoted as \( \rho \). The origin of the position vector is located at the sharp edge for a given radial location as shown in Figure [10].

Tables [IV] to [VI] shows the characterization of the SEV. At azimuth 240 degrees the SEV is very close to the sharp edge and the \( \rho/c \) varies between 0.014 to 0.072. At lower advance ratio, the SEV is observed to be closer \( (\rho/c = 0.014) \) to the sharp edge than at higher advance ratio \( (\rho/c = 0.072) \). The position of the SEV at inboard locations is slightly higher than at the outboard locations. Similar behavior is observed at azimuth 270 and 300 degrees with a greater separation distance from the sharp edge at higher azimuth angles. Figure [11] shows the relative position of the SEV at an advance ratio of 0.7 and azimuth of 300 degrees.
FIG. 10. Position of SEV from the sharp edge

TABLE IV. Position of SEV at Ψ = 240°

| r/R  | µ = 0.7 | µ = 0.85 | µ = 1.0 |
|------|---------|----------|---------|
| -    | ρ/c     | θ°      | r_S/c   | ρ/c | θ°  | r_S/c   | ρ/c     | θ°   | r_S/c   |
| 0.35 | 0.028   | -28      | 5.61    | 0.056 | -9   | 6.50    | 0.065   | -3   | 6.35    |
| 0.40 | 0.010   | -41      | 4.43    | 0.037 | -16  | 4.84    | 0.072   | -1   | 3.49    |
| 0.45 | 0.009   | -63      | 4.36    | 0.035 | -12  | 5.26    | 0.047   | -9   | 5.00    |
| 0.50 | 0.019   | -96      | 3.30    | 0.210 | -3   | 3.55    | 0.232   | -4   | 6.12    |
| 0.514| 0.014   | -18      | 3.86    | 0.011 | -21  | 4.08    | 0.047   | -15  | 5.11    |
| 0.55 | 0.013   | -8       | 2.52    | 0.011 | -28  | 4.60    | 0.030   | -10  | 4.51    |
| 0.60 | 0.019   | -4       | 0.88    | 0.221 | -2   | 2.73    | 0.317   | -82  | 3.621   |
| 0.65 | 0.014   | -6       | 0.65    | 0.073 | -19  | 0.27    | 0.022   | -77  | 2.984   |
| 0.68 | 0.014   | -17      | 1.09    | 0.031 | -45  | 2.45    | 0.038   | -76  | 2.789   |

TABLE V. Position of SEV at Ψ = 270°

| r/R  | µ = 0.7 | µ = 0.85 | µ = 1.0 |
|------|---------|----------|---------|
| -    | ρ/c     | θ°      | r_S/c   | ρ/c | θ°  | r_S/c   | ρ/c     | θ°   | r_S/c   |
| 0.30 | 0.198   | -12      | 10.30   | 0.233 | -2   | 7.14    | 0.178   | -19  | 7.46    |
| 0.50 | 0.139   | -18      | 9.22    | 0.184 | -11  | 7.84    | 0.103   | -1   | 4.15    |
| 0.514| 0.125   | -18      | 9.24    | 0.175 | -8   | 8.56    | 0.119   | -4   | 6.53    |
| 0.60 | 0.064   | -36      | 6.393   | 0.126 | -14  | 8.13    | 0.087   | -5   | 6.78    |
| 0.68 | 0.006   | -38      | 5.95    | 0.069 | -19  | 6.12    | 0.048   | -19  | 2.65    |

TABLE VI. Position of SEV at Ψ = 300°

| r/R  | µ = 0.7 | µ = 0.85 | µ = 1.0 |
|------|---------|----------|---------|
| -    | ρ/c     | θ°      | r_S/c   | ρ/c | θ°  | r_S/c   | ρ/c     | θ°   | r_S/c   |
| 0.40 | 0.245   | -36      | 12.018  | 0.139 | -29  | 10.45   | 0.011   | -31  | 9.22    |
| 0.50 | 0.185   | -29      | 11.110  | 0.077 | -18  | 7.48    | 0.118   | -25  | 9.29    |
| 0.514| 0.151   | -31      | 10.626  | 0.016 | -20  | 3.32    | 0.155   | -17  | 10.40   |
| 0.60 | 0.138   | -53      | 9.772   | 0.231 | -27  | 10.14   | 0.182   | -19  | 8.64    |
| 0.68 | 0.125   | -90      | 3.57    | 0.230 | -89  | 8.14    | 0.180   | -89  | 6.81    |

E. SEV convection speed

The convection speed provides an insight on the relative position of the SEV with respect to the rotor blade. The convection speeds are essential to study the kinetic energy of the SEV in comparison with rotational energy at different advance ratios. The convection speeds (U_P) are calculated as an average over the vortex area as shown in Equation 1, wherein the subscript 'P' denotes the vortex center.

\[ \bar{U}_P = \frac{1}{S} \int_S U dS \]  

The convection speed at 240 degrees azimuth shown in Figure 12 shows a parabolic behavior and the minimum shifts outwards with increase in advance ratio. At outboard radial locations, the forming vortex has lower rotational energy. With increase in advance ratio, this rotational energy increases with a proportional decrease in the kinetic energy drawn from the freestream. At an advance ratio of 0.7 the vortex convection speed monotonically decreases as one moves radially inwards. For higher advance ratios this trend stops at r/R of 0.5 and the convection speeds increase at the inboard radial stations.

At azimuth 270 degrees shown in Figure 13, the vortex convection speed decreases in the outboard radial locations; however at the advance ratio of 0.7 the convection speed still shows a parabolic behavior. The presence of a minimum in the convection speed r/R of 0.5 has direct correlation with the observed vorticity. The vorticity plots show a distinct and perfectly circular SEV at this radial location, indicating the right amount of rotational energy required to sustain the coherent structure. At azimuth 300 degrees shown in Figure 14, no particular behavior was observed at an advance ratio of 0.85, however the parabolic trend is consistent at advance ratios 0.7 and 1.0. In comparison with the convection speeds of a freely shed vortex (0.4U_∞ - 0.6U_∞) discussed earlier, the convection speed of the SEV is observed to be 0.07U_∞ ± 0.27U_∞.

F. Vortex size

The vortex core size gives a measure of evolution of the SEV. The core size is defined by a region of linear velocity variation describing the extent of solid-body core
rotation. The core radius is identified algorithmically by identifying the inflection point in the velocity profile measured across the diameter of the vortex. The algorithm is explained in detail by Michard et al. [50]. Figures 15, 16 and 17 show the size of the vortex core at different advance ratios and azimuths.

At 240 degrees azimuth, the vortex size increases radially from 1% of chord length at the start of the reverse flow region to 6.5%. The SEV originates at a further outboard radial location at higher advance ratios as the extent of the reverse flow region increases. The size of the vortex core increases from 4% to 11.5% at 270 degrees azimuth. At 300 degrees azimuth, the vortex core size is of similar size as it was at 270 degrees. The increase in the vortex core size from 240 degrees to 270 degrees shows the evolution of SEV. The stagnated growth beyond 270 degrees shows a quantitative measure of “history effects”. The 240 degrees azimuth shows a clear trend in the vortex core size with change in advance ratio. Such a behavior is inconsistent at other azimuths.

G. Velocity profiles of the SEV

A Galilean invariance method [50] denoted by $\Gamma_2(P)$ is used to obtain the convection speed and the center of the vortex, wherein the vortex structure is identified in an inertial reference frame. The mean convection speed $\bar{U}_P$ of the vortex is subtracted from the observed velocity field in the rotor reference frame. The point of maximum correlation denotes the center of the vortex. The extent of the vortex core is determined by the position where $\Gamma_2(P) = 2/\pi$.

The velocity profile of the idealized vortex comprises two regions: the solid core rotation that has a linear velocity profile, and an irrotational region that is dictated by the $1/r^2$ decay of tangential speed. In addition there is strong helicity, with the strongest axial velocity in the core. Analogous to the leading edge vortex on a delta wing, the SEV shows similar characteristics. At azimuth angle of 240 degrees when the rotor blade has a forward sweep, a higher relative angles of attack are observed across the span. The vorticity from the sharp edge is fed
into the growing vortex while the axial pressure gradient in the core sustains the vortex by counteracting the centrifugal stresses. Figure 18 shows the velocity profile of the vortex. The contour plot on the left shows the non-dimensional values of $\Gamma_2(P)$ to determine the center, and it is also depicted by the red curve in the right image. The blue line overlaid on the vorticity contour shows the velocity profile. The short extent of the linear region of solid rotation shows that the vore is small and tight. Outside the core, the velocity profile follows the $1/r^2$ rule. At 300 degrees azimuth, the vortex core is stretched all the way to the outer extent of the vortex. As shown in Figure 19, the $1/r^2$ rule is not observed outside the vortex core. This shows similarity with a burst vortex that is commonly observed on delta wings at high angles of attack as the leading vortex disintegrates.

$$\Gamma_2(P) = \frac{1}{N} \sum_{S} \left( \frac{PMA(U_M - \bar{U}_P)}{||PM|| \cdot ||(U_M - \bar{U}_P)||} \right) \hat{z}$$

FIG. 18. Vortex velocity profile at $\Psi = 240^\circ, r/R = 0.45, \mu = 0.7$

FIG. 19. Vortex velocity profile at $\Psi = 300^\circ, r/R = 0.6, \mu = 0.85$

The axial velocity of the SEV is significant and the flow-field is highly three dimensional. The axial velocity profiles show the presence of a helical vortex with a strong axial component. Velocity surfaces are plotted for axial velocities ($w$) by subtracting the spanwise component of the freestream as shown in Equation 3. Figures 20 and 21 show the axial velocity surfaces and contours of the SEV. The increasing values of x-coordinate point in the direction of freestream, the increasing values of y-coordinate point towards the rotor blade, and the increasing negative $U_{zrel}$ value points radially inwards on the rotor blade. The surface plot shows the prominent core axial velocities in comparison with the near far-field velocities. The positive velocities in the near far-field show the effect of centrifugal forces. The approximate size and location of the SEV are denoted by the dotted red circle on the contour.

$$U_{zrel} = w + U_{\infty} \sin(\Psi)$$

At azimuth 240 degrees, a strong axial velocity component is observed at inboard locations, thereby showing the growth of the helical vortex from the outboard location. The axial velocity increases with increase in advance ratio. The positive velocities outside the periphery of the SEV indicate the centrifugal forces in the near farfield of the rotor blade surface. Similarly, the azimuth 270 degrees and 300 degrees show a prominent axial velocity component, comparatively larger than those at the 240 degrees azimuth. With no spanwise component of the freestream at 270 degrees, the positive velocities outside the periphery of the SEV again show the presence of centrifugal stresses. This behavior is not significantly observed at 300 degrees azimuth.

At azimuth 240 degrees, shown in Figure 20, the core axial velocities increase radially inwards on the rotor blade. And a higher peak value is observed with the increase in advance ratio. In comparison to 240 degrees azimuth where there is a prominent peak in the core axial velocity, the broadening of this peak is observed at azimuth 270 degrees as shown in Figure 21. In contrast to 240 degrees, higher peak values are observed at advance ratios of 0.85, and there is no presence of a prominent peak at advance ratios of 1.0. At azimuth 300 degrees, a much broader peak was observed at the inboard radial locations. For the radial stations greater than $r/R 0.514$ shown in Figure 22, the axial velocities at the surface were much higher than the core velocities. This can be observed from the position of the peaks on the surface with respect to the position of the dotted circle on the contour.

H. Pressure signature of the SEV

A helical vortex is comprised of a very low pressure region with the highest suction pressure at the center of the core. The proximity of the SEV to the sharp edge induces sharp excursions in the surface static pressure. This high suction pressure signature would alter the surface pressure distribution and have a profound influence on aerodynamic loads. Typically, for airfoils in subsonic flows, the center of pressure is situated at $x/c = 0.25$ from the edge facing the flow; in the case of reverse flow this would be at 0.75c from the blunt edge. However, due to the presence of the SEV, the center of pressure is shifted further downstream to $x/c = 0.30$ which means 0.7c from the blunt edge. A pressure extraction technique was used to obtain static pressure fields from stereo PIV.
fields. The method uses the velocity field and solves the Navier-Stokes equation for the pressure field, with a Polhamus Suction Analogy technique used to capture the pressure in recirculating flow zones. The technique is described in a Letter which is currently under review. The arxiv id for the article is (arXiv:1804.06047), and the authors will cite this article after its publication.

Figures 23 and 24 show the pressure distribution on the rotor surface. The coefficient of pressure (Cp) is shown at various radial locations, and chordwise locations directed from the sharp edge (S.E.) to blunt edge (B.E.). The presence of suction pressures on the bottom surface of the rotor is indicative of the negative thrust generation in the reverse flow region. At 240 degrees azimuth, the low pressure signature of the SEV extends up to \( x/c = 0.1 \) and is followed by a flatter region with \( C_p = -0.2 \). At 270 degrees azimuth, the low pressure signature extends even beyond \( x/c = 0.25 \). The vortex core is stretched at 270 degrees azimuth with higher axial velocities resulting in higher suction pressures. The expansion of pressure signature of the SEV on the surface from 240 degrees to 270 degrees indicates a change in the center of pressure. Figure 23 shows higher suction pressures in the inboard locations, thereby creating a negative pressure gradient towards the rotor hub. Whereas, the centrifugal stresses caused by the obvious rotation of the rotor would be directed towards the rotor tip. The sustenance of the SEV is dictated by the negative pressure gradient that counteracts the centrifugal stresses.

### I. Life cycle of the SEV

SPIV measurements were performed at smaller increments in azimuth around 240, 270, 290 and 300 degrees azimuth. The velocity fields were obtained at \( \Psi \pm 5^\circ \) at several radial stations for different advance ratio. The average azimuthal gradient \( \left( \frac{d\Gamma}{d\Psi} \right) \) of the circulation is obtained from several radial locations at a given azimuth.

Table VII and Figure 25 show the azimuthal gradient of circulation. The reverse flow region before 270 degree azimuth can be considered as the “evolution” phase and the region after 270 as the “dissipation” phase. In the evolutionary phase, the gradient increases from 240 degrees to 270 degrees. The SEV evolves in this region due to the feeding of vorticity from the sharp edge. The higher advance ratios show higher gradients of circulation. This may be attributed to higher feed rates of vorticity from the sharp edge or to the transfer of kinetic energy...
energy from the mean flow into rotational energy of the vortex. Beyond 270 degrees azimuth is the dissipation phase wherein the SEV bursts or decays. The feed of vorticity from the sharp edge is not sufficient to sustain the vortex. It is counterbalanced by the factors assisting its decay. The counteracting factors are unknown at this point from this research. The circulation gradient in the dissipation region gives a metric for the earlier defined qualitative term “history effects” attributed to the behavior of SEV beyond 270 degrees azimuth. The circulation gradients increase monotonically in the evolutionary phase with the increase in advance ratio, but such a monotonic behavior is not observed in the dissipation phase.

| Ψ (deg) | $\Gamma_\mu$ (m²s⁻¹rad⁻¹) $\mu = 0.7$ | $\Gamma_\mu$ (m²s⁻¹rad⁻¹) $\mu = 0.85$ | $\Gamma_\mu$ (m²s⁻¹rad⁻¹) $\mu = 1.0$ |
|---------|---------------------------------|---------------------------------|---------------------------------|
| 240°    | 0.097 ± 0.017                   | 0.214 ± 0.052                   | 0.416 ± 0.193                   |
| 270°    | 1.167 ± 0.161                   | 1.335 ± 0.262                   | 0.948 ± 0.424                   |
| 290°    | 0.527 ± 0.067                   | -0.215 ± 0.806                  | -0.051 ± 0.072                  |
| 300°    | 0.137 ± 0.114                   | -0.005 ± 0.909                  | -0.310 ± 0.385                  |

FIG. 25. Circulation gradient at various advance ratios

VII. CONCLUSIONS

The morphological features of the sharp edge vortex observed in the reverse flow regime is established in this paper. The similarities with the leading edge vortex on a delta wing draws in attention towards the geometric sweep angle as a key feature to study the life cycle of a sharp edge vortex. The source of vortex generation could be due to the pitching and flapping rate of the rotor blade, but the sustenance of the vortex is dictated by the sweep effects and the differential on-set velocity.

1. As analogous to a forward swept fixed wing, the sharp edge vortex originates at the interface of advancing flow and reverse flow in the forward quadrant. The differential onset velocity gradient induces higher dynamic pressures at the inboard locations there by introducing an inboard directed radial flow. At higher advance ratios, the reverse flow envelope increases and the vortex origination happens further outboards.

2. With the advancement of the rotor blade, the vortex size and strength increases. This is analogous to a fixed wing transitioning from higher sweep angles to moderate sweep angles. The sharp edge vortex ceases to grow as the blade approaches 270 degrees azimuth, or the zero sweep angle.

3. Beyond 270 degrees azimuth, the rotor blade behaves like a backward swept wing. The differential onset velocity gradient changes its sign in the aft quadrant, resulting in higher dynamic pressures at the outboard locations. This effect induces a non-monotonic behavior on the evolved vortex near 270 degrees azimuth. The non-monotonic behavior is predominantly observed in the advance ratio effects and morphological features of the sharp edge vortex.

4. The convection speed of the vortex in the rotor reference frame ranges between $0.07U_\infty - 0.27U_\infty$, which is much smaller as compared to the convection speed of a free vortex. The relatively long convection times results in a near stationary helical vortex, feeding upon the vorticity generated at the sharp edge. The convection speed of the sharp edge vortex shows a parabolic behavior along the span of the rotor blade, and the minima shifts outboards at higher advance ratios.

5. The vortex core is relatively small in the forward quadrant. The velocity profile is linear in the core due to solid core rotation, followed by a power law decay. At 270 degrees azimuth, the velocity profiles show the signs of a burst vortex, wherein the solid rotation core extends to the outer periphery of the vortex. The axial velocities have a prominent peak in the forward quadrant. Whereas at 270 degrees azimuth and beyond, the axial velocity peak flattens out with higher velocities over a broader area.

6. The high suction pressures in the core of the vortex induces sharp excursions in the surface static
pressures. The pressure signatures of the sharp edge vortex on the rotor surface denote the shift in the center of pressure. At 240 degrees azimuth, the negative pressure gradient is directed radially inboards, counteracting the outboard directed centrifugal stresses.

7. The evolutionary phase of the sharp edge vortex shows a monotonic increase in circulation gradient with the increase in advance ratio. The sharp edge vortex is evolved completely as it approaches 270 degrees azimuth. Beyond 270 degrees azimuth, the sharp edge vortex decays non-monotonically with advance ratio. The feed of vorticity from the sharp edge also decreases beyond 270 degrees azimuth.

8. While the origin of a sharp edge vortex could be due to flapping rate, or pitching rate, or vorticity feed rate, the sustenance of the vortex is primarily due to the apparent sweep effects and onset velocity gradient. The feed of vorticity from the sharp edge alone would not be sufficient to sustain the vortex. It is counterbalanced by the factors assisting its decay. The counteracting factors are unknown at this point from this research.

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[1] D. Walsh, S. Weiner, K. Arifian, T. Lawrence, M. Wilson, W. Millott, and R. Blackwell, “High airspeed testing of the sikorsky x2 technology demonstrator,” (2011).
[2] A. Datta, H. Yeo, and T. R. Norman, “Experimental investigation and fundamental understanding of a full-scale slowed rotor at high advance ratios,” (2013).
[3] A. H. Lind, J. N. Lefebvre, and A. R. Jones, “Experimental investigation of reverse flow over sharp and blunt trailing edge airfoils,” (2013).
[4] J. B. Wheatley and M. J. Hood, “Full-scale wind-tunnel tests of a pca-2 autogiro rotor,” (1936).
[5] J. Evans and T. Krauss, “Model wind tunnel tests of a reverse velocity rotor system,” (1973).
[6] A. Bagai, “Aerodynamic design of the x2 technology demonstrator main rotor blade,” (2008).
[7] A. Ruddell, W. Groth, and R. McCutcheon, “Advancing blade concept (abc) technology demonstrator.” (1981).
[8] N. Hiremath, D. Shukla, V. Raghav, S. Pirau, and N. Komerath, “Effects of advance ratio and radial location on the vortex structure on a rotating blade in reverse flow,” (2015).
[9] M. Knight and C. J. Wenzinger, “Wind-tunnel tests on a series of wing models through a large angle of attack range.” (1929).
[10] E. N. Jacobs and A. Sherman, “Airfoil section characteristics as affected by variations of the reynolds number,” (1937).
[11] C. Critzos, H. Heyson, and R. W. Boswinkle, “Aerodynamic characteristics of naca 0012 airfoil section at angles of attack from 0 to 180 degrees,” (1955).
[12] F. E. Bradley, “An expression for rotor blade section loading including reversed flow effects.” (1956).
[13] J. R. Meyer Jr and G. Falabella Jr, “An investigation of the experimental aerodynamic loading on a model helicopter rotor blade,” (1953).
[14] G. E. Sweet, J. L. Jenkins, and M. M. Winston, “Wind-tunnel measurements on a lifting rotor at high thrust coefficients and high tip-speed ratios.” (1964).
[15] J. L. MacCloud, J. C. Biggers, and R. H. Stroub, “An investigation of full-scale helicopter rotors at high advance ratios and advancing tip mach numbers,” (1968).
[16] B. D. Charles and W. H. Tanner, “Wind tunnel investigation of semirigid full-scale rotors operating at high advance ratios.” (1969).
[17] F. D. Harris, “Rotor performance at high advance ratio: Theory versus test.” (2008).
[18] T. Quackenbush, D. Wachspress, R. McKillip Jr, and M. Sibilia, “Aerodynamic studies of high advance ratio rotor systems,” (2011).
[19] M. Potsdam, A. Datta, and B. Jayaraman, “Computational investigation and fundamental understanding of a slowed uh-60a rotor at high advance ratios,” (2012).
[20] A. Datta, J. Sitaraman, I. Chopra, and J. D. Baeder, “Cfd/csd prediction of rotor vibratory loads in high-speed flight,” (2006).
[21] A. Flax, “General reverse flow and variational theorems in lifting-surface theory,” (2012).
[22] R. Niemiec, G. Jacobellis, and F. Gandhi, “Reversible airfoils for stopped rotors in high speed flight,” (2014).
[23] J. Carter and J. Roncz, “Airfoil suitable for forward and reverse flow,” (2001).
[24] Mark Potsdam, Anubhav Datta, and Buvana Jayaraman, “Computational investigation and fundamental understanding of a slowed uh-60a rotor at high advance ratios,” Journal of the American Helicopter Society 61, 1–17 (2016).
[25] Thomas R Norman, Patrick Shinoda, Randall L Peterson, and Anubhav Datta, “Full-scale wind tunnel test of the uh-60a airloads rotor,” (2011).
[26] Matthew W Floros and Wayne Johnson, “Performance analysis of the slowed-rotor compound helicopter configuration.” Journal of the American Helicopter Society 54, 22002–22002 (2009).
[27] B Berry and I Chopra, “Performance and vibratory load measurements of a slowed-rotor at high advance ratios,” Proceedings of the 68th Annual Forum of the American Helicopter Society, (Fort Worth, TX), (2012).
[28] S. Kottapalli, “Performance and loads correlation of a uh-60a slowed rotor at high advance ratios,” (2012).
[29] Sesi Kottapalli, “Enhanced correlation of smart active
flap rotor loads,” *52nd AIAA, ASME, ASCE, AHS, ASC Structures, Structural Dynamics and Materials Conference 19th AIAA, ASME, AHS, Adaptive Structures Conference* 13th, 1874 (2011).

[30] H. Yeo, “Investigation of uh-60a rotor performance and loads at high advance ratios,” (2012).

[31] B Ortun, M Potsdam, H Yeo, and KV Truong, “Rotor loads prediction on the onera 7a rotor using loose fluid/structure coupling,” *AHS 72nd Annual Forum Proceedings, West Palm Beach, Florida, USA*, (2016).

[32] Jin-Ho Park and Duck-Joo Lee, “Numerical simulation of vortex-wedge interaction,” *AIAA journal* 32 (1994).

[33] Andrew Hume Lind, “An experimental study of static and oscillating rotor blade sections in reverse flow,” (2015).

[34] Andrew H Lind and Anya R Jones, “Unsteady airloads on static airfoils through high angles of attack in and reverse flow,” *Journal of Fluids and Structures* 63, 259–279 (2016).

[35] Andrew H Lind, Luke R Smith, Joseph I Milluzzo, and Anya R Jones, “Reynolds number effects on rotor blade sections in reverse flow,” *Journal of Aircraft* 53, 1248–1260 (2016).

[36] Andrew H Lind, Luke R Smith, Joseph Milluzzo, and Anya R Jones, “Reynolds number effects on airfoils in reverse flow,” *53rd AIAA Aerospace Sciences Meeting*, (1973) (2015).

[37] R Ormiston, “A new formulation for lifting rotor performance including comparison with full-scale data,” *Annual Forum Proceedings-American Helicopter Society*, 64, 1799 (2008).

[38] Robert A Ormiston, “Rotor aerodynamic characteristics at high advance ratio relevant to compound rotorcraft,” *American Helicopter Society Vertical Lift Aircraft Design Conference, San Francisco, California, USA, (2012).*

[39] Robert A Ormiston, “An analytical formulation for lifting rotor induced power,” in *AHS International 65th Annual Forum and Technology Display, Grapevine, TX* (2009).

[40] D. Shukla, N. Hiremath, V. Raghav, and N. Komrath, “Dynamic effects in the reverse flow velocity field,” (2015).

[41] V. Raghav, M. Mayo, R. Lozanno, and N. Komrath, “Evidence of vortex-induced lift on a yawed wing in reverse flow,” *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 228, 2130–2137 (2014).

[42] Edward C Pollannus, “A concept of the vortex lift of sharp-edge delta wings based on a leading-edge-suction analogy,” (1966).

[43] V. Raghav, “Radial flow effects on a retreating rotor blade,” (2014).

[44] Markus Raffel, Hugues Richard, Klaus Ehrenfried, B Van der Wall, C Burley, P Beaumier, K McAlister, and Kurt Pengel, “Recording and evaluation methods of piv investigations on a helicopter rotor model,” *Experiments in fluids* 36, 146–156 (2004).

[45] Markus Raffel, Christian E Willert, Steven T Wereley, and Jurgen Kompenhans, *Particle Image Velocimetry: a Practical Guide* (Springer, 2013).

[46] N.J. Lawson and Jie Wu, “Three-dimensional particle image velocimetry: Experimental error analysis of a digital angular stereoscopic system,” *Measurement Science and Technology* 8, 1455 (1997).

[47] Qing Wang and Qijun Zhao, “Experiments on unsteady vortex flowfield of typical rotor airfoils under dynamic stall conditions,” *Chinese Journal of Aeronautics* 29, 358–374 (2016).

[48] JE Rossiter, “Wind tunnel experiments on the flow over rectangular cavities at subsonic and transonic speeds,” (1964).

[49] II Kaufman, G Louis, Algirdas Maciulaitis, and Rodney L Clark, “Mach 0.6 to 3.0 flows over rectangular cavities,” (1983).

[50] Laurent Graffieux, Marc Michard, and Nathalie Grosjean, “Combining piv, pod and vortex identification algorithms for the study of unsteady turbulent swirling flows,” *Measurement Science and technology* 12, 1422 (2001).