Discrete Structures in the Radial Flow Over a Rotor Blade in Dynamic Stall

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This paper confirms the finding of discrete quasi-periodic streamwise vortical structures in the radial flow behind the separation line over a rotor blade undergoing dynamic stall in forward flight. It follows our finding of such structures over a blade undergoing transient stall induced by an inflow obstructer in a hover facility. Co-rotating structures suggest that the free shear layer formed at stall rolls up into discrete cells. The spanwise spacing of structures is approximately the height of the separated flow region. The presence of these structures helps explain the nature of the radial flow variation from root to tip in the separated flow region. This, as far as we know, is the first capture and measurement of the quasi-periodic radial velocity field on a rotating blade, and in particular of the profile of the strong radial velocity above a rotating blade in stall.

Nomenclature

ABS = Advancing blade side
RBS = Retreating blade side
PIV = Particle Image Velocimetry
PLSI = Pulsed Laser Sheet Imaging
u, v, w = Velocity in the x, y, z directions
x, y, z = Cartesian coordinate system in the stream, normal and span directions
U = Velocity
YAG = Ytrrium Alumnium Garnet crystal for a solid state laser
µ = Advance ratio. The ratio of freestream speed to blade tip speed.

I. Introduction

When a helicopter rotor operates in edgewise flight, the dynamic pressure encountered on the advancing blade side (ABS) is higher than that on the retreating blade side (RBS). To maintain equilibrium, the angle of attack on the RBS increases relative to that on the ABS. As the advance ratio \( \mu \) increases, the local angle of attack on the RBS may exceed its static stall value over a substantial portion of the blade. During maneuvers and operation at high altitudes, the rate of increase of angle of attack on the RBS is large enough that the angle of attack and lift coefficient may increase substantially past their static stall values, before stall occurs. This is accompanied by sharp changes in pitching moment and vibratory loads. Reattachment is delayed in a hysteresis loop which persists well into the next quadrant of the rotor disc. This phenomenon has

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been studied extensively as it is a limiter of flight speed at a given altitude and thrust; however, predicting the precise timing, extent and hence the rotor phase of dynamic stall and reattachment, remains elusive. One of the unknowns is the radial velocity field near the blade during dynamic stall. Centrifugal effects in the boundary layer are expected to drive a strong radial flow; however there is no direct evidence of such a sustained velocity field in experimental observations. The subject of this paper is the exploration of this radial velocity field. It is explored using a two-bladed rotor operated under dynamic stall conditions in a wind tunnel, as shown in figure 1.

A. Previous Work

Two-dimensional experiments on pitching airfoils in wind and water tunnels\(^1\) and numerical predictions\(^2\) have proceeded from inviscid formulations to full Navier-Stokes simulations. Detailed diagnostic experiments on dynamic stall by Chandrasekhara, Carr et al\(^3\) defined the role of compressibility in dynamic stall and more recently developed techniques for delaying dynamic stall using surface modifications. In the early 1990s it was concluded that 2-D dynamic stall models were overpredicting the severity of flight results on high-aspect-ratio helicopter blades. Research on 3-D dynamic stall showed that the stall initiation was a localized event, thus making the timing of the stall difficult to predict and control. For instance, Van Dommelen and Shen\(^4\) showed the development of a singularity at the onset of separation, followed by focused, sudden eruptions of boundary layer fluid into the outer stream. Lorber et al\(^5\) discuss the importance of delaying dynamic stall, and the application of separation control techniques to rotorcraft blade stall.

The high relative Mach numbers encountered on the advancing blade side (ABS) dictate the use of thin airfoils with small nose radius and a relatively flat upper surface to reduce shock drag and impulsive noise. As these blades pitch up on the RBS, the flow over the nosetip encounters large negative pressure coefficients (C\(_p\) of minus 5.4 shown at 0.5 percent chord),\(^5\) exacerbated by unsteady effects. Thus local Mach number reaches as high as 1.3. Carr and colleagues\(^3\) have shown the effects of shocks in the development of dynamic stall. Bousman\(^6\) shows that moment stall begins at an early azimuth where the freestream has a substantial spanwise inboard-directed velocity component. An inboard-directed radial velocity is also present due to the acceleration of inflow close to the blade leading edge. Close to the surface, radial acceleration must drive the boundary layer fluid outward along the span. This effect must become pronounced in regions of stall, because the fluid loses its momentum along the chord and stays over the blade for an extended residence time. This must generate a strong velocity gradient which changes rapidly as the spanwise component of the freestream comes to zero at 270 degrees azimuth. Thus, the correct fluid dynamics problem to simulate in experiments to capture stall initiation/suppression appears to be one of three-dimensional separation over a yawed or straight rotating wing with high radial acceleration at the surface. High aspect ratio is a secondary consideration since the focus is on phenomena occurring well inboard of the tip.

While the problem of 3-dimensional boundary layer development between rotating discs and on centrifugal compressor blades has been studied, there is much less found on airfoils for axial-type machines, perhaps due to the difficulty of conducting boundary layer measurements on rotating blades, and of including such detail in computational predictions, where the 2-dimensional flow is dominant. Early experiments in Germany showed anomalously high apparent local lift coefficients on propeller blades near the root. Coton\(^7\) cited the substantial differences in the inboard pressure distribution on rotating wind turbine blades compared to 2-D models, preceding dynamic stall. He also cited the delay in forward movement of the separation region (prior to lift-off of the dynamic lift vortex) due to spanwise flow. Corten\(^8\) used a stall flag method to capture the occurrence of stall on full-scale wind turbine blades. In the dynamic stall region, there was a substantial radial pressure gradient and accompanying radial flow. Corten also cited laser velocimetry

\[\text{Figure 1. Sample PIV image window shown on the rotor at the 270 degree azimuth} \]
showing the formation of vorticity directed parallel to the rotor axis along the aft portions of the blade. Radial acceleration must have a strong influence on the lift and pitching moment evolution after stall occurs. Xu\cite{9} showed a substantial stall delay in the 3D case in full Navier-Stokes simulation, compared to the 2D cases with no rotation effect. Liou\cite{10} at our laboratory compared laser velocimeter results for the same blade operated as a rotor in the 9 facility used in the present work, and as a fixed-wing with the appropriate inflow correction in a 7 x 9 low speed wind tunnel. We found, in cross-flow measurements made at the blade trailing edge, a substantial radial flow induced in the separated zone, compared to the fixed-wing measurements. The angle of attack in the wind tunnel was set to correspond to the pitch angle, corrected for the averaged inflow from the rotor experiment. At the trailing-edge cross-flow plane, the radial velocity was drastically different between the rotating and fixed tests. The effect of the radial acceleration was clearly visible as a stoppage of the radial inflow velocity compared to the fixed-wing mode.

B. Summary of Results from Transient Stall in a Hover Facility.

To summarize the above, it is appropriate to capture the radial flow in a low-Mach number facility. The phenomena of interest occur behind the stall line, and hence deal with fluid that is moving slowly in the rotating frame of reference relative to the rotating blade. Thus, compressibility effects, which are important to the mechanism through which stall occurs,\cite{11} are not important in the flowfield behind stall. In addition, these phenomena occur on the inboard portion of the blade, where local blade tangential velocity is low.

The inflow to a single-bladed rotor set at high pitch angle was interrupted over a selected sector to trigger transient inboard flow separation as shown in figure 2(a). A single NACA0012 blade with a counterweight is driven on a horizontal shaft inside the test cell, with a wake inductor and honeycomb downstream. A plate in the shape of a 60-degree sector is mounted upstream of the rotor disc to restrict the inflow velocity over that part of the disc. PLSI and PIV were used to verify the occurrence of separation, and to capture features of the separated flow at rotor RPMs ranging from 70 to 500. The blade was initially set with the obstructor removed, at a pitch setting well beyond the static blade section stall angle, so that the blade stayed below stall only due to the inflow. With the obstructor installed, the local angle of attack would suddenly exceed stall over the obstructed sector.

Results verified the occurrence of stall in the obstructed-inflow sector, as well as the presence of lift elsewhere in the rotor disc, thus validating the forcing technique. In the stalled region, the radial inflow was stopped near the rotor blade, but strong outward flow was not seen to develop. This appeared to be due to the presence of separation cells along the radius as schematically shown in figure 2(b). The extent of each flow structure is limited to only a couple of centimeters. The columnar flow is distinguished in contour plots of velocity by the presence of regions of opposite flow rotation on either side.

Detailed velocity contour plots of the results are presented in Ref. 12. When several instances of the
velocity field are viewed, basically the same behavior is observed in approximately the same locations; however, the phenomenon is not amenable to phase-locking with the rotor azimuth.

This experiment succeeded in demonstrating that a repeatable stall event was induced, in order to develop diagnostic concepts without the complexities of a forward-flight rotor setup. The interesting fluid dynamics result seen there is that the radial flow rolls up into vortical structures, whose axes were aligned roughly along the blade chord. These features prevented discrete filaments of fluid from remaining in the highly accelerated blade boundary layer, and thus mitigate the centrifugal pumping effects.

II. Results on the Radial Flow Over the Blade in Forward Flight Dynamic Stall

The existence of such structures in the stalled flowfield in forward flight was investigated using a 2-bladed rotor in the John J. Harper wind tunnel. A teetering rotor with adjustable collective and cyclic pitch removed the need to fly the rotor to its operating condition. The hub and swashplate were from a 2700 N (600 lb) gross weight personal helicopter kit, while the two 0.62m span NACA0012 blades were cut to length from one of the 3.25m span metal blades in the kit. Pitch links were strengthened for the dynamic stall rig shown in figure 1. Facility parameters are in Table 1.

The size of the viewing plane used for flow visualization and PIV is shown on a picture of the RBS of the rotor in figure 1. The camera was initially mounted upstream of, and below the 270 degrees azimuth. Operating conditions were selected by trial and error, varying collective and cyclic at selected advance ratio to verify the occurrence of dynamic stall. The rotor speed was set at 200 RPM and the rotor advance ratio was set at 0.33. At 10 degrees collective and 5 deg. cyclic, the effective angle of attack at 270 degrees was calculated to be 18.6 deg., and flow visualization of the chordwise flowfield using mineral oil fog and PLSI verified separation over most of the blade chord at the mid-radius section. Cross-flow images suggest vortical structures in the stalled flow as the trailing edge of the blade passes the measurement plane.

At each image position, a matrix of dots on a paper board was used to calibrate spatial coordinates. The correction for the tilt of the measuring window was applied. One hundred image pairs were taken at each image location for cross-correlation. To reduce the number of erroneous vectors the interrogation window was increased to 128x128 pixels on the first pass and reduced to 64x64 on the second pass.

Figure 3(a) shows a sample velocity vector plot from instantaneous PIV data (100 microseconds between images), taken approximately 1 mm behind the trailing edge in the vertical/radial plane at 270 degrees rotor azimuth. The vectors are color coded by magnitude of the cross flow velocity, with yellow being largest and blue smallest. There are clearly discrete zones of radial flow, though now there is no actual upflow in the trailing edge plane, unlike the case with the inflow-obstructer experiment. The dashed lines show the approximate location of the blade trailing edge. The vertical dashed line indicates the nominal location of the image center, in this case r/R = 0.586. Sampling of numerous such flowfield results showed that the number of discrete zones in the viewing plane was approximately 4 on average, i.e., the spacing between the structures was roughly constant. This spacing worked out to be roughly the same as the nominal height of the separated flow region at the trailing edge of the blade, suggesting discrete vortical structures occupying the stalled region. The average structure diameter is 0.033m, while the height of separated flow region is 0.035 to 0.045m, calculated by assuming that separation occurs at the maximum thickness part of the blade at the given inclination angle.
(a) Sample PIV vector field acquired 1mm after blade trailing edge passage, centered at $r/R=0.586$. Vertical axis is stretched to make vectors visible.

(b) Schematic representation of the roll-up structures in the separated region above the rotor blade in dynamic stall.

Average structure dia $\sim 0.033m$; height of flow region $\sim 0.035-0.045m$

(c) Measurement windows

Figure 3. Instantaneous cross flow field showing discrete cells, corresponding to rollup of the radial flow, and PIV measurement windows.
This lends credence to an approximate model of the dynamic stall flowfield as shown in Figure 3(b), where the separating shear layer rolls into discrete structures that grow with downstream distance. The PIV window was moved in overlapping steps along the blade radius as shown in figure 3(c), and 100 image-pairs were captured at each position. To examine the radial velocity, three vertical lines were chosen in each window as shown. The radial velocity profile from individual velocity fields, was extracted along each vertical line.

Figure 4(b) shows the velocity profile at 0.418 m from the tip, which corresponds to \( r/R = 0.528 \). The vertical axis is the distance along the vertical (i.e., parallel to the rotor axis), and the range shown corresponds to \( z/R \) of 0.102, or \( z/c = 0.51 \), for the blade chord of 0.178 m. This is less than the height of the separated flow region, which is approximately 0.15 to 0.2R above the trailing edge. The bottom of the profile is at the blade surface. Positive radial velocity is flow moving outboard. The viscous boundary layer under the radial flow is partially captured. Above this thin region, the radial velocity profile reaches a peak, and then falls off. These features are qualitatively repeatable in all the images, however, the velocity field features above this region are not consistent from image to image. This is understandable for a separated flow region.

Figure 4(c) shows the profile at \( r/R = 0.643 \), and figure 4(d) shows it at \( r/R = 0.758 \). The peak radial velocity is lower than that at the more inboard location. This is attributable to the formation of the stall cells that exchange the radial flowing fluid away from the blade surface, and to the fact that the tip region is not stalled. Thus the chordwise extent of stall may be expected to be smaller as one moves outboard.

At \( r/R = 0.988 \), the tip vortex influence dominates. Figure 5 captures the tip vortex velocity field. At this condition, the tip vortex has a core diameter of approximately 0.16c, (or 1.33 times thickness), comparable to the expected 0.12c, if the core is the same size as the thickness of the airfoil. The center of the tip vortex is approximately at this location. However, the point is that the tip vortex is still fairly strong, indicating positive lift generation in the outboard region, whereas the inboard region is stalled. Again, substantial differences occur from one velocity field to another at the same blade azimuth (not shown here), above the radial flow region. This is to be expected, since it is a separated flowfield.

Next, mean and root mean square (RMS) radial velocity profiles were created. Figures 6(a) and (b) show the profiles of radial velocity averaged over 100 instances of the velocity field, at \( r/R = 0.586 \) and
Figure 5. Radial velocity profile at $r/R=0.988$, and corresponding flow image, showing the tip vortex.

Figure 6. Profiles of the average and root-mean-square variation of radial velocity over 100 samples, at the trailing edge.
0.814 respectively. Figures 6 (c) and (d) show the root-mean-square variations in the radial velocity at the respective locations. In the planar velocity fields, (not shown), the cells disappeared upon averaging as expected, showing that they are not precisely repeatable in location from one rotor cycle to another. Similar to the instantaneous radial velocity profiles, the radial velocity peaked close to the surface of the blade and decreased as the positions moved outboard. Again, positive radial velocity is flow moving outboard.

III. Discussion

Similar structures to those observed in this wind tunnel experimentation were seen in the inflow obstructer cases. These structures seem to be formed by the free shear layer formed at stall rolling into columns or cells. Unlike the inflow obstructer experiment, no upward flow was observed. Furthermore, these cells seem to be located within the separated region which leads to the assumption that they are forming at the point of separation. The spacing, although initially thought to be equal to the height of the separated region, cannot be clearly determined as the number of cells and the cells height above the surface vary greatly from image to image.

The radial velocity profiles that were created show strong radial outflow at inboard portions of the blade. As images moved outboard, the radial outflow decreased. This supports work done by Yang and colleagues that concludes that centrifugal flow is dominating over the inboard inflow at the trailing edge. Additionally, the tip vortex measurements correspond to the theory that there is deep stall inboard and weaker stall near the tip. This suggests that the stall line will move towards the trailing edge as one moves outboard as expected. These radial velocity profiles were repeatable near the surface of the blade.

A review of the literature on the nature of the separated flow over lifting surfaces, reveals very little on the dynamic stall flowfield, but does include some studies on stalled fixed-wings. The findings from these are briefly summarized below. Gregory appear to be the first to have studied this flowfield, and detected three-dimensional flow patterns on airfoils. They based their observations on surface visualization, and were interested in the problem of obtaining two-dimensional characteristics in the presence of such three-dimensionality. Winkelmann and Barlow extended these studies for a rectangular planform finite wing beyond stall, again focusing on the surface streaklines in oil flow visualization. Weihs and Katz reported cells in the post-stall flowfield over straight wings. Yon reported coherent structures in the wake of a stalled rectangular wing, and a NASA contractor report arising from Yons PhD thesis, showed cells in the separated flow, and fluctuations attributed to these cells. The issue here was the separation of the flow over flaps, with a span/flap chord ratio of 2. There is no mention of spanwise flow here.

Broeren and Bragg did a systematic study of structures in the separated flow, and fluctuations due to these. They developed a classification based on whether the separation was a trailing-edge separation or a leading edge separation. They found low-frequency oscillations characteristic of leading edge separation, with a separation bubble growing aftward. In this case it was essentially 2 D separation. On the other hand, spanwise separation cells were seen to arise from trailing-edge separation, but this was mostly steady. Thus from the above, it appears that spanwise cells have been observed in the stalled flow over fixed wings, and even on nominally 2-D airfoil test models. This raises the question whether the radial flow on rotating blades is a stabilizing influence that attenuates these structures and the resultant fluctuations, or is it a driver of such discrete structures, and fluctuations? An initial answer comes from the ensemble-averaged profiles of radial velocity and the root mean square variation of the profile, at each of the 3 vertical lines in each window, obtained from the 100-odd image pairs in each PIV window. The argument used for the initial hypothesis is as follows: If the radial flow is a stabilizing influence, then the rms fluctuation intensity in radial velocity should be higher in the region well above the wall, and low in the region where the strong radial flow exists. If the radial flow is a driver of instability, then high fluctuations should be seen in the regions of high radial velocity, nearer the wall. Clearly the RMS is highest near the wall layer, so that the fluctuations do appear to originate from the wall.

A. Measurements at different chordwise stations

Twelve image windows were examined. Of the four spanwise positions as shown in figure (c), position four was omitted because of the strong tip vortex influence there. Four chordwise positions were chosen for each of the other three: 2, 4 and 6 inches from the leading edge. One hundred image pairs were again
taken at each location. Discrete structures again appeared, except in the data forward of the separation line. The cell structures are strongest in the data closest to the surface (most forward locations downstream of the separation line). This supports the hypothesis that these cells are formed near the surface. The radial velocity was seen to again peak close to the blade surface and decrease outboard. This strengthens the theory that deep stall is occurring inboard and getting weaker towards the tip.

At each spanwise location, the radial velocity appears to remain essentially constant at all stations downstream of the separation line. Forward of the separation line the radial velocity begins to decrease as the inboard-directed inflow begins to dominate the flow. This conclusion is supported by Yang's experiments in phase one. The RMS profiles of all of the positions show the peak being close to the surface similar to the peak mean radial velocity. This suggests that all along the span and chord, the radial flow is a driver of instability.

### IV. Conclusions

Discrete structures were found in all measurement locations along the span and chord that fell downstream of the separation point. These started immediately downstream of the separation line. These cells did not have even spacings or consistent numbers per image and are not periodic on the rotating blades. The diameter of these cells decreased as measurement positions moved from the root of the blade to the tip and from the trailing edge to the point of separation. The radial velocity did not vary significantly along the chord, but varied significantly across a cell. It is believed that these structures are what prevent the centrifugal influence from further increasing the radial velocity as one moves from root to tip by exchanging elements of fluid away from the radially accelerated boundary layer. Radial velocity profiles created along the span and chord show strong radial outflow at inboard portions of the blade. This radial outflow peaks at points just above the blade surface. The radial flow for each measurement seems repeatable in the separated region. RMS profiles prove that the radial flow is a driver of instability. To summarize, then:

1. A single-blade hover facility was used in the prior reporting period to study temporal evolution of flow close to a rotating blade. An inflow obstructor was validated as a means of inducing transient stall to simulate dynamic stall features downstream of the separation line.
2. PLIS and PIV verified occurrence of stall based on stoppage of through-flow.
3. Downstream of the stall line in the inflow obstructor case, radial velocity along the blade sharply develops an outward direction. However, the formation of stall cells along the radius exchanges fluid away from the blade boundary layer.
4. Time-varying cells of radial flow separation in the inflow obstructor case, comparable in scale to blade chord, occurred in the flowfield downstream of the stall line. These were not phase-locked to the rotor.
5. The same form of structures appears clearly in the forward flight dynamic stall flowfield studied during this reporting period in a wind tunnel rotor experiment. Co-rotating structures similar to a shear layer appear, and suggest that the free shear layer formed at stall, rolls up into discrete structures, or cells. However, actual upflow regions are not observed.
6. The spanwise spacing of structures is approximately the height of the separated flow region.
7. Radial velocity profiles show strong radial flow inboard, and weaker radial flow at outboard stations, corresponding to the expectation of deep stall inboard and attached flow near the tip.
8. The boundary layer under the radial flow is captured in the PIV data.
9. The radial flow profile appears to be fairly repeatable near the surface. However, above this region, the velocity profile is not repeatable from one cycle to another.
10. Evidence from the profiles of the root mean square variation of radial velocity suggests that the instabilities originate from the surface rather than from the outside flow.
11. This, as far as we know, is the first capture and measurement of the quasi-periodic radial velocity field on a rotating blade, and in particular of the radial velocity profile above a rotating blade in stall.
12. The occurrence of discrete quasi-periodic but spatially repeatable vortical structures in this type of flow is also captured for the first time.

V. Acknowledgements

The authors gratefully acknowledge support of this work by the United States Army Research Office under Grant W911NF0410184. The technical monitor is Dr. Thomas L. Doligalski.

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