A Qualitative Examination of Dynamic Stall from Flight Test Data

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Abstract

Three flight conditions from the UH-60A Airloads Program are examined where dynamic stall occurs on the rotor: a symmetric pull-up that includes non-zero angular rates and accelerations; a high-speed, diving turn that includes non-zero angular rates, but nominally zero angular accelerations; and a level flight case with zero angular rates and accelerations. The two maneuver conditions result in severe pitch-link loads and represent design conditions for this military aircraft. Dynamic stall characteristics are identified in the section lift, the section pitching moment, and the trailing edge pressure and are used to create rotor disk maps that show the location and behavior of dynamic stall for this rotor. The measured blade pressures are used to examine the dynamic stall process itself and airfoil maps are developed that show the behavior of the dynamic stall vortex on the blade and its interaction with areas of supercritical flow. It is shown that the torsional dynamics of the rotor control where dynamic stall may occur, while the flight condition and the resulting aerodynamic inflow determine whether it will occur.

Notation

- \( a \): speed of sound, ft/sec
- \( b \): number of blades
- \( C_L \): lift coefficient
- \( C_{L_{max}} \): maximum static lift coefficient
- \( C_M \): moment coefficient
- \( C_{W/\sigma} = \frac{GW}{\pi \sigma \Omega^2 R^4} \): gross weight coefficient
- \( c \): blade chord, ft
- \( GW \): aircraft gross weight, lbs
- \( g \): acceleration due to gravity
- \( L \): section normal force, lbs/in
- \( M \): local Mach number
- \( M^2C_L = \frac{2L}{\rho a^2 c} \): coefficient
- \( \rho \): section pitching moment coefficient
- \( M_{L} \): upper surface pressure coefficient
- \( n_x \): sect. pitching moment, in-lb/in
- \( P/L_{osc} \): load factor, g
- \( p \): oscillatory pitch-link force (half peak-to-peak), lbs
- \( p_\infty \): surface pressure, lbs/ft^2
- \( q \): static pressure, lbs/ft^2
- \( R \): pitch rate, deg/sec
- \( \tau \): blade radius, ft
- \( \alpha \): radial coordinate, ft
- \( \phi \): chordwise coordinate, ft
- \( \theta \): angle of attack, deg
- \( \theta_{cont} \): induced flow angle, deg
- \( \theta_{elas} \): advance ratio
- \( \rho \): blade control angle, deg
- \( \rho \): blade torsional deformation, deg
- \( \sigma \): air density, slug/ft^3
- \( \Omega \): rotor solidity, bc/nR
- \( \psi \): rotor rotational speed, rad/sec
- \( \psi_{0.5c} \): rotor azimuth, deg
- \( \psi_{0.5c} \): rotor azimuth where dynamic stall vortex crosses 50% chord, deg

Introduction

Dynamic stall on a helicopter rotor in high-speed or maneuvering flight causes large blade torsional moments and control system loads and, in some cases, will size control system components for a new aircraft design. The ability of present analyses to predict rotor loads under dynamic stall conditions is largely unsatisfactory. Analytical approaches to this problem have, as a first step, examined the modeling of dynamic stall on a twodimensional (2D) basis. Much has been learned about the basic phenomenon from 2D wind tunnel testing (Ref. 1) and numerous empirical models have been developed that can be incorporated into conventional lifting-line analyses. In addition, recent calculations using a Navier-Stokes flow
solved with a variety of turbulence models (Ref. 2) have shown promising results, but again for the 2D problem. Experiments on an oscillating wing in a wind tunnel have been used to assess the importance of three-dimensional dynamic stall effects (Ref. 3) and initial evaluation, based on a variety of computational methods, suggests that 2D models provide a reasonable estimate of the computational task (Ref. 4). The recent availability of flight test data on a UH-60A, including measured blade pressures (Ref. 5) provides an opportunity to assess the accuracy of current analysis methods for the prediction of dynamic stall effects on an aircraft. A first step in the assessment process is a careful examination of the dynamic stall measurement obtained in flight. That assessment is the purpose of this paper.

The paper will initially discuss the nonlinear characteristics of airfoils and how this affects the loads that are seen on a helicopter at the limits of the flight envelope. These test cases from a UH-60A in flight will be examined to observe both similarities and differences in the effects of dynamic stall on the loads. Initially, dynamic stall will be observed in terms of conditions on the rotor, that is, where does blade stall occur in azimuth and rotor radius. Following this, examination of stall in a global sense the remainder of the paper will focus on details of dynamic stall on the blade sections. A number of conclusions will be offered relative to characteristics of dynamic stall on helicopter rotors.

**Dynamic Stall and Control System Loads**

A well-designed rotor will not experience significant dynamic stall effects developing. However, in maneuvering flight or under heavily loaded conditions a rotor will reach its thrust limit and dynamic stall will occur, resulting in increased blade torsion and control system loads. As an example, for the UH-60A, the pitch-link loads in severe maneuvers are about 2.5 times greater than the loads incurred in a speed of 160 knots. The cause of this increased loads is related to aerodynamic forces – the blade under stalled conditions. Figure 1 shows Cl as a function of CM for the UH-60A airfoil based on both static and dynamic 2D wind tunnel test data (Ref. 7 and 8). For lift coefficients below Cl,max, there is very little change in the moment with changes in lift as is typical of helicopter airfoils. The slightly negative moment in this region results in the negative mean pitch-link loads (compression) seen on this aircraft. For the static data the section moment increases strongly negative for all angles of attack beyond the maximum static lift coefficient. For the dynamic data, however, there is a lift increase or overhight that is related to dynamic stall on the blade. About 10 percent increase in Cl,max can be obtained beyond the static stall angle without severe penalties in section pitching moment and this overhlight regime is sometimes referred to as the "flight stall" region (Ref. 9). Beyond this region of light stall, large negative pitching moments dominate the problem and any slight improvement in lift performance is paid for in excessive control system loads. Within this region of large negative pitching moments, referred to as the "deep stall" region (Ref. 9), the extensive measurements and visualization that have been obtained from numerous 2D wind tunnel experiments provide a good understanding of the phenomena involved. As the angle of attack exceeds the dynamic stall limit one or more vortices are shed from the forward part of the airfoil. These vortices are convected back along the airfoil all at a speed somewhat less than the free stream and pass off the trailing edge. "Moment stall" is generally associated with the formation of the dynamic stall vortex while "lift stall" occurs when the dynamic stall vortex leaves the airfoil trailing edge. The dynamic stall process in the lift stall region is sensitive to various parameters and significant differences are seen between airfoils. Within the deep stall region, however, the dynamic stall behavior shows little difference between airfoils (Ref. 9).

The knowledge obtained on dynamic stall from 2D wind tunnel testing provides a useful basis for understanding dynamic stall on a helicopter rotor in forward flight (2D) or in 3D. Significantly different differences exist between the two environments and it is useful to mention some of these differences here. The angle of attack on an airfoil can be expressed as

$$\alpha = \theta_{e} + \theta_{l}$$

In a conventional 2D wind tunnel test, the model is made rigid so that elastic motion, even at the highest frequencies, is one to two orders of magnitude smaller than the control angle (Ref. 3). Similarly, the induced flow angle is normal to the blade and independent of the inflow induced by the fuselage. These angles are not easily measured or calculated. Pressure measurements obtained in flight will provide valuable information, particularly as concerns section normal force and pitching moment. However, the lack of an accurate knowledge of the blade angle of attack in flight will be a source of frustration in interpreting the data.

**UH-60A Flight Test**

A UH-60A helicopter was extensively instrumented for flight test measurements including the installation of 242 pressure transducers on one blade that are arranged to allow the calculation of section lift, pitching moment, and chord force at nine radial stations. The aircraft, its instrumentation, and the flight test program are described in Ref. 5. Maneuver data obtained during the test program have been examined and noted in order of the severity of the loading in Ref. 6. The data from two high-von-Kármán load maneuvers, a symmetric pull-up and a high-speed, diving turn, are used here as a basis for an examination of dynamic stall. In addition, a steady flight case at high altitude, near the rotor thrust boundary, is also selected. Figure 2 compares the selected test conditions with a rotor thrust boundary determined from model rotor test data by McHugh (Ref. 10). The y-axis is defined as the product of the vehicle load factor and the weight coefficients, n*CG/COH, to allow a comparison of both steady and maneuvering flight. The maneuver is a 2 ½ UTAS pull-up (Counter 11209), shown in Fig. 2 by plotting the mean n*CG/COH for each revolution as a function of the mean advance ratio. The aircraft is able, in this case, to achieve a rotor thrust boundary that is about 35 degrees off of the McHugh boundary, which is based on steady rotor performance. The second maneuver is a diving right turn at high speed (Counter 11239) and in this case the load factor is less than for the pull-up, but the airspeed is greater. The aircraft descent rate for this maneuver is about 4000 ft/min and a bank angle of about 55 degrees is achieved. Nominally, the angular accelerations for this maneuver are zero (unless the pitch attitude is being changed). In the third case, a steady flight condition at CG/COH = 0.13 (Counter 9017). Steady, level flight data were obtained at six values of CG/COH during this test program, as shown in Fig. 2, and the selected case was the maximum load flight condition obtained. The high loading for this condition was obtained by flying at high altitude to reduce density, rather than by increasing the gross weight. Specific revolutions

![Figure 1. Moment coefficient as a function of lift coefficient for SC1059 airfoil.](image)

![Figure 2. n*CG/COH as a function of advance ratio showing selected test conditions.](image)
cases and the azimuth associated with this event is one indicator of stall. In a similar manner the pitching moment time histories are examined and the radius and azimuth where moment stall is observed represents a second indicator of stall. Finally, the upper surface pressure time history at 0.96x is examined which shows whether the boundary layer is separated or attached and this represents a third indicator of stall on the disk. Each revolution of data in the maneuver is treated here as a separate event and the thrust, airspeed, pitch rate, and so forth are assumed to be represented by the mean values computed over the one revolution. This quasi-steady assumption is appropriate for the level flight case, but is an approximation for the maneuver cases.

Figure 4 shows the section normal force as a function of blade azimuth for Rev 14 of the UTTAS pull-up. The nondimensional section normal force, \( \frac{N}{p_c A_c} \), is normalized by the speed of sound rather than the local section velocity and, hence, is a global representation of force on the blade. The azimuth range shown is unconventional in that the starting azimuth is 135 deg, half way through the second quadrant of the rotor. This shift in the starting azimuth is because as stall on the UH-60A develops near the beginning of the third quadrant and, in some cases extends through the end of the first quadrant. By shifting the plot to the 135 deg reference it is possible to study the stall cycles in their entirety. In the plot of normal force in Fig. 4 the data at each radial station are offset by an arbitrary amount so that the behavior of the normal force at each radius can be clearly seen and related to the behavior at adjacent stations.

The rotor data were acquired at a fixed sample rate that is equivalent to an azimuth stepsize of about 0.72 deg. Anti-aliasing filters were used with a frequency cut-off of 550 Hz and this is equivalent to an azimuth stepsize of about 1.42 deg. For this paper the data obtained in the experiment on a time base have been transferred to an azimuth base using linear interpolation. The azimuth base selected here is a stepsize of 1.5 deg and is equivalent to the anti-aliasing filters used. No section data are shown at 0.55R for this counter because of instrumentation failures on the lower surface that prevent an integration of the acceptable pressure measurements.

The normal force time histories in Fig. 4 were examined for cases of lift stall and the associated azimuth was recorded as one indicator of dynamic stall on the blade. Lift stall is most clearly observed in Fig. 4 for the radial stations from 0.775R to 0.92R. Stall is initially seen between 273 and 278 deg. A second peak indicative of lift stall is seen at about 350 deg and is more prominent outboard. At the very beginning of the first quadrant, at about 5 deg, a limited area of lift stall can be seen towards the tip. Finally, in the center of the first quadrant lift stall is observed between 51 and 54 deg and extends from 0.675R to the tip. There is also a suggestion of lift stall at about 172 deg and 0.233R and also at about 150 deg at 0.40R although its occurrence is unclear. A short duration pulse at 272 deg at 0.225R is seen just before the reversed flow boundary and this is caused by a disturbance at the rear of the airfoil, mostly at 0.40R. The change in pressure is unknown and it does not occur in other revolutions for this maneuver or in the other maneuvers. Although the azimuth of lift stall is determined to the nearest 1.5 deg, as defined by the resolution of the data, the accuracy of this determination is less. In some cases it is unclear which of two or more features in the time history best indicates lift stall and, in these cases, multiple azimuths are recorded.

The section moments for the UTTAS pull-up, Rev 14, are shown in Fig. 5 in the same offset plot format as in Fig. 4. These time histories were examined to identify incidences of moment stall and the azimuths associated with moment stall were recorded. In Fig. 5 moment stall is observed at nearly all of the stations and, where most pronounced, appears similar to traces of moment stall data obtained in 2D wind tunnel tests. Moment stall is observed at the inboard stations, occurring at 164 deg at 0.225R and 166 deg at 0.40R. Outboard, from 0.775R to 0.92R, moment stall associated with a first dynamic stall cycle is seen from 252 to 263 deg. A second stall cycle is apparent from 0.675R to the tip and occurs between 320 and 350 deg. A third cycle, occurring at about 45 deg to the first quadrants causes large moments from 0.775R to 0.92R, but not outboard.

Trailing edge pressure data are shown in Fig. 6 for Rev 14 of the UTTAS pull-up using the offset plot format. Under normal flight condition the trailing edge pressures show little variation with azimuth except that outboard on the rotor, there is a slight lobe variation that peaks in the fourth quadrant. The time histories in this figure, however, all show significant excursions in the pressure that are associated with boundary layer separation and leading by the dynamic stall vortex. These trailing edge pressures were examined to identify these separation events and the associated azimuths were recorded. Inboard, at 0.225R, the flow starts to separate at about 176 deg and then reattaches at about 227 deg. There is a similar area of separation at 0.40R and interestingly, a very small area of separation at about 15 deg that is associated with the second stall cycle. At 0.675R to 0.85R three distinct areas of separated flow are observed and these correspond

with the three stall cycles seen in the pitching moment data. At 0.92R it appears that the separated flow associated with the first dynamic stall cycle continues into the second cycle and the boundary layer is never able to reattach. At 0.96R the flow appears to be separated continuously from 282 to 17 deg. At 0.99R, about three in from the blade tip, minor flow separation is observed beyond 315 deg that is associated with dynamic stall, but the greatest effects seen are around 270 deg where a large separation zone forms that is probably related to the tip vortex lifting off the tip portion of the airfoil under these high lift conditions.

The azimuths identified from the qualitative analysis of the time histories of normal force, pitching moment, and trailing edge pressures, as described above, are mapped onto the rotor disk at a moment capturing how stall occurs on this rotor. Figure 7 provides such a map of blade stall for the UTTAS pull-up. Rev 06, the only to the maneuver. The rotor maps are shown for every other revolution through the maneuver. The rotor maps are centered in the conventional fashion with the 0 deg azimuth at the rear of the disk and with the wind coming from the front at 180 deg. A reference line is shown at 135 deg as a reminder that the data analysis starts at this azimuth. The circumferential lines on the maps represent the nine measurement stations plus the blade tip at 1.08R. These circumferential lines are shown as dotted lines for the radial stations with the SC10095 airfoil and as dashed-dashed lines for sections with the SC10048R airfoil. The SC10048R is a modification of the SC10095 with added carver and droop at the nose and is used over the center span of the blade. Moment
stall azimuths are shown with an open circle and, where appropriate, a line connects adjacent stations. The lift stall azimuth locations are indicated with an "x" in a similar fashion. Separated flow is shown with a dotted boundary and the portion of the disk where the flow is separated is shown with a hatched area. Adjacent edges in each rotor map are the mean values of the advance ratio, load factor, pitch rate, and oscillatory pitch-link load during the single revolution that is mapped. The section forces and moments could not be obtained for the 0.55R station because of failed instrumentation on the lower surface. Moreover, the upper surface pressure transducer at 0.96Sc at 0.55R also failed but it was possible to use the lower surface transducer at 0.96Sc to indicate regions of separated flow. Thus the maps include markers for separation at this station but none for lift or moment stall.

Rev 06, Fig. 7a, is essentially the starting point of the maneuver with $\mu = 0.358$, the load factor just above one g, and the pitch rate non-zero. There is no indication of stall anywhere on the rotor disk. As the pitch rate becomes positive and the load factor increases in Rev 08, there are signs of moment stall just past 180 deg for the two inboard stations and two patches of separated flow are observed at the aft edge of the disk towards the tip of the blade. There are indications of stall associated with both patches although moment stall was detected only prior to the first patch. For Rev 10, the airspeed has not begun to bleed off, while both the load factor and pitch rate continue to increase. Four patches of separated flow are observed for this revolution, three outboard on the blade and mostly towards the rear of the disk and one patch inboard on the blade just to the left of the nose of the aircraft. It seems clear that this loaded pitch in is related to an increase in the local angle of attack that is induced by aerodynamic flow over the nose of the aircraft. At Rev 06 the engine pitch attitude is between four and five deg, but as the nose is pitched up, the fuselage angle of attack becomes progressively higher. While the pitching moment attitude is about plus six deg and rapidly increasing. The first two stall cycles for Rev 10 give clear indications of both lift and moment stall, while the third cycle only shows indications of lift stall. Clear, unambiguous signs of lift stall or moment stall are not always obvious in the normal forces and pitching moments data and, in these cases, no marker is placed on the rotor map. In other cases, there may be an obvious indication of lift or moment stall, but some ambiguity in the azimuth at which it occurs. In some cases two or more markers are used to indicate a stall event, for example, in Rev 10 for the lift stall in the second cycle. The use of multiple markers is an indication of uncertainty in identifying the azimuth of lift stall in the critical area. The maximum pitching rate is reached in Rev 12, although the load factor is still below its maximum and the alternating loads are only about 70% of the maximum observed in the maneuver. The stall on the inboard blade stations that occurs over the nose of the aircraft is now connected in a continuous fashion with the first stall cycle on the outer part of the blade. Because the radial location of stall for this first cycle is such a strong function of azimuth, stall is only occurring over a limited portion of the blade at any one time. There is some indication of lift in Rev 03, and the flow is not completely reattaching before the second stall cycle begins. However, full reattachment is achieved prior to the third stall cycle in the second quadrant.

Rev 14 is the first of the revs at the top of the high pitch-link load conditions indicated in Fig. 5. The advance ratio is still above 0.34, the load factor is about 2.1 g, and the pitch rate remains near its maximum. The first dynamic stall cycle appears to be continuous from the nose inboard stations, where it occurs over the nose of the aircraft at about 170 deg to the blade tip where moment stall starts just before the 270 deg azimuth. Outboard of 0.86Sc the boundary layer never reattaches between the first and second stall cycles but remains separated for a full quadrant. Near the end of the second stall cycle outboard there are indications of lift stall, even though the flow has not reattached (see also Fig. 4). At the beginning of the first quadrant the boundary layer reattaches along the entire blade and then, at about 45 deg, stall occurs simultaneously from 0.55R to the tip.

Although the airspeed is reduced in Rev 16 the load factor and oscillatory pitch-link loads remain at their peak. The area of separated flow that connects the first two stall cycles now extends inboard of 0.77Sc. Even though the flow is fully separated there are clear indications of moment stall in the section moment data from 0.77Sc to 0.92R. By Rev 18 the advance ratio has decreased to 0.315, but the load factor is still in excess of two. The separated flow region that connects the first two cycles now extends inboard of 0.55R. At this point in the maneuver, over a quarter of the disk is further separated. The third stall cycle, at the end of the first quadrant on the advancing side, still remains distinct from the first two cycles. Rev 20 shows significant areas of separation connecting the first two stall cycles as was seen in Rev 18. For Rev 10, the aircraft pitch at reattached flow that occurs at 0.86Sc and 0.92R between the first and second cycles. The third stall cycle appears much as before, based on this qualitative map, but the amplitudes of the moments for the third cycle are significantly reduced in Rev 20 from Rev 18. The mean advance ratio has dropped to 0.291 by Rev 22 and the mean load factor to 1.56. Interestingly, the alternating pitch-link loads still exceed 2500 lbs while the pitch rate is now slightly negative. There is some indication of stall in the first half of the third quadrant, but it is not clear how this is related to the stall cycle that starts just prior to 270 deg at the outboard stations. The flow reattaches after this cycle and a new stall cycle starts again at about 330 deg. The third stall cycle, in the last part of the first quadrant, that had been prominent in previous revolutions is largely gone. There is no clear indication of lift or moment stall and the separated flow mapped here may be more directly related to shock-boundary layer separation than dynamic stall. As the aircraft recovers in the maneuver the loads decline rapidly as the number and extent of the stall cycles decline.

Rev 24 two stall cycles remain, but the areas of separated flow have lessened. Finally, in Rev 26, moment stall is observed only at two small areas for 0.92Sc and only a small area of separated flow is associated with each patch.

The examination of stall growth and decay during the UTTAS pull-up is valuable for the perspective it provides on the development of stall on the rotor disk during limiting flight conditions. However, it is not immediately apparent how much of the stall characteristics observed are dependent upon unsteadiness in the aircraft state during the maneuver and how much is directly associated with the basic stall characteristics of the airfoil and the elasticity of the blade and controls. The second maneuver of interest for this paper is a high-speed, diving turn and, nominally, all angular accelerations are zero and the only difference from a steady case are the non-zero angular rotations that are associated with the steady turn. As a practical matter, obtaining steady conditions in a diving turn is a difficult piloting task, but it appears that at least four contiguous revolutions near the peak load factor obtained for this maneuver are repeatable (Ref. 12). One revolution from this maneuver has been examined, Rev 20, using the same qualitative approach as described for the UTTAS pull-up. Figure 8 shows the rotor map for this case and although the advance ratio, 0.39, is higher than in the UTTAS pull-up, the load factor is less. The oscillatory pitch-link loads of 2600 lbs are comparable to the most severe loading in the UTTAS pull-up. Comparison of this figure with Rev 14 of the pull-up, Fig. 7e, shows some similarities, particularly in the distribution of the first and third stall cycles and the extent of the separated flows. However, what is lacking in Fig. 8 is an indication of a second stall cycle beginning near 330 deg. Outboard on the blade there appears to be a limited area of lift stall and, perhaps, a bit of moment stall at 0.67Sc, but there is no clear indication of a new stall cycle starting at the middle or end of the fourth quadrant. The differences with, for instance, Rev 14 or Rev 22 of the UTTAS pull-up remain as interesting as do the similarities.

The third test condition examined is the maximum level flight loading case obtained in the flight test program. This level flight condition was flown just under 17,000 ft to obtain a high thrust coefficient by using decreased density instead of increased weight. As shown in Fig. 2, the Caw of 0.13 is at the steady thrust boundary as determined by McFlug. The rotor map for this condition is shown in Fig. 9 and two stall cycles can be seen in much the same positions as observed in Figs. 7 and 8. Note, however, there is no indication of a third stall cycle in the first quadrant of the rotor. As is expected for a level flight condition, the pitch attitudes of the aircraft is nose down and little effect of fuselage induced flow should be evident on the rotor and that is, in fact, the case as there is no suggestion of stall over the aerofoil nose. The first stall cycle is seen to start midway through the third quadrant and then move outboard to 330 deg at 0.95Sl. The flow reattaches and then a second cycle occurs towards the end of the fourth quadrant. This steady case shows strong similarities with both the UTTAS pull-up and the diving turn in terms of the stall map. Note, however, that the oscillatory pitch-link loads are much lower. This is a result, in part, of the low density at the flight altitude for this condition.

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**Figure 8. Dynamic stall rotor map for high-speed, diving turn; Rev 20.**

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**Figure 9. Dynamic stall rotor map for steady, level flight; Rev 01.**
Discussion of Global Stall Characteristics

An examination of the rotor stall map for the cases shown here suggests that the qualitative indicators of stall that is, lift stall, moment stall, and trailing edge separate flow, all provide considerable insight into the stall characteristics of the blade. The wealth of experimental results from 2D wind tunnel testing shows that deep stall is characterized by the formation of a dynamic stall vortex over the forward part of the airfoil and that moment stall is related directly to this vortex formation. As the stall vortex moves over the upper surface of the airfoil the pitching moment becomes more negative but the lift is maintained and lift stall does not occur until the dynamic stall vortex leaves the airfoil’s trailing edge. Lift stall then, lags moment stall by the time it takes for the vortex to pass over the airfoil. Large separated flows occur at the trailing edge when the vortex leaves the trailing edge. The rotor maps show these characteristics, for the most part, indicating that knowledge based on 2D wind tunnel testing is of value in understanding the stall shown here on the rotor disk.

The stall maps also provide qualitative information on the three-dimensional characteristics of dynamic stall on a flight vehicle. Except for the area of stall inboard on the blade that occurs over the nose of the aircraft because of fuselage-induced flows, stall is largely an outboard phenomenon on this rotor. Stall and the formation of the dynamic stall vortex we observed right to the blade tip, unlike the wind tunnel tests of an oscillating wing reported in Ref. 3 where the dynamic stall vortex was not observed within the tip region (about 0.865R for this rotor). The formation and shedding of the dynamic stall vortex occurred in the third stall cycle (in the first quadrant) and referring to Fig. 7e or 7f it is easy to visualize a continuous dynamic stall vortex forming, growing, and moving rearwards on the airfoil as a single, continuous structure from 0.40R to the tip. However, for the initial stall cycle that is observed in the blade angle of attack is unknown in the sense that while it is leaving the trailing edge at 260 deg at 0.475R, for example, it has not yet formed outboard at 0.775R. It seems likely that the dynamic stall vortex for this initial cycle is also a single, continuous structure that is formed and shed over a broad azimuth range and its passage over the blade at any radius occurs over a narrow azimuth range.

A blade stall that is striking is the regularity of the stall patches. This is particularly apparent comparing the three different flight cases. The usual blade angle of attack is unknown for these conditions, as discussed earlier, but the pattern is obviously the consequence of the angle-of-attack variation along the blade and around the azimuth. The stall patches occur at about a frequency of 4Rev or 5Rev and as the forward blade angle has only first harmonic variation it cannot explain the higher frequency cycles seen here. The inboard angle may well vary at higher frequencies, but the regularity of this pattern over all flight conditions strongly suggests that the torsional deflection in the blade, which is a result of both blade and control system flexibility, is the cause of this repeated pattern. The qualitative similarities of the stall maps for the three test conditions are quite interesting, but it is also important to note differences in these maps for conditions that result in high oscillatory pitch-link loads. A comparison of Revs 14 and 22 from Fig. 7 and Rev 20 from Fig. 8 show a number of differences even though each of these cases shows approximately the same oscillatory loads. Rev 14, from Fig. 7, shows a dynamic stall vortex shed prior to each of the three stall cycles. Rev 22, on the other hand, shows a dynamic stall vortex for the first two cycles, but not the third, while Rev 20 from Fig. 8, shows an extended dynamic stall vortex for the first cycle, a smaller vortex for the third, and essentially none for the second cycle. While the pattern of these stall maps is controlled by the torsional dynamics, the actual angles of attack and the resulting loads are a consequence of the many factors affecting the induced flow.

Dynamic Stall on the Blade

Blade Surface Pressures

The blade upper surface pressures are shown in Fig. 10a as a function of rotor azimuth for the 0.865R station for Rev 14 of the UTTAS pull-up. The offset format is used with the initial azimuth at 135 deg and the time histories of the individual pressures transducers are ordered from the leading edge to trailing edge. The formation of a dynamic stall vortex in the front of the airfoil and its correction along the airfoil and off the trailing edge is made apparent in this figure by the offset of the individual transducers. The initial passage of the vortex occurs at about 260 deg and passes the trailing edge at about 275 to 280 deg. The flow remains largely separated on the upper surface and a second cycle starts at about 310 or 315 deg. This second dynamic stall vortex is more difficult to distinguish than the first, perhaps, and it appears to leave the trailing edge at about 335 or 340 deg. Just past zero deg, at the start of the first quadrant the first three pressure transducers show a significant drop and there is a loss in lift associated with this pressure drop. However, this loss in lift does not appear to be associated with the formation of a dynamic stall vortex on the blade. This stall and a third dynamic stall vortex is shed from the blade.

Other features of the flow that are observed in Fig. 10a include the passage of shocks over individual pressure transducers. To better identify the locations of shocks and regions of supercritical flow on the airfoil surface the sonic point has been computed for each pressure transducer and this is shown in the figure as an open circle. As an example, at 135 deg, the flow is supercritical at 0.320c but subcritical at the next station at 0.395c and a shock is located between the two stations. As the blade advances until 0.395c that the reduction in velocity is sufficient to cause the flow to be supercritical. At the same time the pressure peak at the dynamic stall vortex remains supercritical until rearward of 0.607c. This dynamic stall event appears complicated by the high local Mach number in the dynamic stall vortex, shocks, and supercritical flows.

Airfoil Maps

Features in the pressure signatures shown in Fig. 10a can be mapped onto a representation of the airfoil surface as shown in Fig. 10b. The central rectangular portion of Fig. 10b graph represents both the upper and lower surfaces of the airfoil, unfoiled so that the upper portion is the upper surface with the trailing edge at the top boundary and the lower portion is the lower surface with the trailing edge at the bottom boundary. The center line of the rectangle, at x = 0.0, is the leading edge of the airfoil. The x-axis is blade azimuth so the graph is a representation of airfoil surface events as a function of azimuth and, as before, the initial azimuth is 135 deg so the full sequence of dynamic stall cycles can be observed.

The azimuths associated with various peaks in the pressure time histories of Fig. 10a can be identified and, knowing the appropriate chord locations these peaks are mapped onto the airfoil surface in Fig. 10b using a "z". In some cases the peaks are readily identified, for example, for the first dynamic stall cycle in Fig. 10a. In other cases there are ambiguities in identifying the actual peaks and subjective judgment is needed, generally by selecting the two or three highest peaks and mapping all of these onto the airfoil surface. The same method applies to the second quadrant (third cycle) of Fig. 10a. It is to some extent controlled by the dynamic stall vortex peak on the lower side and a maximum associated with pressure recovery on the downstream side. Both the upstream and downstream peaks are mapped in Fig. 10b as a means of visualizing the trough-like structure. The convection of the dynamic stall vortex in the first stall cycle is fairly well marked by the pressure peaks in Fig. 10a and the vortex passage is emphasized on the airfoil surface of Fig. 10b by fanning a polynomial which is in indicated. A polynomial is also used to fit the peaks for subsequent dynamic stall cycles as well as the boundary on the leading edge of the trough associated with the third dynamic stall cycle.

The sonic points identified in Fig. 10a can also be mapped onto Fig. 10b to define the boundaries of the supercritical flow region on the airfoil surface. The mapped sonic points are shown in Fig. 10b with the same open circle symbol used in Fig. 10a. These points are then connected and the supercritical flow regions are shown as a stippled area in the manner of Ref. 13. These points are then connected and the supercritical flow regions are shown as shown in the figure as an open circle. As an example, at 135 deg, the flow is supercritical at 0.320c but subcritical at the next station at 0.395c and a shock is located between the two stations. As the blade advances...
a maximum at about 90 deg, but the blade angle of attack is being reduced in the first quadrant. These two effects, Mach number and angle of attack, work against each other to define the supercritical flow region. At the end of the second quadrant the angle of attack is once again increasing, but the Mach number is decreasing and the supercritical flow region moves forward until it disappears as the first dynamic stall vortex is formed. Sonic points have also been determined on the lower surface of the airfoil, but no attempt has been made to map pressure peaks on that surface. When lower surface peaks occur they are usually substantially smaller that the upper surface peaks.

Along the bottom of the Fig. 10b graphic is a plot of the section pitching moment and this clearly shows the moment stall. The moment stall is shown across the entire graphic with a chain-dot line and is labeled "MS" at the top of the graphic. Although a plot of lift is not included here, the lift stall azimuth previously used for the rotor disk maps is shown with a dashed line and is labeled "LS." Along the top of the graphic is a modified form of the trailing edge pressure. An estimate has been made of the trailing edge pressure in the absence of stall and this unsteady pressure time history has been subtracted from the measured trailing edge pressures to provide the modified pressure shown in the graphic. This method of presentation emphasizes dynamic stall and other flow disturbances at the trailing edge and eliminates the normal flow variation.

The last featured included in the Fig. 10b graphic are calculations based on the position of the dynamic stall vortex, which is the airfoil where the dynamic stall vortex crosses the 50% chord point, calculated from the polynomial fit mentioned above to represent the location of the dynamic stall vortex. This azimuth, θсет, is used to compute the onset Mach number, which is printed at the top of the graphic, and it is also used to calculate the azimuth range expected for a dynamic stall vortex to pass the entire length of the airfoil if it was connected at 40% of its free stream velocity, a rate based on extensive 2D wind tunnel testing. This azimuth range is shown as a bar immediately below the onset Mach number.

Airfoil Map for UTTAS Pull-up, Rev. 14. Figure 11 maps characteristics of the blade surface pressures for six radial stations for the UTTAS pull-up, Rev. 14. At the most inboard station shown, 0.675R, supercritical flows are seen on the advancing side of the disk. The airfoil at this station is the SCI094R8. The first stall cycle starts at about 205 deg and it appears that the dynamic stall vortex is connected at a much slower rate than would be expected from 2D wind tunnel tests. This is due to most of the dynamic stall vortex being observed in this paper. The formation of two more dynamic stall vortices is observed in both the section moment and the trailing edge pressure suggest that the last of these, the one in the first quadrant, is quite weak. Outboard, at 0.775R, where the airfoil section is the same as at 0.675R, the extent of the supercritical flow is increased and the first of three dynamic stall vortices is formed as the supercritical flow shrinks to a small area at the leading edge of the airfoil. The flow appears to remain at about 315 deg and the second dynamic stall cycle is initiated a few degrees later. Supercritical flow develops over the forward part of the airfoil in the first quadrant and the flow again rematchs before the third stall cycle occurs. At this station both the section pitching moment and the trailing edge pressure indicate that the three stall cycles are roughly equivalent in their influence on torsional loading.

The airfoil section transition from the SCI094R8 to the SCI105 occurs between the 0.775R and 0.865R measurement stations. At 0.865R, as seen in Fig. 11e, the extent of the supercritical flow has increased slightly on the upper surface and, for the first time, supercritical flow appears on the lower surface as well. The behavior of the three dynamic stall cycles at 0.865R is similar to 0.775R and, again, the strength of the three dynamic stall vortices appears similar based on the pitching moment and the trailing edge pressure. However, at this station the area of boundary layer reattachment is very small or nonexistent between the first and second dynamic stall cycles.

At 0.92R, just before the sweep tip section begins, the supercritical flow at the leading edge of the airfoil extends to 270 deg, and ceases as the first dynamic stall vortex forms. The flow never rematches prior to the formation of the second dynamic stall vortex and, interestingly, just before the vortex for the second cycle is formed a small patch of supercritical flow forms over the leading edge of the airfoil. The third dynamic stall vortex forms at about 45 deg and the supercritical flow associated with this vortex extends all the way back to the trailing edge. This third stall cycle happens extremely quickly. Based on a conventional velocity of 40% of the free stream, the vortex will take only seven and a half deg to go from the leading edge to the trailing edge, which represents only five samples of the time history. The actual interaction of the dynamic stall vortex with the extensive supercritical flow at this onset Mach number of 0.79 is unclear and the phenomena may be much more complex than would be indicated from 2D wind tunnel testing at lower Mach numbers. The pitching moment caused by this third dynamic stall vortex is greater than the moments caused by the first two vortices. At 0.965R, three dynamic stall vortices are again observed although both the section pitching moment and the trailing edge pressure indicate that the influence of these vortices is reduced from inboard on the blade. Near the blade tip, at 0.99R, there are still signs of the three dynamic stall vortices that were seen inboard. However, at this station the trailing edge pressure appears to be most strongly affected by the separated flow created when the tip vortex appears to lift off the rear of the airfoil and, locally, the largest moments observed are caused by this factor which has little to do with dynamic stall.

Figure 11. Airfoil map for UTTAS pull-up, Rev. 14.
Airfoil Map for UTTAS Pull-up, Rev. 22. The airfoil maps for the six outboard stations are shown in Fig. 12 for Rev. 22 of the UTTAS pull-up. Referring back to Figs. 3 and 7, this revolution is the last of the high pitch-link load cycles in the maneuver. Although the oscillatory pitch-link loads remain high for this revolution, the advance ratio, compared to Rev. 14, has dropped from 0.34 to 0.29 and the load factor from 2.1 g to 1.6 g. At 0.675R there is less supercritical flow on the airfoil than was seen for Rev. 14 and only two dynamic stall vortexes appear. Unlike the Rev. 14 case, the calculated passage time for the first dynamic stall vortex is a good match of the measurement. At 0.775R, a third dynamic stall vortex appears, but the initial vortex appears quite weak while the second and third show moments in excess of what was observed for Rev. 14 at this station. There is an area of supercritical flow in the first quadrant and some weak separation on the trailing edge. However, there is no indication of dynamic stall at this location and the separation may be caused by shock boundary layer interactions rather than dynamic stall.

At 0.865R, the initial or first dynamic stall vortex at about 300 deg is greatly weakened and does not extend all on the airfoil. The second and third dynamic stall vortexes are quite strong, particularly the third one. A fourth dynamic stall vortex now appears on the advancing side, as was seen for Rev. 14, but it is quite weak and there is no indication that it affects the pitching moment. At 0.925R for Rev. 22 of the UTTAS pull-up, Fig. 12d, three dynamic stall vortexes are seen. The first two, especially the second, show large pitching moments, but the third one on the advancing side is weak and has little effect on the loading. Only two dynamic stall vortexes appear at 0.965R and the first one is quite weak. The second, however shows large negative moments and areas of separated flow. At the most outboard station, two dynamic stall vortexes remain. The first one is quite weak and the second is associated with it and is caused dynamic effects of the tip vortex separation rather than dynamic stall. The second and third dynamic stall vortexes are still quite strong even at this station near the blade tip, indicating that the dynamic stall vortex may extend right to the blade tip. In addition, these two dynamic stall vortexes are indications of a much weaker, secondary vortex, and this has been observed in a number of cases in this study. Separated flows are observed in two other azimuthal locations and may be associated with supercritical flows near the front of the airfoil.

Airfoil Map for Level Flight. Figure 14 shows the airfoil maps for the six outboard stations for the level flight case. The moments at all stations are lower than observed for the maneuver conditions and this is expected as the density for this case is about 65% of the density for the maneuver flying. At 0.675R, two dynamic stall vortexes are seen, the first one at about 325 deg being stronger than the second. A secondary vortex also appears to be associated with this first dynamic stall event. The second dynamic stall cycle is quite weak at this radial station. At 0.775R, two dynamic stall cycles are seen and well, considering the reduced air density, both indicate that fairly strong dynamic stall vortexes are being shed. The dynamic stall vortexes at 0.865R is quite substantial and these two stall vortexes appear in the same location as observed for the UTTAS pull-up. A pressure disturbance on the advancing side, at about 10 deg, is suggestive of light stall, but does not extend to the root.

The outboard stations, from 0.925R to 0.999R show supercritical flow over the upper surface of the blade at almost all azimuths. Two dynamic stall vortexes are observed at each of these stations, and the pitching moment at 0.925R is fairly substantial. As with the other
cases examined, the loading at the tip is more strongly affected by separated flow associated with the blade's tip vortex than with the dynamic stall.

Discussion of Dynamic Stall on the Blade

The detailed investigation of dynamic stall on the blade using the airflow maps in Figs. 11-14 reemphasizes the number of the conclusions that were obtained from the rotor disk maps. The airflow maps confirm that dynamic stall on the rotor has many of the same features as seen in 2D wind tunnel tests and this relationship is, perhaps, seen more easily with these maps. The multiple dynamic stall cycles and their repetitive nature is also apparent with the airflow maps. In addition, the airflow maps provide more quantitative information about these dynamic stall cycles. The severity of the dynamic stall can be judged from the airflow maps by the amount of trailing edge separation and the size of the pitching moment and this amplitude information is a valuable adjunct to the rotor disk maps. The airflow maps also provide new information about the dynamic stall environment, or which, the most interesting perhaps is the range of onset Mach numbers. The Mach number along the blade varies from 0.3 to 0.5 for the first or second stall cycles and although most 2D wind tunnel test data have been obtained at lower Mach numbers, there are a number of experimental studies that cover this range. The onset Mach number for the third dynamic stall cycle, however, exceeds 0.8 in some cases and this is largely outside of the range of 2D wind tunnel test experience. The interaction of the dynamic stall vortex and the supercritical flow in this third cycle is quite complicated and is certainly less easily understood than the characteristics of the earlier cycles at lower Mach numbers.

The formation of the dynamic stall vortex in the first or second stall cycle is onset associated with a small area of supercritical flow over the leading edge of the airfoil. The onset Mach numbers for these conditions are well within the range of 2D wind tunnel test experience and it may well be that work in this area will aid in improved predictions of the dynamic stall process in transonic flows. The dynamic stall vortex locations defined by the passage of the dynamic stall vortex at the 0.50c position can be mapped onto the rotor plan and these data may more accurately characterize the dynamic stall cycles than the rotor disk maps. Figure 15 provides a map of these events for all of the cases examined in this paper. The vortex locations are tightly grouped, particularly for the stall vortices at the end of the fourth quadrant (second stall cycle) and on the advancing side of the first quadrant (third stall cycle). These two latter locations indicate the characteristics of the dynamic stall vortex passage changes only slightly with radial location and little difference is observed for the different conditions despite the significant differences in flight condition. The first grouping of dynamic stall vortex azimuths, however, appears to be significantly affected by this location.

The pattern of the dynamic stall vortex locations indicates that the blade and control system torsional pitching moment as the vortex is formed (moment stall), and a negative peak in the moment as the vortex leaves the trailing edge. The lift is maintained while the vortex passes over the blade, but lift stall occurs as the vortex leaves the airfoil.

2. Multiple dynamic stall cycles are observed on this rotor for most conditions. In many cases three cycles are observed.

3. The dynamic stall vortex appears to be a continuous structure along the length of the blade and in most cases is clearly present at the blade tip. For this aircraft, the initial dynamic stall cycle is observed inbound and moves out to the tip and, in this sense, the dynamic stall vortex has already been shed while it is just being formed outbound. For subsequent stall cycles, however, the formation and shedding of the dynamic stall vortex occurs over the outer blade simultaneously.

4. The location of the dynamic stall vortices occurs in a simple pattern in terms of azimuth and radial station for this rotor and it is apparent that this pattern is controlled by the torsional dynamics of the blade and control system. When dynamic stall occurs it is always observed at these specific locations, but a stall cycle is not always seen for every location for every flight condition.

5. Under the most severe loading conditions the boundary layer may be fully separated over most of the blade for a full quadrant of the rotor. Despite this separation the blade continues to go through repeated dynamic stall cycles.

6. Dynamic stall occurs inbound on the blade over the nose of the aircraft and this is likely caused by an increased angle of attack in this region resulting from flow over the fuselage. Outboard, however, there is no evidence that dynamic stall depends upon aerodynamic interference of the fuselage.

7. Onset Mach numbers range from less than 0.3 inbound on the blade for the first cycle to over 0.8 near the blade tip for the final dynamic stall cycle that occurs in the first quadrant.

8. In the majority of the cases the initial formation of the dynamic stall vortex is associated with supercritical flow near the leading edge of the airfoil indicating a close interaction of compressible flow characteristics with the dynamic stall phenomena.

9. The third dynamic stall cycle that occurs in the first quadrant of the rotor results in the apparent shedding of a dynamic stall vortex at a point where the flow is supercritical over most of the front of the airfoil. It appears that the dynamic stall vortex in this case reduces the surface velocity, but the flow remains supercritical. In this quadrant the dynamic stall event occurs very quickly, perhaps within five or ten deg of azimuth and the exact details of this high Mach number, high loading condition are not completely clear.

References


