

UC Davis

UC Davis Previously Published Works

Title

Investigation of Dynamic Stall Leading-Edge Flow Features at a Low Transitional Reynolds Number

Permalink

<https://escholarship.org/uc/item/5t87c9z0>

Journal

78th Vertical Flight Society Annual Forum and Technology Display Forum 2022

Authors

Batther, J

Lee, S

Publication Date

2022

Investigation of Dynamic Stall Leading-Edge Flow Features at a Low Transitional Reynolds Number

Jagdeep Batther

Graduate Student

Seongkyu Lee

Associate Professor

Department of Mechanical and Aerospace Engineering

University of California, Davis

Davis, California, 95616 U.S.A.

ABSTRACT

The unsteady laminar separation and subsequent dynamic stall vortex (DSV) formation is investigated on a NACA 0012 airfoil section subject to a constant pitch rate motion using Delayed Detached Eddy Simulations (DDES) in NASA's OVERFLOW 2.3 solver. This study focuses on the complex flow features during the initial DSV formation and analyzes the distinct mechanisms from which the vortex is formed. It is shown that DDES accurately predicts the bursting of a laminar separation bubble (LSB), which triggers the onset of a DSV. In parallel to studying the feasibility of DDES in terms of capturing distinct flow features compared to Large Eddy Simulation (LES) results, a turbulence model study is also carried out, analyzing the influence of state-of-the-art turbulent and transition models on the DSV formation and subsequent stall onset. These include the fully turbulent Spalart Allmaras (SA) turbulence model and three different transition models: SA Coder Amplification Factor Transport (AFT), SA Medida-Baeder $\gamma - \tilde{Re}_{\theta_i}$, and the Shear Stress Transport (SST) Langtry-Menter $\gamma - \tilde{Re}_{\theta_i}$. It is found that the Coder SA AFT model provides the closest results with LES and the SST Langtry-Menter model predicts the earlier onset of the DSV. The fully turbulent model shows an abrupt development of a turbulent separation bubble and the under-prediction of the lift coefficient at lower angles of attack. At higher angles of attack, after the collapse of the separation bubble, all the models provide similar trends with each other and LES results.

INTRODUCTION

Dynamic stall is a complex flow phenomenon that occurs in the realm of rapid maneuvering fixed and rotary-wing aircraft, turbomachinery, and wind turbines. It is characterized by a delay in the onset of boundary layer separation on a blade subject to transient alterations in angle of attack beyond the static stall angle, which increases aerodynamic loads considerably larger than those associated with static stall. When stall itself is onset, there is a massive flow separation on the upper surface that results in a gradual or abrupt loss of lift, an increase in drag, and a large nose down pitching moment. The unsteady loading and vibrations encountered during dynamic stall severely hinder the performance, as it restricts forward flight limits and compromises the structural integrity of the rotor blades. Due to the chaotic nature of this flow phenomenon, it remains a very difficult task to accurately capture and predict through experimental and computational methods (Ref. 1). DDES has been widely used in rotorcraft research to predict dynamic stall, and it was found that DDES predicts the airloads on the rotor blades very well during dynamic stall (Refs. 2–5). However, the validity and predictive capabilities of DDES in terms of capturing the detailed flow

physics related to the onset of dynamic stall have not been studied before. Smith (Ref. 6) provided a comprehensive discussion on the current state of knowledge regarding this flow phenomenon. Despite the tremendous progress that has been made in this field of study, further knowledge is still required. Some of the conclusions/recommendations from (Ref. 6) are listed:

- Two-dimensional dynamic stall must be solved in three-dimensional space to capture the separation region. Purely two-dimensional computations exhibit stronger, non-physical responses that impact the ability to capture the onset of dynamic stall.
- Integration of computational studies with coordinated experimental studies will provide results that are valuable for code validation. Combined use of validated computational results and high-quality experimental results are likely to yield the greatest advancement in understanding.
- A better understanding of the timing and impact of dynamic stall flow features under different conditions and combinations of conditions, such as unsteady inflow, aeroelasticity, wake interactions, boundary layer transition, and airfoil shape, is needed.

Currently, LES (Ref. 1) has proven to be the most effective in capturing important flow features during the dynamic stall process, however the required computational resources make it impractical for industry use. This paper aims to focus on understanding the viscous mechanisms from which dynamic stall is onset using DDES, which provides much faster solutions than LES. Our research aims to unveil the predictive capabilities of DDES in terms of the detailed and complex flow physics pertinent to the onset of dynamic stall in addition to airloads predictions at a low Reynolds number ($M = 0.1, Re_c = 200,000$). Typically, DDES is several orders of magnitude faster than LES due to the smaller mesh size and larger time step. An important question is whether DDES can provide a similar accuracy level of numerical solutions as LES in terms of capturing detailed physical mechanisms regarding the onset of dynamic stall with such a small fraction of computational cost. The events leading up to stall, rather than the analysis of the stalled flow itself, will be investigated due to modern-day modeling tools being more so calibrated for pre-stall. Not only will predictions of aerodynamic loads and the comparison between DDES and LES be discussed, but the distinct flow features relevant to the DSV will be studied to provide a concrete answer to whether complicated flow features can be realized from an industry oriented CFD approach. In addition, a detailed comparison and evaluation of state-of-the-art turbulence and transition models coupled with DDES will be conducted for the prediction of the onset of the DSV.

METHODOLOGY

A. Problem Description

In this paper a NACA 0012 airfoil section is studied in detail. The three mesh resolutions studied are reported in Table 1. To prevent a sudden ramp-up motion, the pitch rate, $\dot{\alpha}$, is given by

$$\dot{\alpha}(t^*) = \psi_o^+ (1 - e^{-4.6t^*/t_o}) \quad (1)$$

where $t^* = tU_\infty/c$ denotes the non-dimensional time, $t_o = 0.5$, and ψ_o^+ is 0.05. This allows the pitch rate to reach 99% of its asymptotic value, or ψ_o^+ , fairly quickly ($t_o = 0.5$). Although a constant pitch motion is more relevant to fixed-wing fighter aircraft and wind turbine blades, the underlying viscous flow physics is still applicable to rotorcraft environment. Based on studies done by Visbal and Garmann (Ref. 1), a span of 10% chord was found to be a viable option for capturing three-dimensional effects at a reasonable computational cost. Prior to the initial pitch up motion, a well resolved static solution is first found. The boundary conditions are prescribed as follows: no-slip adiabatic condition on the airfoil surface, grid periodicity imposed in the chordwise direction at the trailing edge, and for keeping a nominal 2D configuration, spanwise periodic conditions are imposed. This essentially removes finite three-dimensional effects such as the influence of tip vortices in this case study, but also allows for the study of

spanwise features and effects within the flow. In regards to the temporal resolution, a small non-dimensional time step $\Delta t^* = 0.000256$ is utilized in this study. This correlates to 35,000 steps during the upstroke motion, and 1300 steps per angular degree of rotation. This small time step not only ensures numerical accuracy, but provides an adequate temporal resolution for capturing complex flow features. Furthermore, 30 sub-iterations are used for numerical convergence based on studies conducted in Liggett and Smith (Ref. 7).

B. Grid Generation

The airfoil section is comprised of a single near-body curvilinear O-mesh. The NACA 0012 airfoil coordinates are imported into OVERGRID (Ref. 8). The modules HYPGEN, GRIDED, and SRAP, within the Chimera Grid Tools (CGT) package were used to generate the grids. CGT provides a graphical user interface and a unified environment for the visualization, processing, and diagnosis of the grid. The first 2D volume grid is generated through the use of HYPGEN, where a volume grid is created from the NACA 0012 surface coordinates. The marching distance, initial and/or end spacings are user specified. The leading-edge and trailing-edge chordwise spacings are kept at $0.02\%c$, where c denotes the chord length, to have a sufficient resolution for capturing the flow physics. Mesh smoothing parameters are kept at default values, a process that is standard when considering grids that are not overly complex (Ref. 8). After a 2D volume grid is generated, it is duplicated and concatenated in the spanwise direction to generate the 3D volume grid. The grid stretches 100 chords away from the surface, in accordance with (Ref. 1). It is replicated in the same manner for this study in order to make a fair comparison with LES results. Moreover, a majority of the grid points are concentrated within one chord length away from the airfoil surface, and 50 points are used in the far field, which provides a large grid stretching and dissipation of flow variables at the far-field boundary. Although the grid is stretched rapidly, the stretching ratio was maintained below 1.3 in accordance with OVERGRID best practices (Ref. 8). For all grids, the average y^+ calculated from the solution data is approximately 0.4 across the upper surface of the blade. This calculation of y^+ is done through an iterative process of adjusting flat plate approximations, and cross referencing with the solution data. The first grid point is placed within the boundary layer, approximately $5.19 \times 10^{-5}m$ from the airfoil surface. General schematics and information of the domain are found in Figs. 1 and 2.

Table 1. Mesh Properties

Grid	Dimensions	N_{upper}/N_{lower}	$\Delta z/c$
1	$511 \times 100 \times 50$	350/150	0.002
2	$811 \times 200 \times 100$	600/200	0.001
3	$1349 \times 400 \times 100$	900/400	0.001

*Note: Dimensions are reported as (Chordwise $\times$ Normal $\times$ Spanwise). $\Delta z/c$ indicates the nominal spanwise spacing.

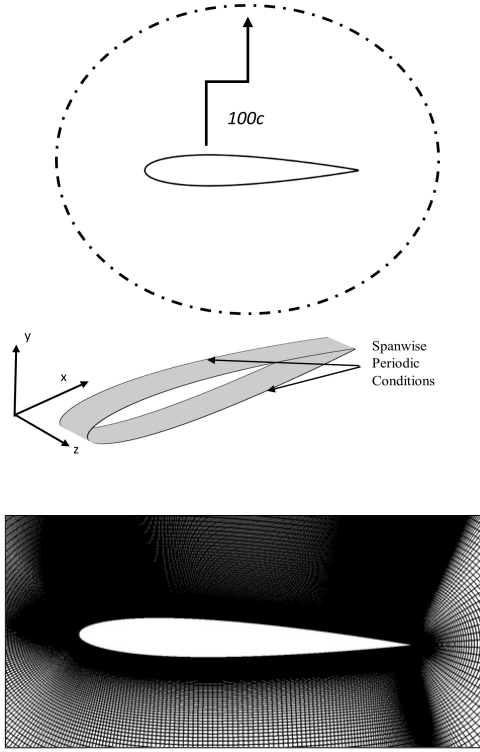


Fig. 1. Overview of airfoil section mesh.

Table 2. Wall Units

Grid	Δx^+	Δy^+	Δz^+	$\overline{\Delta x^+}$	$\overline{\Delta y^+}$	$\overline{\Delta z^+}$
1	40.0	0.463	8.93	35.5	0.392	9.49
2	23.1	0.488	9.41	17.6	0.375	7.22
3	15.0	0.526	10.4	11.4	0.399	7.69

*Note: Δx^+ , Δy^+ , and Δz^+ indicate the grid spacing at $x/c = 0.8$. $\overline{\Delta x^+}$, $\overline{\Delta y^+}$, $\overline{\Delta z^+}$ indicate the grid spacings averaged across the airfoil upper surface.

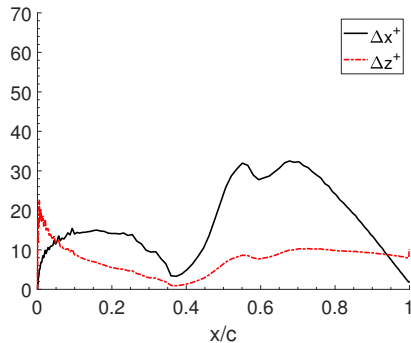


Fig. 2. Streamwise (x) and spanwise (z) mesh spacings on Grid 2.

B. Numerical Procedure

The numerical integration of the unfiltered fluid transport equations is carried out using NASA's OVERFLOW 2.3 CFD

code (Ref. 9). It is an implicit structured overset grid Navier-Stokes solver that is capable of computing time-accurate and steady state solutions with several options for temporal and spatial discretization. OVERFLOW was used to study 2D and 3D dynamic stall, (Refs. 4, 10, 11), and recent high-speed rotorcraft simulations, (Refs. 12–14). This code has a variety of turbulence and transition models available. The transition models used in this study are the following: (i) the correlation based two equation Langtry-Menter transition model (Ref. 15), which is based on the year 2003 version of Menter's Shear Stress Transport (SST) model (Ref. 16) with modifications to account for cross-flow induced transition; (ii) the correlation based Medida-Baeder transition model (Ref. 17), which is a reformulation of the Langtry-Menter Transition model to allow for integration with the Spalart-Allmaras (SA) Turbulence model, and (iii) Coder's Amplification Factor Transport (AFT) model (Ref. 18). Furthermore, as previously stated, the fully turbulent SA model (Ref. 19) is also used.

RESULTS

A. Static Validation

Static results are validated against XFOIL and LES results as a sanity check. These static cases are run continuously until there is stabilization of the aerodynamic loads and residual values. Figure 3 shows the time and spanwise-averaged surface pressure and skin friction coefficients with respect to the three grid resolutions for Coder's AFT transition model against LES results (Ref. 1). The purpose of this was to identify if the natural transition location and the overall surface pressure and skin friction coefficients are within acceptable margins. Prior to running the 3D dynamic cases, the mesh and numerical parameters are also validated via 2D RANS simulations on a 2D surface grid comprised of the same number of points as Grid 2. The CFD results are compared against experimental data by (Ref. 20) at a $M = 0.10$ and $Re = 1 \times 10^6$. The lift, drag, and pitching moment coefficients up until the static stall inception point can be seen in Fig. 4. Both the 2D and 3D static predictions show acceptable results to permit further analysis of the 3D dynamic case.

B. Grid Resolution Study

This section presents an overall overview of the dynamic stall process using the Coder SA AFT transition model. Figure 5 shows the effect of all the grid resolutions during the upstroke phase as well as the residual drop across all grids. Similarly with the static case, validation is done through comparing predictions of the aerodynamic loads against the LES computations (Ref. 1). Grids 2 and 3 show relatively similar predictions in the converged aerodynamic loads and stall inception point during the dynamic stall process whereas Grid 1 shows an early onset of dynamic stall, which is an expected result considering the coarse grid resolution. The residual drop confirms a numerical accuracy of the solution with all grid resolutions showing close to a two-order drop across each time step.

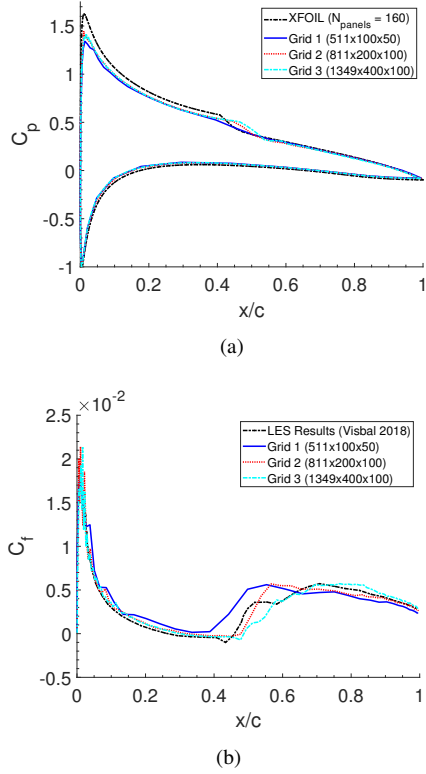


Fig. 3. Time and spanwise-averaged a) surface pressure, C_p and b) skin friction, C_f at $\alpha = 4^\circ$.

For all cases the peak lift coefficient is under-predicted compared with LES. However, the predicted aerodynamic loads are within acceptable margins, permitting the study of flow physics with respect to Grid 2 ($811 \times 200 \times 100$) for the remainder of this study. The parallel computations are made over computational domains decomposed through OpenMPI. The elapsed calculation time for Grid 2 was roughly 20 seconds per time step using 192 cores on CPU 3.3 GHz at UC Davis High Performance Computing Center, which corresponds to about 1,500 total CPU hours. This computational cost is significantly lower than that of LES as the latter typically requires several million CPU hours.

C. Dynamic Stall Stages

The dynamic stall process is broken down into various stages and studied more in depth within this section with respect to Grid 2 using the Coder SA AFT transition model. These stages signify the important points during the dynamic stall process, similar to those described by McCroskey (Ref. 21) and Visbal and Garmann (Ref. 1), which include an initial shear layer separation, loss of suction at the leading edge, and the subsequent formation and propagation of the DSV. It is important to note that in the following sections, many parameters of interest will be spanwise averaged and/or low pass filtered due to the extremely transient nature especially at high angles of attack. Analyzing a single instantaneous spanwise cross section is sufficient for attached flows, however, averaging is more suitable to represent the averaged patterns of

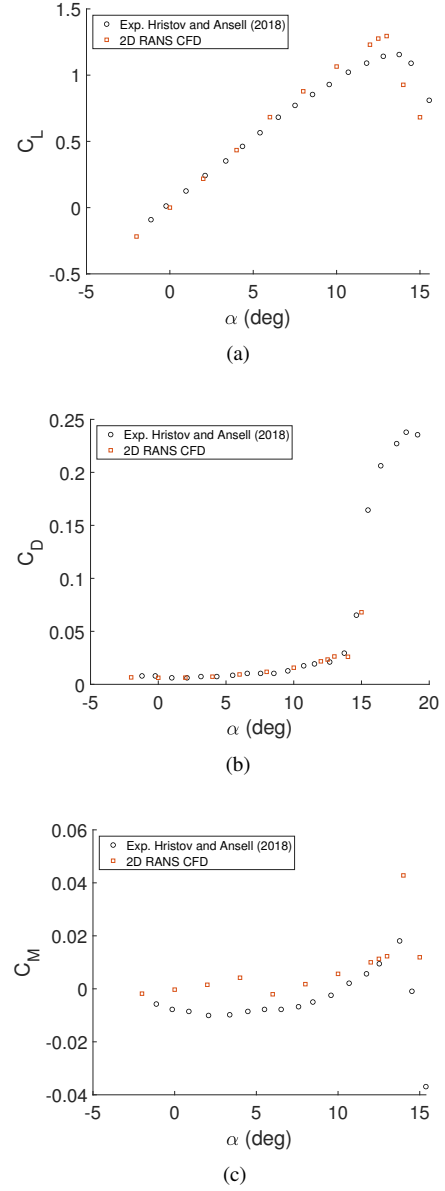


Fig. 4. 2D RANS static validation of a) C_L , b) C_D , and c) C_M on a NACA 0012 airfoil at $M = 0.10$, $Re = 1 \times 10^6$.

highly fluctuating flows. The different stages during the dynamic stall process can be seen in Fig. 6, along with their respective descriptions and flow topologies reported in Table 3.

Figure 7 shows the vorticity magnitude during the various stages described above during the unsteady pitch up motion. From stage 1 ($\alpha = 8^\circ$), transition can be seen through the small vortices present within the boundary layer as the transition point propagates upstream. Moreover, in the earlier stages, the formation and presence of a LSB can be seen through the vorticity magnitude production at the leading edge. As the angle of incidence increases there is a gradual increase in the boundary layer thickness that can be seen in Figs. 7(b)-(e). In Fig. 7(f) the presence of an initial trailing edge vortex (TEV) is seen through the rapid spatial growth in vorticity production towards the trailing edge. Even in the

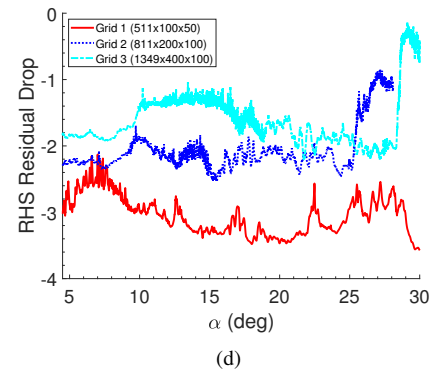
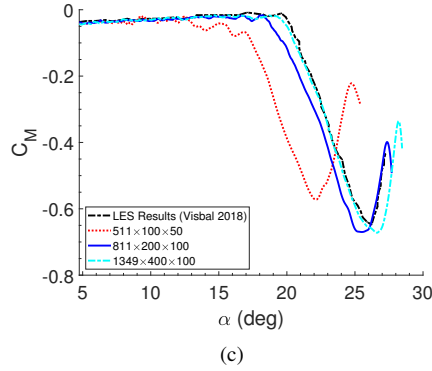
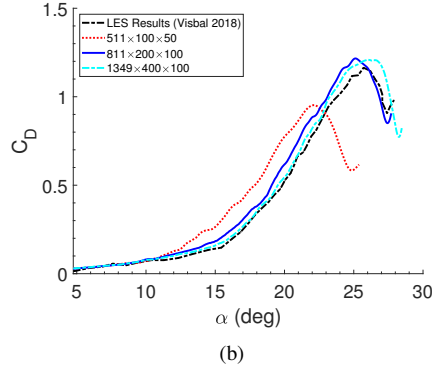
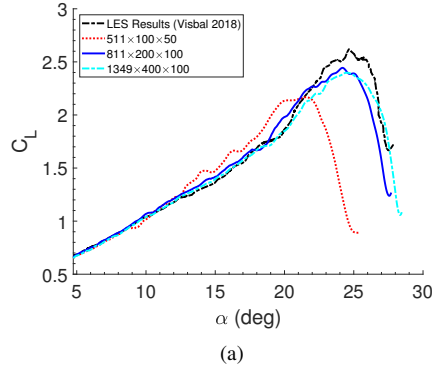


Fig. 5. Dynamic stall grid resolutions study on a) lift coefficient, C_L , b) drag coefficient, C_D , c) pitching moment coefficient, C_M , and d) respective residual drops on Grid 2.

presence of vorticity production at the trailing edge, the overall external flow is not greatly deviated as the lift force contin-

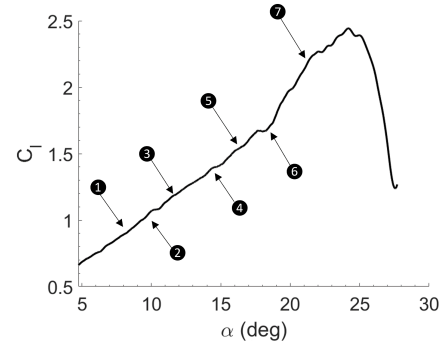


Fig. 6. Various stages of dynamic stall (Grid 2).

Table 3. Dynamic Stall Stages

Stage	Flow Topology
1 (8°)	Boundary layer transition point is propagating upstream.
2 (10.6°)	A laminar separation bubble forming at the leading edge with initial shear layer separation and subsequent reattachment as a turbulent boundary layer.
3 (12.9°)	Increase in suction at the leading-edge and reattachment of turbulent boundary layer slightly further downstream than the previous stage. Gradual thickening of the boundary layer over the entire blade section.
4 (15.2°)	Suction still increasing at the leading edge, however an adverse pressure gradient begins to have a more pronounced effect on the separation bubble, as instabilities begin to settle in, resulting in two reattachment branches of the boundary layer.
5 (16.9°)	Suction is lost at the leading edge as the laminar separation bubble collapses due to the strong adverse pressure gradient, causing a large region of unsteadiness at the leading-edge. Lift is still increasing linearly.
6 (18.6°)	The separated shear layer following the bubble collapse begins to roll up into a DSV. Significant increase in the $C_L - \alpha$ slope due to DSV formation.
7 (21.5°)	DSV is fully formed and is propagating downstream, up until roughly 50% chord length where it detaches from the surface.

ues to increase linearly. This is opposite to static stall, where flow reversal usually provokes a massive flow separation followed by a drastic loss in lift and increase in drag (Ref. 22). Up until Fig. 7(d) there still exists suction at the leading edge, however the instabilities begin to settle in, which eventually causes the collapse of the bubble due to the large adverse pressure gradient induced at higher angles of attack, as shown in Figs. 7(d)-(e) through the sudden decrease in vorticity magnitude at the leading edge. This is the initial trigger for the further events correlated with the dynamic stall process. Following the collapse of the LSB, the separated shear layer be-

ings to roll up into a DSV. Further details regarding the shear layer roll up and DSV formation will be discussed in subsequent sections. The suction collapse and successive formation of the DSV was indicated in the C_l , α curve in Fig. 6 through the sudden increase in the slope of the lift coefficient beyond the linear region at approximately $\alpha = 18.6^\circ$. This sudden change of the lift-curve slope was also documented by McCroskey (Ref. 23), as well as Visbal and Garmann (Ref. 1). The nature of the DSV rotation results in entrainment of outer flow into the boundary layer near the point where the DSV is still attached to the surface (Ref. 1). This results in a strong reverse flow region under the DSV, indicated by the strong signature of vorticity magnitude seen close to mid-chord in Fig. 7(f). While the DSV continues to take up vorticity, counter-rotating vortices emerge near the airfoil's surface as a result of increasingly strong interactions between the DSV and the reversed flow due to entrainment, a feature that was experimentally captured and described by Mulleners and Raffel (Ref. 22). The rotating DSV pushes the counter rotating structures towards the leading edge, thereby forcing itself to detach; a process that is known as vortex-induced separation (Ref. 22). In the latter stages close to the lift stall point, there is the presence of longitudinal vortex sheets downstream of the DSV indicated by the distinct streaks in the vorticity magnitude close to the airfoil surface beyond the DSV, which were also noted by (Ref. 1). These vortex sheets will be visualized and analyzed in more detail in later sections. At stage 7 ($\alpha = 21.5^\circ$) in Fig. 7 (g) the airfoil section is getting closer to the point of lift stall, as the DSV is still propagating downstream. Lift stall is onset just after Fig. 7(h) when the DSV is shed from the airfoil surface. The overall sequence of the events described lies in parallel to observations by other researchers (Ref. 1), (Ref. 24), (Ref. 25), and (Ref. 26).

The spanwise averaged surface pressure and skin friction coefficients from stage 3 ($\alpha = 10.6^\circ$) to stage 7 ($\alpha = 21.5^\circ$) are seen in Figs. 8(a) and (b). As the angle of attack increases there is the gradual increase in maximum suction. However, as the flow begins to get closer to the point of the suction collapse, the flow near the leading edge starts becoming unstable, as indicated by the oscillations in the pressure recovery region for the surface pressure and skin friction coefficients. This is in line with the findings of (Ref. 27), who found on 2D static stall experiments that for stronger adverse pressure gradients corresponding to increased suction, the separated region lengthened and small oscillations developed in the skin friction. The two distinct spikes in the surface pressure at stage 4 ($\alpha = 15.2^\circ$) is due to the unsteadiness of the flow, causing nearly two reattachment points of the boundary layer just downstream of the LSB before full pressure recovery. This occurs just prior to suction collapse as the adverse pressure gradient becomes too strong for the boundary layer to reattach smoothly.

The surface pressure contour in Fig. 9(a) shows the clear formation of the LSB and the propagation of the DSV. More interestingly, the contour of skin friction, shown in Fig. 9(b), indicates that this stall process is related with “pressure gradient bubble bursting” leading-edge stall rather than “turbulent

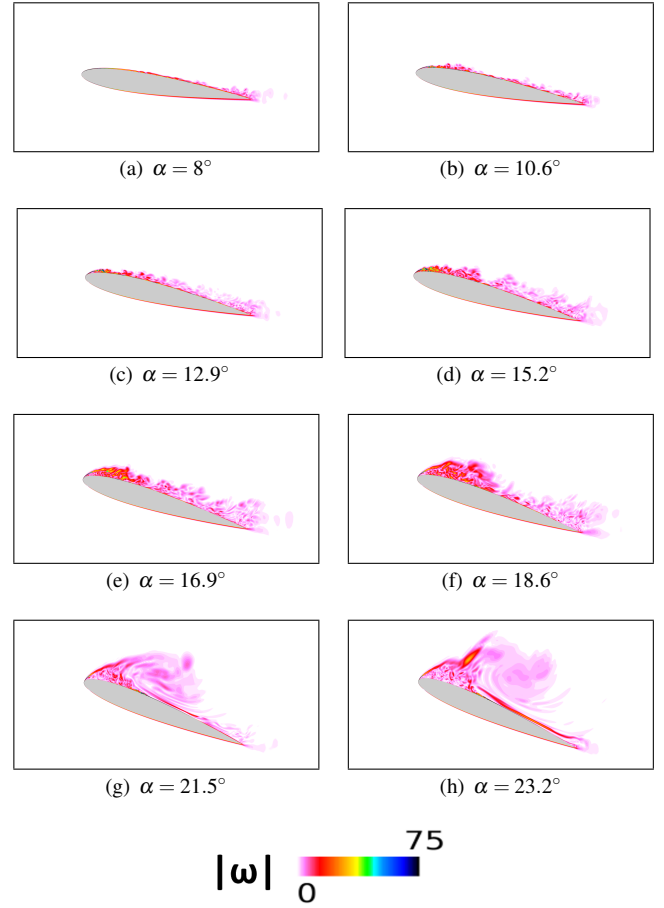


Fig. 7. Vorticity magnitude during various stages of the onset of dynamic stall.

leading-edge” stall caused by the rapid upstream propagation of the reverse flow through the trailing edge. It can be seen that the reversed flow, indicated by the negative regions of the skin friction near the trailing edge, does not propagate upstream throughout the duration of the prescribed motion. With some overall flow features pertaining to the dynamic stall process being established, a more in-depth analysis into leading-edge flow features before and after DSV formation is carried out.

D. Leading-Edge Flow Features

This section will investigate the unsteady flow physics at the leading edge in more detail, focusing on the process of DSV formation. The existence of a LSB within this flow regime is very well known and has been documented in high fidelity LES or experiments in (Ref. 1), (Ref. 21), and (Ref. 26). Even though its highly unsteady nature makes it difficult to fully grasp, there are some general characteristics which have been identified regarding the influence of the LSB on the dynamic stall process. For example, at high Reynolds numbers, it has been documented that the bursting of the LSB is induced more so by the upstream propagation of the reverse flow within the boundary layer, starting from the trailing

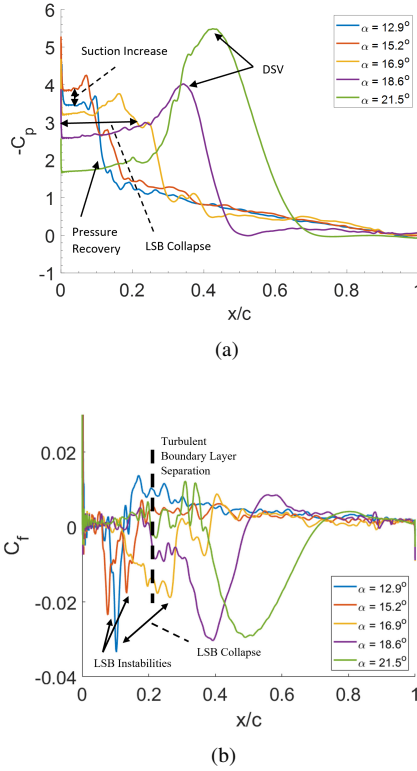


Fig. 8. Spanwise-averaged a) C_p , and b) C_f during different stages in the dynamic stall process.

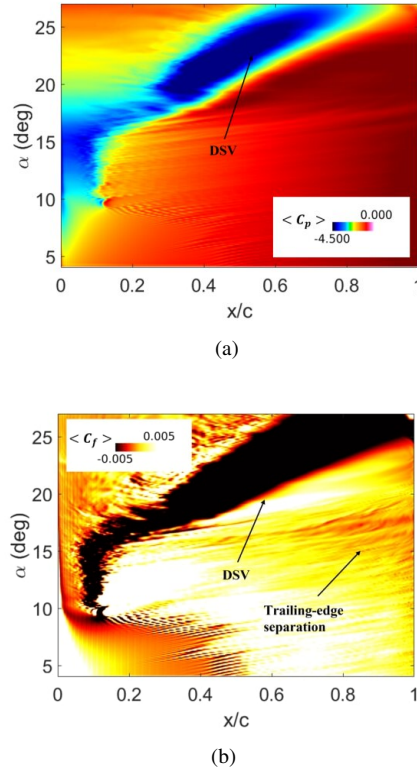


Fig. 9. Spanwise-averaged contours of a) C_p and b) C_f during the dynamic stall process.

edge (Ref. 28). At lower Reynolds numbers, the LSB collapse has been documented as a result of pressure gradient-induced bursting. Initial experiments by Ham and Garelick (Ref. 29) first linked the formation of the DSV to the LSB prior to airfoil stall, documenting it on a NACA 0012 airfoil at a Reynolds number of 300,000. Ham along with a variety of other researchers (Ref. 30), (Ref. 31), (Ref. 32), all documented the presence of a LSB at the leading edge prior to stall but could not clearly identify the bursting process and the effect it had on the overall DSV formation process. Many studies showed a high sensitivity of dynamic stall behavior to the Reynolds number, hence accurate conclusions could not be made to the influence of solely the LSB. McCroskey et al. (Ref. 26) identified different mechanism in which dynamic stall is onset. For lower speed applications, the stall process has been documented by pressure-gradient induced bursting of the laminar separation bubble. They stated that the laminar separation bubble can remain small, but the turbulent flow over the bubble can reach a state where the reattachment is no longer possible, causing a breakdown of the bubble, and producing "leading-edge bubble-bursting stall." This section will investigate the feasibility of DDES in terms of capturing the overall leading-edge boundary layer behavior.

Figure 10 shows the behavior of the LSB at the leading edge through the representation of the reversed flow. Here, the formation of the LSB is seen through the presence of a slightly reversed flow at the leading edge. There is a gradual increase in the reversed flow within this region up until Fig. 10(b) where there is a clear visual of the LSB itself. Prior to the collapse of the LSB, the upstream propagation of the bubble is apparent from Figs. 10(c)-(d), where the reversed flow propagates towards the leading edge between $\alpha = 12.9^\circ$ and 13.5° . The profile at $\alpha = 15.2^\circ$ suggests the claims previously mentioned of instabilities starting to settle in the flow. The collapse of the LSB is captured at $\alpha = 16.9^\circ$, where there no longer exists a concentrated region of reversed flow at the leading edge, and there is the presence of a more chaotic velocity distribution. Previous predictions by Visbal and Garmann (Ref. 1) with a denser grid configuration showed a maximum contraction and suction peak at 15.2° , followed by the abrupt collapse of the bubble. From this current study, although there is a contraction of the bubble seen from $\alpha = 12.9^\circ - \alpha = 13.5^\circ$, prior to the complete loss of suction, a slight increase in LSB length can be identified. This indicates that prior to the LSB bursting, the strong adverse pressure gradient causes slight expansion of the bubble. The expanded LSB profile at $\alpha = 15.2^\circ$ seems to lie in parallel with the instabilities seen in the surface pressure and skin friction in Fig. 8. Figure 10(f) shows that the initial stages of the DSV formation can be seen through the large unsteady reverse flow region present. The reverse flow profiles indicate that although the separation bubble itself does not lead to the onset of stall directly and immediately, it does have a significant influence on the overall stall process, as upon collapse, there is the distribution of unsteady flow downstream that eventually leads to the formation of a DSV. Moreover, during these earlier stages, there is not a significant indica-

tion of strong reversed flow near the trailing edge, as shown in Fig. 10, further indicating that this type of stall is in parallel with the description of abrupt leading-edge stall induced through the LSB bursting through a strong adverse pressure gradient ((Ref. 1), (Ref. 24), and (Ref. 33)) rather than rapid propagation of reversed flow upstream meeting the LSB.

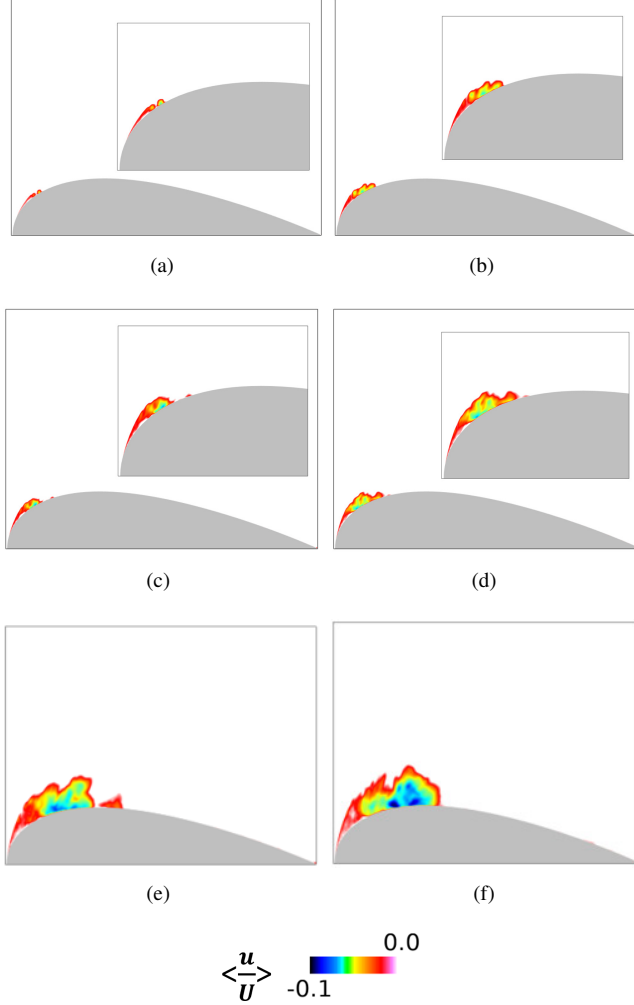


Fig. 10. Spanwise-averaged contours of reverse flow during DSV formation at $\alpha =$ a) 10.6° , b) 12.9° , c) 13.5° , d) 15.2° , e) 16.9° , f) 17.4° .

Figure 11 shows a clearer representation of the separated shear layer behavior through the spanwise vorticity. As the angle of incidence is increased, there is a localized region of the high spanwise vorticity at the leading edge of the airfoil, indicating the presence of a LSB. With a larger angle of attack, the region of the high vorticity continues to expand, indicated by Fig. 11(c). An interesting observation is that at $\alpha = 15.2^\circ$ there exists the two distinct reattachment branches in the flow, that were discussed previously. These reattachment zones present themselves as individual branches of the vorticity that move towards the surface with a small pocket of low vorticity in between. The complex nonlinear interactions in the leading-edge region, just after suction collapse, are what

lead to the eventual formation of the DSV (Ref. 22) as shown in Figs. 11(d)-(e). The strong interactions between counter-rotating vortices and the DSV can be seen at the leading edge from the instantaneous spanwise vorticity in Fig. 11(f). There are distinct pockets of the negative vorticity interacting with the positive vorticity prior to the DSV formation. Based on the spanwise averaged profiles, the instantaneous profile indicates that the negative vorticity contribution is arising from the separated flow downstream after a suction collapse.

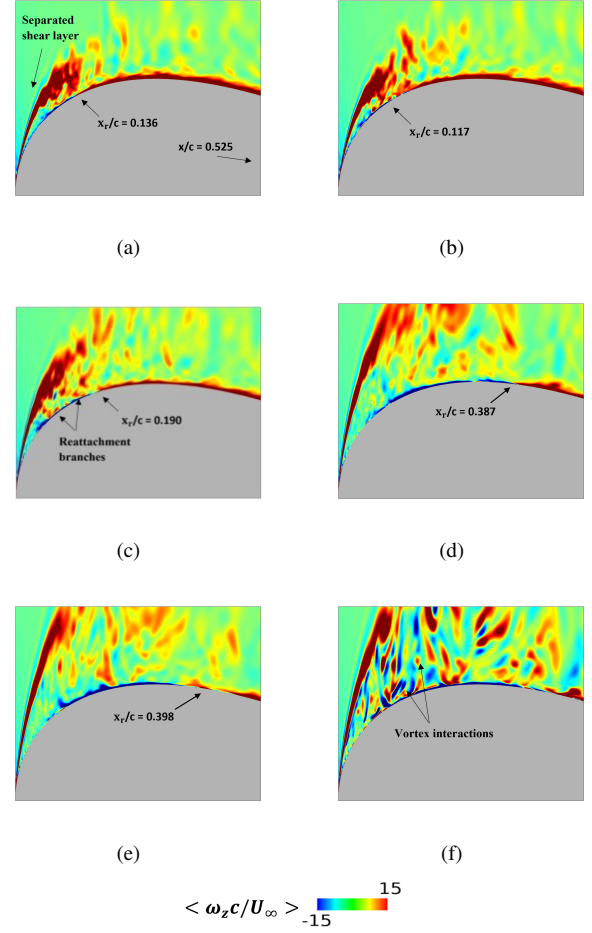


Fig. 11. Spanwise-averaged contours of spanwise vorticity during DSV formation at $\alpha =$ a) 12.9° , b) 13.5° , c) 15.2° , d) 16.9° , e) 17.4° , f) 17.4° (instantaneous).

Although researchers posed the question of if the LSB plays a significant role in the DSV process, after its initial separation, it does seem to have a significant effect on the dynamics of the DSV as a majority of the turbulent interactions seem to be stemming from the separated shear layer and its interaction with the reversed flow region just downstream after a suction collapse. As mentioned previously, the bursting of the LSB is what initially triggers the process. It was found that at a higher Reynolds number (10^6) that through a high frequency actuation the LSB bursting was suppressed, and the onset of stall was delayed (Ref. 28). In that case, a gradual upstream propagation of trailing edge separation was observed rather

than abrupt leading-edge stall. A further investigation would be required to assess the onset and formation of the DSV at this low Reynolds number if the bubble is not present or its bursting is suppressed by a means of flow control.

The time history of the dynamic stall process at $x/c = 0.05$ is depicted in Fig. 12. Prior to the collapse of the LSB there exists significant oscillations in the spanwise averaged pressure coefficient, as seen in Fig. 12. These strong oscillations prior to the realization of the DSV were also noted in an experiment done by (Ref. 34) on a NACA 0012 airfoil, where they identified similar high frequency oscillations at the leading edge. Moreover, the difference in instantaneous and low-pass-filtered pressure in Fig. 12 shows a significant spike prior to LSB formation, which might be crucial when considering implementing flow control technologies.

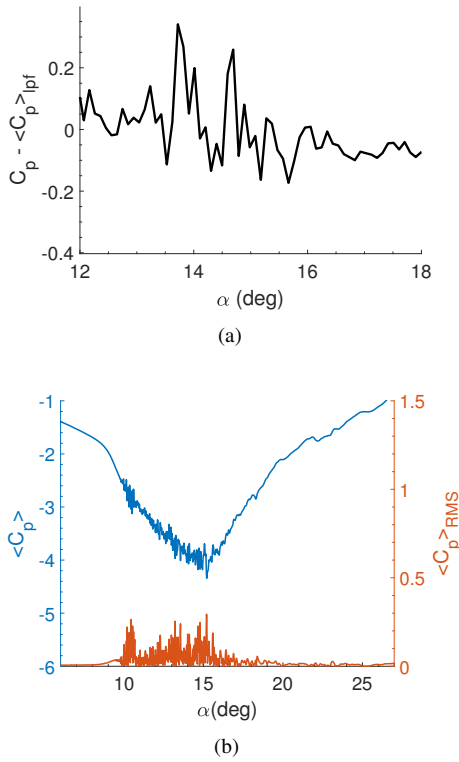


Fig. 12. a) Instantaneous - low-pass-filtered surface pressure at $x/c = 0.05$ and b) instantaneous and root-mean-square surface pressure.

E. Comparison of Transition Models

A more in-depth study is carried out on the second grid configuration ($811 \times 200 \times 100$) to analyze the effect of turbulence models on the dynamic stall process, and compare them to benchmark LES results (Ref. 1). From Fig. 13, it can be seen that the predicted airloads remain relatively similar between all three transition models, despite the oscillations that are seen in the SA Medida-Baeder model at lower angles of attack. The fully turbulent SA model indicates under-prediction of the lift coefficient at lower angles attack compared to the

transition models. However, at the larger angles of attack all trends match up well with the LES results. The under-predictions of the lift coefficient with the fully turbulent SA Model outlines the deficiency of capturing the flow physics in this low Reynolds number case. This is investigated more in detail in the following section. The SST Langtry-Menter model shows the earliest onset of stall while both SA models show similar points of stall onset.

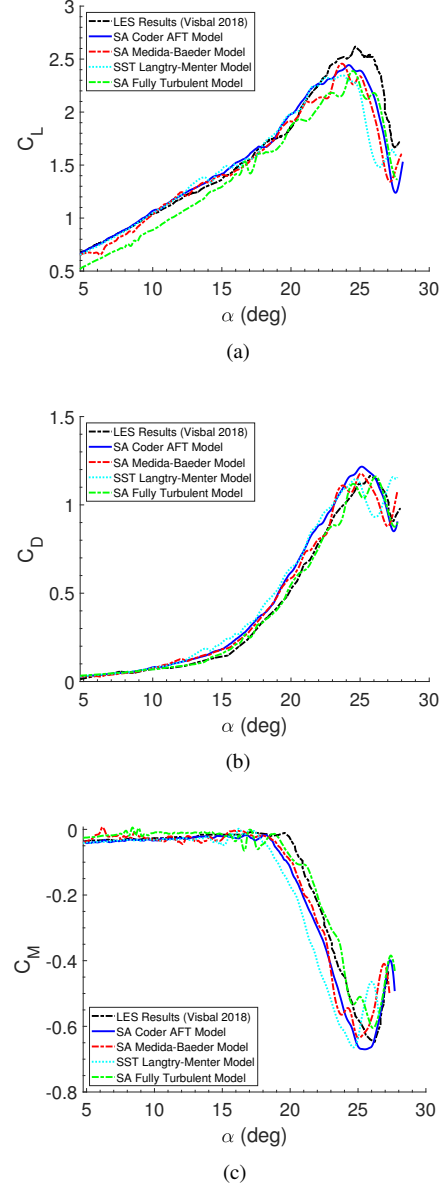


Fig. 13. a) C_L , b) C_D , and c) C_M for the four different turbulence models studied.

Figure 14 shows the spanwise-averaged pressure coefficient distributions depicting DSV formation and propagation using the three different transition models. It can be seen that the duration of time from the burst of the LSB to the occurrence of the DSV stretches approximately over 2° angles of incidence. The bursting of the LSB occurs earlier in the SST Langtry-Menter model at $\alpha = 15.2^\circ$, as shown by the pro-

file of the surface pressure coefficient in Fig 14(b), where there exists large oscillations in the pressure profile from mid-chord towards the trailing-edge, and no longer exists a steep pressure recovery region compared to the Coder SA AFT and SA Medida-Baeder models. The earlier LSB burst in the SST Langtry-Menter model is confirmed from a drop in the pressure suction below $C_p = -4$, and the elongated length of the LSB at $\alpha = 15.2^\circ$. However, there still exists a distinct pressure peak and steep pressure recovery at $\alpha = 15.2^\circ$ for the Coder SA AFT and SA Medida-Baeder models as shown in Fig. 14(a) and (c), indicating the LSB is still intact. Since the burst of the LSB in the SST Langtry-Menter model occurs earlier compared to the other transition models, this allows the DSV to reach its maximum strength earlier during the downstream movement, while it was still developing in the Coder SA AFT and SA Medida-Baeder model. The interesting aspect to note here is that there exists a common ground for the flow physics post suction collapse, regardless of the transition model, as seen from the formation of the DSV itself. Although some of the flow features between both SA models and the SST model are different up to the point of the LSB bursting, including the presence of an elongated bubble and indication of strong vortices being shed from the surface prior to the LSB bursting, the events following the loss of suction are fairly similar, emphasizing the point that the LSB is the initial trigger for the dynamic stall process, more specifically, the formation of the DSV. The LSB's prior history before collapse seemingly does not have a significant impact on the overall process of DSV formation. Although there exist differences in flow features leading up to LSB collapse, after $\alpha = 16.9^\circ$, and up to the point of stall onset ($\alpha = 23.2^\circ$), the C_p profiles for all transition models show similarities with one another.

F. Fully Turbulent Model

Another interesting aspect in the study is the validity of a fully turbulent model in terms of capturing the flow physics related to the DSV. Through the contours of spanwise vorticity shown in Fig. 15(b),(d),(e), the leading-edge flow features indicate the formation of an abrupt turbulent separation bubble. Contrary to the well-documented process of a laminar separation bubble formation, which stems from leading-edge laminar separation and subsequent turbulent reattachment, this turbulent separation bubble forms suddenly and abruptly in the fully turbulent model. The side by side comparison of the spanwise-averaged spanwise vorticity in Fig. 15 against the transition model indicates no signs of significant flow disruption in the fully turbulent model, especially before $\alpha = 15.2^\circ$. Figure 16 shows instantaneous vorticity magnitude contours at the mid-plane prior to DSV formation. It is seen that the earlier stages of vorticity magnitude do not indicate significant flow features prior to the turbulent separation bubble formation. The turbulent separation bubble is formed abruptly during $\alpha = 14.1^\circ - \alpha = 14.5^\circ$. This type of behavior of the separation bubble has not yet been documented in literature. Another interesting aspect to note in the fully turbulent

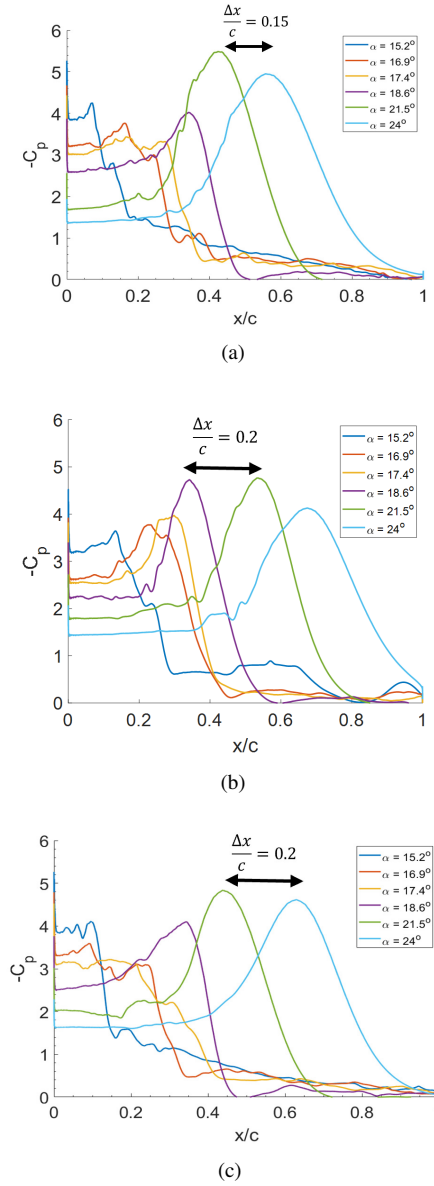
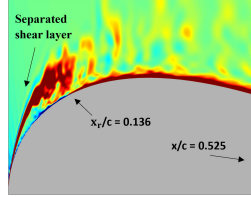


Fig. 14. Spanwise-averaged C_p distributions depicting DSV formation/propagation for a) Coder SA AFT, b) SST Langtry-Menter, and c) SA Medida-Baeder transition models.

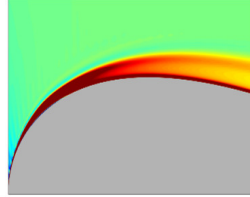
model is the presence of significant trailing-edge flow separation compared to the transition models shown in Fig. 7. However, it does not seem this trailing-edge separation propagates upstream to cause the separation bubble burst. The results discussed indicate that the use of a fully-turbulent model in a low Reynolds number regime may not be optimal, even though the flow features and overall airloads predictions seem to be stable in the latter stages of the dynamic stall process.

Coder SA AFT Model

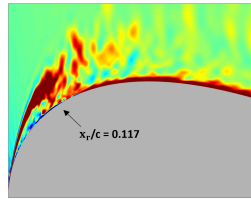
SA Turbulent Model



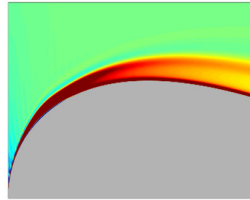
(a)



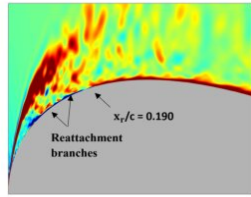
(b)



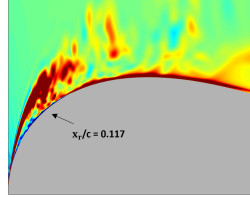
(c)



(d)



(e)



(f)

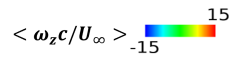
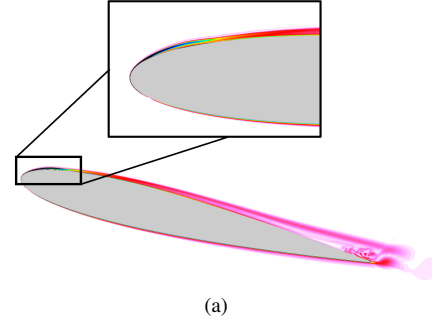
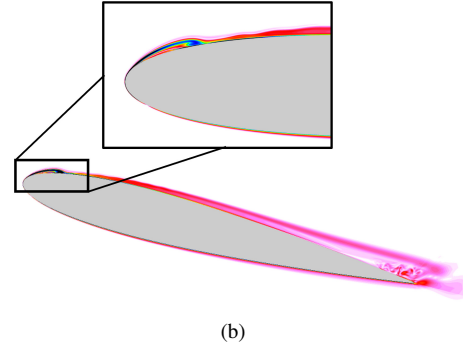


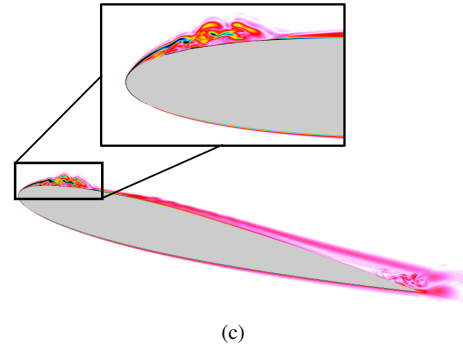
Fig. 15. Spanwise-averaged contours of spanwise vorticity during DSV formation at $\alpha =$ a-b) 12.9° , c-d) 13.5° , and e-f) 15.2° for the Coder SA AFT and the SA fully turbulent models.



(a)



(b)



(c)



Fig. 16. Instantaneous (midplane) vorticity magnitude contours at a) 13.7° , b) 14.1° , and c) 14.5° depicting turbulent separation bubble formation for the SA fully turbulent model.

CONCLUSION

This paper investigated the feasibility of DDES in terms of capturing important leading-edge flow physics and predicting the aerodynamic loads during the dynamic stall process. An in-depth study of the complex features during dynamic stall was carried out using NASA's OVERFLOW code, using a grid configuration comprising of roughly 16 million grid points and Coder's AFT transition model. The key findings presented lie in parallel with earlier experimental and numerical studies. DDES accurately captured the overall dynamic stall process, which comprised of the formation and collapse of a leading-edge laminar separation bubble (LSB), and the roll up of an unstable shear layer into a dynamic stall vortex (DSV) that propagates downstream. Upon investigation of these features, it was found that the LSB had a direct impact on the stall onset itself, as it served as the trigger for the particular events described leading up to the point of stall, in particular, the formation of the DSV. Its importance was emphasized through analyzing the interactions between the separated flow upon loss of suction, and the separated shear layer emanating from the leading-edge whose complex nonlinear interactions lead to the formation of the DSV. It remains to be investigated how using flow control at this low Reynolds number would affect the process. Although flow control studies at a higher Reynolds number ($Re_c > 10^6$) suggested stall onset is delayed through bubble suppression, the mechanism of stall onset was more from upstream propagation of trailing-edge separation. The regime of ($10^4 < Re_c < 10^5$) has not been analyzed in detail. Moreover, the predictions of the surface pressure at the leading edge showed significant oscillations prior to suction collapse, which could allow the possibility of flow control technologies being employed to delay or mitigate the effects of dynamic stall. These distinct oscillations were in parallel with earlier findings.

All transition models within OVERFLOW showed a significant promise in terms of predicting aerodynamic loads as well as the complex flow physics in comparison with high resolution LES. The primary takeaway from these findings is that the use of DDES coupled with state-of-the-art transition modeling seems to be proficient in capturing the fundamental viscous mechanisms from which dynamic stall is onset. The overall behavior of the flow and the complex flow features at the leading-edge were able to be captured through not only the predicted pressure and skin friction profiles but also through the contours of surface pressure, vorticity, and reversed flow. Moreover, the turbulence model investigation also outlined poor performance of the fully turbulent model in this low Reynolds number and attached flow regime. Although predictions were improved at the larger angles of attack, under-predictions of the lift coefficient at angles of attack up to $\alpha = 17^\circ$ indicate the necessity of a transition model to capture the relevant flow physics at lower angles of attack. It is found that Coder SA AFT model provides the closest results with LES and SST Langtry-Menter model predicts the earlier onset of the DSV. After the collapse of the separation bubble, all the models provide similar trends with each other

and LES results.

The effect of numerical methods with respect to the various transition models within OVERFLOW remains to be investigated in the framework of studying dynamic stall. It is unknown whether different numerical methods have a positive or negative effect on the predictions. Furthermore, it is evident that without the presence of experimental data, the question of prediction remains open ended. However, with the purpose of this study focusing on the capabilities of DDES, the validation of the process against experimental data was not of utmost importance, although sufficient experimental validation should be employed in future work for more accurate studies. It is also important to emphasize again that the dynamic stall process is heavily influenced by a variety of factors including compressibility, airfoil geometry, as well as the pitching rate. These factors influence the type of stall that is onset, as the process can be completely different from the sequence of events described in this paper.

The numerical study carried out in this report has shown significant implications for future design work of the next generation of rotorcraft, fixed-wing aircraft, and wind turbines, as simulations on the temporal and spatial order of this study provide quicker turnaround times than LES, permitting more large-scale testing covering an array of flow conditions and design configurations. This research topic remains an open area of study given its significant complexity. Yet, the promising results presented in this study can assist in further investigations at a reasonable computational cost.

REFERENCES

- ¹Visbal, M. R. and Garmann, D. J., "Analysis of Dynamic Stall on a Pitching Airfoil using High-Fidelity Large-Eddy Simulations," *AIAA Journal*, Vol. 56, (1), 2018, pp. 46–63. doi: 10.2514/1.J056108
- ²Castells, C., Richez, F., and Costes, M., "A numerical analysis of the dynamic stall mechanisms on a helicopter rotor from light to deep stall," *Journal of the American Helicopter Society*, Vol. 65, (3), 2020, pp. 1–17. doi: 10.4050/JAHS.65.032005
- ³Richez, F., "Analysis of dynamic stall mechanisms in helicopter rotor environment," *Journal of the American Helicopter Society*, Vol. 63, (2), 2018, pp. 1–11. doi: 10.4050/JAHS.63.022006
- ⁴Jain, R., Pape, A. L., Grubb, A., Costes, M., Richez, F., and Smith, M., "High-Resolution Computational Fluid Dynamics Predictions for the Static and Dynamic Stall of a Finite-Span OA209 Wing," *Journal of Fluids and Structures*, Vol. 78, 2018, pp. 126–145. doi: 10.1016/j.jfluidstructs.2017.12.012
- ⁵Letzgus, J., Gardner, A., Schwermer, T., Keßler, M., and Krämer, E., "Numerical Investigations of Dynamic Stall on a Rotor with Cyclic Pitch Control," 43rd European Rotorcraft Forum, Stuttgart, Germany, September 12–15 2017.
- ⁶Smith, M. J., "An Assessment of the State-of-the-Art from the 2019 ARO Dynamic Stall Workshop," AIAA Aviation 2020 Forum, Virtual Event, June 15–19 2020.
- ⁷Liggett, N. and Smith, M., "Temporal Convergence Criteria for Time-Accurate Viscous Simulations of Separated Flows," *Computers and Fluids*, Vol. 66, 2012, pp. 140–156. doi: 10.1016/j.compfluid.2012.06.010
- ⁸Chan, W., "The OVERGRID Interface for Computational Simulations on Overset Grids," 32nd AIAA Fluid Dynamics Conference and Exhibit, St. Louis, Missouri, June 24–26 2002.
- ⁹Jespersen, D., Pulliam, T., Buning, P., Jespersen, D., Pulliam, T., and Buning, P., "Recent Enhancements to OVERFLOW," 35th Aerospace Sciences Meeting and Exhibit, Reno, Nevada, January 6–9 1997.
- ¹⁰Shum, J. G. and Lee, S., "Computational Fluid Dynamics Best Practices for 2D Dynamic Stall Predictions," AIAA Aviation 2020 Forum, Virtual Event, June 15–19 2020.
- ¹¹Medida, S. and Baeder, J., "Numerical Investigation of 3-D Dynamic Stall using Delayed Detached Eddy Simulation," 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Nashville, Tennessee, January 9–12 2012.
- ¹²Jia, Z. and Lee, S., "Aerodynamically Induced Noise of a Lift-Offset Coaxial Rotor with Pitch Attitude in High-Speed Forward Flight," *Journal of Sound and Vibration*, Vol. 491, 2021, pp. 115737. doi: 10.1016/j.jsv.2020.115737
- ¹³Jia, Z. and Lee, S., "Impulsive Loading Noise of a Lift-Offset Coaxial Rotor in High-Speed Forward Flight," *AIAA Journal*, Vol. 58, 2020, pp. 687–701. doi: 10.2514/1.J058295
- ¹⁴Jia, Z., Lee, S., Sharma, K., and Brentner, K., "Aeroacoustic Analysis of a Lift-Offset Coaxial Rotor using High-Fidelity CFD/CSD Loose Coupling Simulation," *Journal of the American Helicopter Society*, Vol. 65, 2020. doi: 10.4050/JAHS.65.012011
- ¹⁵Langtry, R. B. and Menter, F. R., "Correlation-Based Transition Modeling for Unstructured Parallelized Computational Fluid Dynamics Codes," *AIAA Journal*, Vol. 47, (12), 2009, pp. 2894–2906. doi: 10.2514/1.42362
- ¹⁶Menter, F., Kuntz, M., and Langtry, R., "Ten Years of Industrial Experience with the SST Turbulence Model," *Heat and Mass Transfer*, Vol. 4, 2003.
- ¹⁷Medida, S. and Baeder, J., "Application of the Correlation-based $\gamma-Re_{\theta}$ Transition Model to the Spalart-Allmaras Turbulence Model," 20th AIAA Computational Fluid Dynamics Conference, Honolulu, Hawaii, June 27–30 2011.
- ¹⁸Coder, J. G. and Maughmer, M. D., "Computational Fluid Dynamics Compatible Transition Modeling Using an Amplification Factor Transport Equation," *AIAA Journal*, Vol. 52, (11), 2014, pp. 2506–2512. doi: 10.2514/1.J052905
- ¹⁹Spalart, P. and Allmaras, S., "A One-Equation Turbulence Model for Aerodynamic Flows," 30th Aerospace Sciences Meeting and Exhibit, Reno, Nevada, January 6–9 1992.
- ²⁰Hristov, G. and Ansell, P. J., "Poststall Hysteresis and Flowfield Unsteadiness on a NACA 0012 Airfoil," *AIAA Journal*, Vol. 56, (7), 2018, pp. 2528–2539. doi: 10.2514/1.J056774
- ²¹Carr, L. W., "Progress in Analysis and Prediction of Dynamic Stall," *Journal of Aircraft*, Vol. 25, (1), 1988, pp. 6–17. doi: 10.2514/3.45534
- ²²Mulleners, K. and Raffel, M., "The Onset of Dynamic Stall Revisited," *Experiments in Fluids*, Vol. 52, 2011, pp. 779–793. doi: 10.1007/s00348-011-1118-y
- ²³McCroskey, W., "The Phenomenon of Dynamic Stall," Nasa tm, Rhode-Saint-Genese, Belgium, March 1981.
- ²⁴Carr, L., Mcalister, K., and McCroskey, W., "Analysis of the Development of Dynamic Stall based on Oscillating Airfoil Experiments," Nasa tn, Pasadena, California, January 1977.

²⁵Shih, C., Lourenco, L., Van Dommelen, L., and Krothapalli, A., “Unsteady Flow Past an Airfoil Pitching at a Constant Rate,” *AIAA Journal*, Vol. 30, (5), 1992, pp. 1153–1161. doi: 10.2514/3.11045

²⁶McCroskey, W., Carr, L., and McAlister, K., “Dynamic Stall Experiments on Oscillating Airfoils,” *AIAA Journal*, Vol. 14, (1), 1976, pp. 57–63. doi: 10.2514/3.61332

²⁷Pauley, L. L., Moin, P., and Reynolds, W. C., “The Structure of Two-Dimensional Separation,” *Journal of Fluid Mechanics.*, Vol. 220, 1990, pp. 397–411. doi: 10.1017/S0022112090003317

²⁸Benton, S. I. and Visbal, M. R., “The Onset of Dynamic stall at a High, Transitional Reynolds Number,” *Journal of Fluid Mechanics*, Vol. 861, 2019, pp. 860–885. doi: 10.1017/jfm.2018.939

²⁹Ham, N. D. and Garelick, M., “Dynamic Stall Considerations in Helicopter Rotors,” *Journal of The American Helicopter Society*, Vol. 13, 1968, pp. 49–55. doi: 4050/JAHS.13.49

³⁰Chandrasekhara, M. S., Carr, L. W., and Wilder, M. C., “Interferometric Investigations of Compressible Dynamic Stall over a Transiently Pitching Airfoil,” *AIAA Journal*, Vol. 32, (3), 1994, pp. 586–593. doi: 10.2514/3.12025

³¹Lee, T. and Gerontakos, P., “Investigation of Flow over an Oscillating Airfoil,” *Journal of Fluid Mechanics*, Vol. 512, 2004, pp. 313–341. doi: 10.1017/S0022112004009851

³²Martin, J. M., Empey, R. W., McCroskey, W. J., and Caradonna, F. X., “An Experimental Analysis of Dynamic Stall on an Oscillating Airfoil,” *Journal of American Helicopter Society*, Vol. 19, 1974, pp. 26–32. doi: 10.4050/JAHS.19.26

³³Gupta, R. and Ansell, P. J., “Unsteady Flow Physics of Airfoil Dynamic Stall,” *AIAA journal*, Vol. 57, (1), 2019, pp. 165–175. doi: 10.2514/1.J057257

³⁴Lorber, P. F. and Carta, F. O., “Airfoil Dynamic stall at Constant Pitch Rate and High Reynolds Number,” *Journal of Aircraft*, Vol. 25, (6), 1988, pp. 548–556. doi: 10.2514/3.45621