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Major Goals: This project addressed these gaps in the basic knowledge of dynamic stall through consistent, concise analysis of physics. The three primary objectives were: 1) extending the gains obtained thus far in numerical simulation of dynamic stall in two dimensions, including secondary vortex-shedding phenomena, 2) studying the nature of the physical phenomena that accompany dynamic stall in three dimensions, and 3) addressing the spatial and temporal numerical issues associated with modeling dynamic stall that are roadblocks in an engineering environment.

Accomplishments: See attached pdf file

Training Opportunities: Summer presentations at Georgia Tech on this research (2014, 2015, 2016) to University of Alabama Aerospace Engineering NSF REU program.

Joachim Hodara completed his PhD Dissertation under 50% funding of this task in 2016.

Amanda Grubb performed two summer internships at ADD-Ames in Mountain View, CA during 2016 and 2017 at AED, CCDC in Huntsville, AL. Her PhD Dissertation (expected in 2019) is a direct result of this research.

Results Dissemination: The Peters reduced order model advancements have been/are being implemented into the flight simulation tool, FlightLab by ART. It has also been shared with Dr. Hong Xin, Sikorsky Arlington, GENHEL; Dr. Bill Welsh, Sikorsky Hartford, GENHEL; Prof. James Gregory, OSU, experiments; Indrajit Mukherjee, IISC, for hummingbird flight.

The new turbulence and transition methodologies developed by the GT VLRCOE for dynamic stall have been implemented into the NASA FUN3D solver, which is also a near-body solver for the CREATE-AV Helios framework.

Peters' reduced order dynamic stall model served as the inspiration of the Georgia Tech Aerodynamics of Bluff Bodies (GTABB) reduced order model developed under the GT VLRCOE. This model has been adopted by the US Army, industry and academia for modeling of slung loads, airdrops, towed loads, and maneuvering UAVS.

The CFD knowledge and the reduced-order developments are being utilized in the NATO AVT-282 Technical Working Group on Gusts, as well as a task on transients for UAVs in the 2016-2021 GT VLRCOE.

A Dynamic Stall Workshop at Georgia Tech will be held in September 2019 to gather researchers from across the globe.

1.1. Refereed Journal Publications

1. Jain, R., Le Pape, A., Grubb, A., Costes, M., Richez, F., and Smith, M. J., "High-resolution CFD Predictions for the Static and Dynamic Stall of a Finite-span OA209 Wing," Journal of Fluids and Structures, Vol. 78, April, 2018
2. Modarres, Ramin and Peters, David A., "Real-Time Simulation of Dynamic Stall with Unsteady Free-Stream Velocity," Journal of the American Helicopter Society, Vol. 62, No. 3, July 2017, pp. 1-10.
3. Hodara, J. and Smith, M. J., "Hybrid Reynolds-Averaged Navier-Stokes/Large-Eddy Simulation Closurefor Separated Transitional Flows," AIAA Journal, Vol. 55, No. 6, pp. 1948-1958, 2017, doi: 10.2514/1.J055475.
4. Modarres, Ramin and Peters, David A., "Dynamic Stall with Circulation Pulse and Hysteresis for NACA 0012 and VR-12 Airfoils" Journal of the American Helicopter Society, Vol. 61, No.4, October 2016.
5. Hodara, J., Lind, A., Jones, A., and Smith, M. J., "Collaborative Investigation of the Aerodynamic Behavior of Airfoils in Reverse Flow," Journal of the American Helicopter Society, Vol. 61, No. 3, 2016.

1.2. Conference Publications

1. Grubb, A., Castells, C., Jain, R., Richez, F., and Smith, M. J., "High Fidelity CFD Analyses of Dynamic Stall on a Four-Bladed Fully Articulated Rotor System," in Proceedings of the 2018 AHS 74th Annual Forum, Phoenix, AZ, May 14-17, 2018.
2. Malick, Michael and Peters, David A., "Simulation of Pitching Moment and Drag by a State-Space Dynamic Stall Model—Experimental Correlation," Proceedings of the 73rd Annual National Forum of AHS International, Ft. Worth, Texas, May 9-11, 2017.
3. Jain, R., Le Pape, A., Grubb, A., Costes, M., Richez, F., and Smith, M. J., "High-resolution CFD Predictions for the Static and Dynamic Stall of a Finite-span OA209 Wing," Proceedings of the 2017 AHS 73rd Annual Forum, May 2017.
4. Grubb, A. and Smith, M.J., "Temporal Adaption Methods for Computationally Intensive Rotorcraft CFD Simulations," AIAA Aviation, June 2017, Denver CO.
5. Smith, L., Lind, A., Jacobson, K., Smith, M. and Jones, A., "Exp. and Comp. Investigation of a Linearly Pitching NACA0012 in Reverse Flow," American Helicopter Society 72nd Annual Forum, West Palm Beach, FL, May, 2016.
6. Cross, P., Hodara, J. and Smith, M., "Evaluation of Transitional Effects in Rotorcraft Applications," American Helicopter Society 72nd Annual Forum, West Palm Beach, FL, May, 2016.
7. Modarres, Ramin and Peters, David A., "Reduced-Order Dynamic Stall Model with Unsteady Free-Stream—Experimental Correlation," AHS International Technical Meeting on Aeromechanics Design for Vertical Lift, San Francisco, California, January 20-22, 2016.
8. Hodara, J. and Smith, M. J., "Improved Turbulence and Transition Closures for Separated Flows," 41st European Rotorcraft Forum, Munich, Germany, September 1–4, 2015
9. Smith, M. J., Jain, R., Grubb, A., and Jacobson, K., "Time-and-Spatially Adapting Simulations for Efficient Dynamic Stall Predictions,"41st European Rotorcraft Forum, Munich, Germany, September 1–4, 2015
10. Hodara, J., Lind, A., Jones, A., and Smith, M. J., "Collaborative Investigation of the Aerodynamic Behavior of Airfoils in Reverse Flow," American Helicopter Society 71st Annual Forum, Virginia Beach, VA, May, 2015
11. Modarres, R., Peters, D.A., and Gaskill, "Dynamic Stall with Circulation Pulse and Hysteresis for NACA 0012 and VR-12 Airfoils, American Helicopter Society 71st Annual Forum, Virginia Beach, VA, May, 2015

12. Hodara, J. and Smith, M. J., “Improvement of Crossflow Aerodynamic Predictions for Forward Flight,” in Proceedings of the 40th European Rotorcraft Forum, Southampton, UK, Sept. 2–4, 2014

Honors and Awards: 71st American Helicopter Society Forum Best Paper, Aerodynamics: Hodara, Lind, Jones, Smith

Professor Marilyn J. Smith
2018 – present: Deputy Technical Director, Aeromechanics for Vertical Flight Society
2017: NASA Group Achievement Award, FUN3D Rotorcraft Development
2017 – present: Director, Southern Region of Vertical Flight Society (formerly AHS)
2016: Fellow, American Institute of Aeronautics and Astronautics
2015: Technical Fellow, American Helicopter Society
2014: Agusta-Westland International Fellowship Award, American Helicopter Society for the US/French Partnership Agreement (US Army, ONERA, DGA, NASA, GIT). Participation by GIT in Dynamic Stall task has been part of analysis and collaborative effort in this project

Professor David A. Peters
Technical Director of American Helicopter Society, 2014-2016
2017: Honorary Fellow, AHS

Student Awards
2016-2017 Vertical Flight Foundation Fellowship:
Amanda Grubb, GIT (PhD)
Michael Malick, WU (PhD)

2014-2015 Vertical Flight Foundation Fellowship:
Joachim Hodara, GIT (PhD)

2015-2016 Vertical Flight Foundation Fellowship
Amanda Grubb, GIT (MS)
Ramin Modarres, WU (PhD)

Protocol Activity Status:

Technology Transfer: The Peters reduced order model advancements have been/are being implemented into the flight simulation tool, FlightLab by ART. It has also been shared with Dr. Hong Xin, Sikorsky Arlington, GENHEL; Dr. Bill Welsh, Sikorsky Hartford, GENHEL; Prof. James Gregory, OSU, experiments; Indrajit Mukherjee, IISC, for hummingbird flight.

The new turbulence and transition methodologies developed by the GT VLRCOE for dynamic stall have been implemented into the NASA FUN3D solver, which is also a near-body solver for the CREATE-AV Helios framework.

Collaboration with US Army - French International Partnership Agreement on the study of dynamic stall.

Peters’ reduced order dynamic stall model served as the inspiration of the Georgia Tech Aerodynamics of Bluff Bodies (GTABB) reduced order model developed under the GT VLRCOE. This model has been adopted by the US Army, industry and academia for modeling of slung loads, airdrops, towed loads, and maneuvering UAVS.

The CFD knowledge and the reduced-order developments are being utilized in the NATO AVT-282 Technical Working Group on Gusts, as well as a task on transients for UAVs in the 2016-2021 GT VLRCOE.

A Dynamic Stall Workshop at Georgia Tech will be held in September 2019 to gather researchers from across the globe.

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Participant: Marilyn J Smith

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Authors: Joachim Hodara, Andrew Lind, Anya Jones, Marilyn Smith
Keywords: Dynamic Stall, reverse flow, computation, cfd, Experiment
Abstract: Two (static and dynamic) fundamental models of the flow over airfoils in the reverse flow region of a helicopter in forward flight are investigated experimentally and computationally at Reynolds numbers of O(105). The first model examines the time-averaged and unsteady flow resulting from a two-dimensional NACA 0012 airfoil held at a static angle of attack. Computational tools successfully predict the presence of three unsteady wake regimes and time-averaged airloads measured experimentally at the University of Maryland (UMD). A second model is investigated by pitching a NACA 0012 airfoil through deep dynamic stall in reverse flow. Both experimental and computational results reveal flow separation at the sharp leading edge for shallow angles of attack, leading to the early formation of a reverse flow dynamic stall vortex. Subsequent flow features in the pitching cycle (i.e., a trailing edge vortex and a secondary dynamic stall vortex) are also captured by the numerical simulation, alth
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Authors: Ramin Modarres, David Peters
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Abstract: Airfoils undergoing dynamic stall often display a secondary lift peak after the lift has begun to decrease. A study of this phenomenon for the NACA 0012 and VR-12 airfoils shows that the secondary peak is followed by a damped oscillation in lift. It is found that this underdamped lift can be modeled by an ONERA-type equation for secondary lift that is driven by a simple pulse. It is known that the physical basis of this pulse is the attaching of a secondary vortex to the airfoil. The onset and duration of this pulse can be predicted in terms of angle of attack in a general time-domain model. When added to the present Ahaus–Peters stall equations, this new stall equation gives a total finite-state model for dynamic stall that can include the secondary stall peak.
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Authors: Ramin Modarres, David A. Peters
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Abstract: We show that a simple enhancement to the Peters et al. dynamic-stall model (an ONERA-type model) results in large improvements in the correlation of experimental data with unsteady free-stream velocity. The core of the enhancement is that the free-stream velocity in the governing differential equation (for phase-lag and overshoot of the loads) is frozen when the dynamic-stall vortex is shed to reflect the constant strength of the shed vortex. To use the enhanced model, one need only train the new model on data for a steady free stream, and the resultant model then gives good correlation for results with unsteady free-stream as well. This improvement is demonstrated by comparisons with experimental data from Favier et al. (American Helicopter Society 48th Annual Forum Proceedings, Washington, DC, June 3–5, 1992, pp. 1385–1407) for CL under various pitch angles and free-stream velocities.
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Authors: Rohit Jain, Arnaud Le Pape, Amanda Grubb, Michel Costes, François Richez, Marilyn Smith
Keywords: dynamic stall, rotorcraft, cfd
Abstract: High-resolution computational fluid dynamics (CFD) simulations were performed using Unsteady Reynolds-averaged Navier- Stokes (URANS) and Delayed Detached Eddy Simulation (DDES) models for the static and dynamic stall of a finite-span OA209 wing. The flow was modeled as both fully turbulent and laminar with transition to turbulence. NASA OVERFLOW and ONERA elsA flow solvers were used for the simulations. A comprehensive, comparative study was carried out between the predictions and the ONERA finite-wing test data for pre- and post-stall measurements that included blade section loads, surface pressure, velocity field at chord and span planes, and spanwise flow. The high spatial and temporal resolutions employed in the present simulations resulted in good correlations with the test data. In particular, the inclusion of a transition model reduced the overprediction of the static stall angle generally seen in CFD predictions, and, as a result, also led to the observed improvements in the d
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Authors: Joachim Hodara, Marilyn J. Smith
Keywords: CFD, transition, Hybrid RANS-LS
Abstract: The numerical prediction of transition from laminar to turbulent flow has proven to be an arduous challenge for computational fluid dynamics, with few approaches providing routine accurate results within the cost confines of engineering applications. The recently proposed ?–Re? transition model shows promise for predicting attached and mildly separated boundary layers in the transitional regime, but its accuracy diminishes for massively separated flows. In this effort, a new turbulence closure is proposed that combines the strengths of the local dynamic kinetic energy model and the widely adopted ?–Re? transition model using an additive hybrid filtering approach. This method has the potential for accurately capturing massively separated boundary layers in the transitional Reynolds number range at a reasonable computational cost. Comparisons are evaluated on several cases, including a transitional flat plate, NACA 63-415 wing, and circular cylinder in crossflow. The new closure captures
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Authors: Michael Malick, David Peters, Daniel Pargas
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NONLINEAR BEHAVIOR OF TWO- AND THREE-DIMENSIONAL AERODYNAMIC FLOW FIELDS WITH DYNAMIC STALL

Final Report

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Table of Contents

1. Executive Summary

Computational fluid dynamics (CFD) and reduced-order nonlinear models have been successfully applied to investigate the complicated dynamic fluid-structure interactions that can occur when compliant aerodynamic surfaces undergo rapid changes in angles of attack that are accompanied by separation and reattachment, otherwise known as *dynamic stall*. While future concept design goals call for no dynamic stall, current (and future) vehicles encounter dynamic stall when missions are extended through propulsion upgrades, etc. Engineers and designers must be able to accurately and efficiently predict dynamic stall using both high and low fidelity computational approaches to assess performance and fatigue on new and existing rotor blades. There is a need to also understand the physics sufficiently so that inflight sensors to identify the onset of dynamic stall for pilot warning systems can be designed.

The fundamental physics that modify dynamic-stall behavior when transitioning from two-dimensional (2-D) to three-dimensional (3-D) configurations have been studied and quantified. These results have practical applications to aerospace systems, such as compliant or morphing surfaces in fixed- and rotary-wing systems that encounter transient or periodic separation and reattachment during phenomena such as dynamic stall.

This project addresses these gaps in the basic knowledge of dynamic stall through consistent, concise analysis of physics associated with each forcing function (rotation, velocity, etc.) accomplished with three phases: 1) extending the gains obtained thus far in numerical simulation of dynamic stall in two dimensions, including secondary vortex-shedding phenomena, 2) studying the nature of the physical phenomena that accompany dynamic stall in three dimensions, and 3) addressing the spatial and temporal numerical issues associated with modeling dynamic stall that are roadblocks in an engineering environment.

The PI team has utilized high fidelity, trusted experimental data (US Army, ARO-Gregory, AFOSR/VLRCOE – Jones, ONERA, DLR) and collaborated with experts in international community (US-French PA task, NATO-AVT gust task). The results of this project have identified and mitigated (entirely or in part) current prediction shortcomings associated turbulence modeling. Best practices for the computational modeling of these phenomena for semi-infinite airfoils and wings, including rotating wings in actual rotorcraft main rotors, have been developed. For design, a reduced-order *physics-based* model to predict dynamic stall which include both 2D and 3D analysis, as well as secondary dynamic stall for yawed and unsteady free stream conditions has been developed and validated.

These results have been disseminated to the rotorcraft community and are currently in practice by the US Army, academia, and industry.

2. Statement of Problem

Significant resources over multiple decades have been invested in the understanding and simulation of aerodynamic bodies that undergo rapid changes in angles of attack that are accompanied by separation and reattachment. This fundamental aeroelastic phenomenon occurs on a plethora of applications that span Reynolds number, both with and without the assumption of flexibility of the aerodynamic component. For aerospace applications, this phenomenon is classed as *dynamic stall*. Dynamic stall (DS) is the rapid loss, followed by recovery of lift and moment due to the changing angle of attack of the component. Despite prior technical efforts, computational simulations, even with the application of Reynolds Averaged Navier-Stokes (RANS) computational fluid dynamics (CFD) methods, still do not capture all of the pertinent physics of this complex aerodynamic/aeroelastic phenomenon. In addition, reduced-order modeling, necessary for design and industry analysis, also do not capture many of the different salient phenomena that can arise from dynamic stall.

2.1. RANS CFD-Based Prediction Methods

Some aspects of dynamic stall such as leading-edge separation and the upstroke portion of the cycle where flow remains attached are well understood and predicted. Other aspects such as trailing edge stall and the role of transition are not well understood. In recent efforts (1, 2, 3, 4, 5, 6, 7), CFD has had increasing success in the prediction of reattachment and secondary-stall phenomena in infinite wing studies for some combinations of Mach number and higher reduced frequency ($k > 0.1$), but even in these successes, there are still gaps in understanding the role and appropriate numerical modeling fidelity needed to capture the physics.

Trailing edge stall and the accompanying separation "creep" from trailing to leading edge continue to elude consistent success in CFD simulations. Recent studies suggest that the trailing edge vortex has a much greater influence on the behavior of the leading-edge separation and vortex formation than previously postulated. In addition, computational methods must address issues of transition and turbulence modeling in order to be able adequately to predict both leading-edge and trailing-edge stall. Large eddy simulation (LES) and hybrid RANS/LES-based turbulence methods have demonstrated improvement in understanding the physics of dynamic stall (6, 7).

The application of reduced-order models has yielded keen insight into significant nonlinear behavior of fluid-structure interactions. For example, Ref. 8 used a reduced-order model for transonic aerodynamic loads and was able to elucidate significant flutter and limit-cycle behavior of airplane wings in transonic flow that had been seen in aeroelastic CFD codes but could not be studied in detail due to the high cost of CFD. The principal investigators' prior collaborations on dynamic stall (9) have shown a similar trend. Prof. Peters' reduced-order model provided more accurate solutions to a set of dynamic stall simulations than CFD. Further examination led us to understand that while the computations were numerically converged, they had converged to the incorrect physical solution. This has been the standard convergence criterion used by the CFD community, and the new convergence criterion has provided significant insight into the problem of modeling two-dimensional dynamic stall (7).

Efforts prior to 2013 using the two-dimensional experimental data have mainly been useful in that it has defined how to integrate experiment, CFD, and reduced order modeling in order to comprehend the physics of dynamic stall. These earlier studies, however, may not be directly applicable to dynamic stall in a rotating environment that occurs in many Army-centric systems. Comprehensive codes equipped with these models sometimes give good correlation, but not always.

During dynamic stall, the leading edge of the lifting surface encounters large negative pressure coefficients that are exacerbated by unsteady effects and the presence of shocks. Bousman (10,11) determined that the flow field during moment stall can be characterized when the free stream has a substantial radial velocity component flowing inboard, while adjacent to the viscous surface, radial acceleration drives the boundary layer outward. The influence of radial acceleration has been debated in the literature. Coton (12) cites the differences preceding dynamic stall of the inboard pressure distribution observed on rotating wind turbine blades when compared to two-dimensional airfoil models, as well as Corten's observations (13) of the presence of a significant radial pressure gradient and flow. These are also influenced by the local pitching rate.

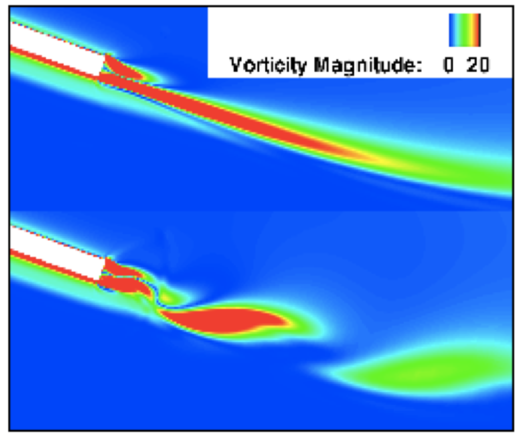

Figure 1: Vorticity at blunt trailing edge for stalled VR7 flow at the same physical time with two different time steps; $\Delta t = 0.01$ on top and $\Delta t = 0.005$ on bottom.

The spatial grids that researchers have found necessary to capture the salient physics of two-dimensional dynamic stall imply the need for an order of magnitude increase in the fidelity of the current size of typical three-dimensional engineering grids to adequately capture the fluid-structure interaction within the boundary layer. Further, an additional order of magnitude increase in the cost of temporal integration appears from our initial analyses to be necessary. These increases put the cost of CFD beyond the reach of most engineering analyses. It is thus difficult to determine what can and cannot be predicted on full-scale rotors. There exists a need to improve the numerical efficiency for all levels of three-dimensional results, including time step algorithms, grid adaptation and boundary layer treatments.

2.2. Reduced-Order Modeling Prediction Methods

As noted earlier, the use of reduced-order models can and has yielded keen insight into significant nonlinear aeroelastic behavior of fluid-structure interactions. For example, Ref. 14 used a reduced-order model for transonic aerodynamic loads and was able to elucidate significant flutter and limit-cycle behavior of airplane wings in transonic flow. This behavior had been seen in aeroelastic CFD codes with transonic fluid-structure interactions, but the effect could not be studied in detail due to the high computational times of CFD. The reduced-order models on the other hand, based on low order models that reproduced the transonic data, were able to run much faster and locate the stability limits and the limit-cycle behavior. Reference 15 demonstrated that dynamic stall can produce instabilities, limit cycles, and chaos. Since rotorcraft and fighter aircraft exhibit nonlinear buffet and vibrations in dynamic stall (which they routinely encounter), such phenomena are important.

Reference 16 introduced a linear airloads theory that could treat unsteady aerodynamic phenomenon of conventional airfoils, of airfoils with movable segments, and of airfoils with an arbitrarily morphing camber line. The theory is general enough to treat unsteady free-stream with large airfoil motions and to accommodate any induced-flow model, either in 2-D or 3-D. The paper also demonstrated that this model implicitly reproduces the simpler models of Theodorsen Theory, Garrick Theory, Greenburg Theory, Isaacs Theory, and Loewy theory––under the appropriate simplifications to recover the assumptions of each model. The model is in the time domain but can be transformed to the frequency domain if desired.

References 1616 and 17 established experimental correlation of the model with dynamic wind-tunnel data for lift, pitching moment, moment about a flap hinge, and drag for airfoils oscillating at various reduced frequencies (up to 0.85) and Mach numbers (up to 0.74). The theory predicts not only the traditional lift, pitching moments, and drag, but it also computes the generalized loading of any airfoil deformation. Thus, this model can form the foundation of aeroelastic studies of compliant airfoils with arbitrary cross-sectional dynamics.

References 18, 19, and 20 extended this compliant airfoil model to include the highly nonlinear dynamics of dynamic stall––including its inherent bifurcations. The resultant lower-order nonlinear models were shown to be able to be trained by simple genetic algorithms based on a reduced set of dynamic stall data (for un-morphed airfoils) and then to be able to predict highly nonlinear phenomena involving dynamic stall of morphing airfoils at multiple frequencies. Reference 21 further demonstrated the models are very robust, requiring only a very few fundamental dynamic parameters (5 coefficients) and a limited amount of static stall data in order to be effective. Reference 22 showed that such models could be used in preliminary design studies to create airfoils and airfoil motions that could alleviate dynamic stall.

2.3. Project Approach

Three tasks were performed that 1) extended the gains obtained thus far in numerical simulation of dynamic stall in two dimensions, including secondary vortex-shedding phenomena, 2) studied the nature of the physical phenomena that accompany dynamic stall in three dimensions, and 3) addressed the spatial and temporal numerical issues associated with modeling dynamic stall that are roadblocks to analysis in an engineering environment. Although either a RANS-CFD or reduced-order modeling approach could stand on its own without the other method, together with experimental data they create important synergistic interactions that will help both approaches be more productive. An illustration of this synergy is illustrated in an earlier collaboration (9) that helped to identify that the CFD community has relied upon a definition of convergence in dynamic stall that can result in a numerically converged result that is physically inaccurate. With this information, new definitions of computational convergence for dynamic stall have been proposed (7).

In **Task 1**, the recent gains using CFD and the 2-D dynamic stall model (hereafter called Unsteady Airloads Theory, UAT) to understand and capture dynamic stall in two dimensions. **Task 2** extended of two-dimensional dynamic stall results to three dimensions. Concurrent to the CFD efforts, 3-D dynamic stall with the reduced-order UAT models was also investigated. The intermediate step of analyzing yawed wings (wings with sweep) with CFD was forgone given that the data from experiments was relatively old and the rotating frame analysis was ready. **Task 3,** which was concurrent to Task 2, focused on the numerical implications of modeling dynamic stall in an engineering environment. This included both temporal and spatial assessments.

3. Objectives

This project addressed these gaps in the basic knowledge of dynamic stall through consistent, concise analysis of physics. The three primary objectives were: 1) extending the gains obtained thus far in numerical simulation of dynamic stall in two dimensions, including secondary vortex-shedding phenomena, 2) studying the nature of the physical phenomena that accompany dynamic stall in three dimensions, and 3) addressing the spatial and temporal numerical issues associated with modeling dynamic stall that are roadblocks in an engineering environment.

4. Summary of Most Important Findings

The project has focused on validating with high fidelity, trusted experimental data (US Army, ARO-Gregory, AFOSR/VLRCOE – Jones, ONERA, DLR) and collaborating with experts in international community (US-French PA task, US-French-German informal collaboration/workshops, NATO-AVT gust task). In addition, algorithm development and assessment has leveraged a Georgia Tech Vertical Lift Research Center of Excellence (VLRCOE) task on turbulence and transition modeling.

4.1. Understanding of the Physics

The simulations over estimated nonlinear lift due to vortex shedding at stall onset, though LES-based simulations reduced the stall peak. In 2016, Ramasamy reinvestigated experimental data that indicated that these nonlinear peaks appear with phase lags and leads over each cycle, so that prior experimental analyses smoothed out this phenomenon. Correlation of the cycle-to-cycle variation in experiments indicates that the computational analyses, when performed with best practices (See Section 4.2), capture the nonlinear lift peaks prior to stall very accurately.

4.2. High Fidelity Computational Fluid Dynamics Modeling

At the beginning of the project, the following items had been quantified or determined by collaborations between the US (ADD/AED/GIT), France (ONERA), and Germany (DLR). The stages of advancing rotor dynamic stall were known (23), and that the Spalart-Allmaras turbulence closure was not sufficient for dynamic stall. The most accurate turbulence model for unsteady Reynolds-averaged Navier-Stokes (URANS) simulations was the Menter Shear Stress Transport (SST) model (7). Spatial and temporal restrictions were found to be significant; the simulation needs 35-60 normal cells in boundary layer and a total of 180k time steps x subiterations per cycle in order to adequately capture the 2D dynamic stall behavior (3,7). Transition models worked well for attached flows, but the performance characteristics were missed when separation with or without reattachment was present. Lower reduced frequency behavior was more difficult to capture than higher reduced frequencies.

The results from this project confirmed that improved predictions could be obtained by using large eddy simulation (LES)-based simulations correlated with experimental data for two-dimensional (2D) or quasi-2D (three-dimensional (3D) meshes for wing with periodic boundary condition). This did not significantly improve transition with separation, although there was some improved accuracy under some conditions.

A new prototyping code (GTSim) was developed and validated through leveraging of a complementary task for the Vertical Lift Research Center of Excellence (VLRCOE) (24). Using GTSim to correlate with experimental data from UMD (Jones) has led to the first successful analysis of retreating blade reverse flow dynamic stall. Stages of physical static and dynamic behavior were characterized, and significant insights into the behavior of CFD modeling were quantified. Using an adequate mesh and time step size with the hybrid LES model, all of the salient spatial and temporal physics were captured by the CFD simulation for static stall. During dynamic stall, the spatial features were all captured although some differences were observed in the separated region when angle of attack decreases. These differences were traced to variable phase lag shifts between the experiment and computation, where the computation lagged the experiment. Visualizations clearly indicated that these phase lags resulted in differing interactional behavior of the salient phenomena, giving different integrated performance parameters. These lags were driven by the failure of the underlying URANS turbulence model to shed the vorticity at the proper (faster) rate that is observed in experiments and LES-based simulations. These results have been published in a conference paper at the American Helicopter Society (AHS) Forum in 2015 (25), which was awarded the Best Paper award in Aerodynamics, as well as a *Journal of the American Helicopter Society* (JAHS) journal paper (26).

A number of LES wake algorithms were developed and assessed in Hodara's PhD dissertation (24) and in an AIAA journal paper (27). The important findings that advance the state of the art are briefly summarized next.

The importance of the subgrid length scale was quantified. This local grid spacing was found to be important in supersonic applications (jet flow), but it had not previously been analyzed for the low speeds with dynamic motion, as encountered during dynamic stall. Many approaches use the maximum of the three cell lengths (*x, y, z*, assuming structured hex cell) as the filter width, which is the more cost-efficient option. This can cause significant dissipation, and revert the solution to a RANS-like response. Instead, if the filter width is computed as the cube root of the volume size, then the dissipative qualities of the model are minimized. This impacts the prediction of the dynamic stall performance in two ways: first, it minimizes the strength of the nonlinear lift as the LEV is developed and released; and it secondly minimizes the large excursions of lift, drag and moment observed in the separated region. This is true for both 2D and 3D calculations. The development of the shear layer and LEV at the beginning of the stall event are more over a shorter period of time. The change in the behavior of the integrated performance quantities is clearly elucidated by viewing the near wake. The LES model is similar to the URANS with the original, more cost-efficient filter, but details such as von Karman vortex streets and improved interactional aerodynamics are seen with the modified cube root of the cell volume filter. These differences in the length scale were also observed with the DDES turbulence closure.

The derivation of the URANS-LES terms results in hybrid or cross derivative terms that most approaches ignore. This can be important for dynamic stall as the region between URANS and LES has errors in the momentum transfer. The appearance of non-physical momentum supercells could influence the vortex shedding. Only one of these terms appears to be important, as derived and validated fully in Hodara (24).

Finally, the blending functions are also key to capturing the physics more accurately. With a "true" hybrid approach, the switching between URANS and LES should occur where it is needed, contrary to zonal approaches where the user defines the zones. However, in large quiescent separated flows, there is a tendency to move to URANS rather than staying with LES, and the boundary layer needs to be protected from premature switching to LES. A number of different filters have been developed to protect the boundary layer from switching too early to LES and switching back to URANS during quiescent separation.

Correlations on the OA209 finite wing were made with FUN3D using the Delayed Detached Eddy Simulation (DDES) compared with two different structured approaches, OVERFLOW and Elsa run by ADD and ONERA, respectively. It was clear that inboard, where the flow is primary 2D, that transition played a key role. Once separation occurred, cross-flow was observed, indicating that the need to study yawed wings in dynamic stall was not a necessary step. Some computational phase lags compared to experimental data in the downstroke, similar to what was observed in the prior year with the Jones reverse flow dynamic stall were observed. These tended to be at the onset of the dynamic stall and were not as obvious during the later downstroke portion of the dynamic stall. This is illustrated in *Figure 2* with LDV data from ONERA (28). The outboard stall behavior is strongly influenced by the tip vortex, which appears to dominate the flow field over the outer quarter-radius. Differences across the solvers were observed, but appear to be due to the differences in meshes and spatial schemes.

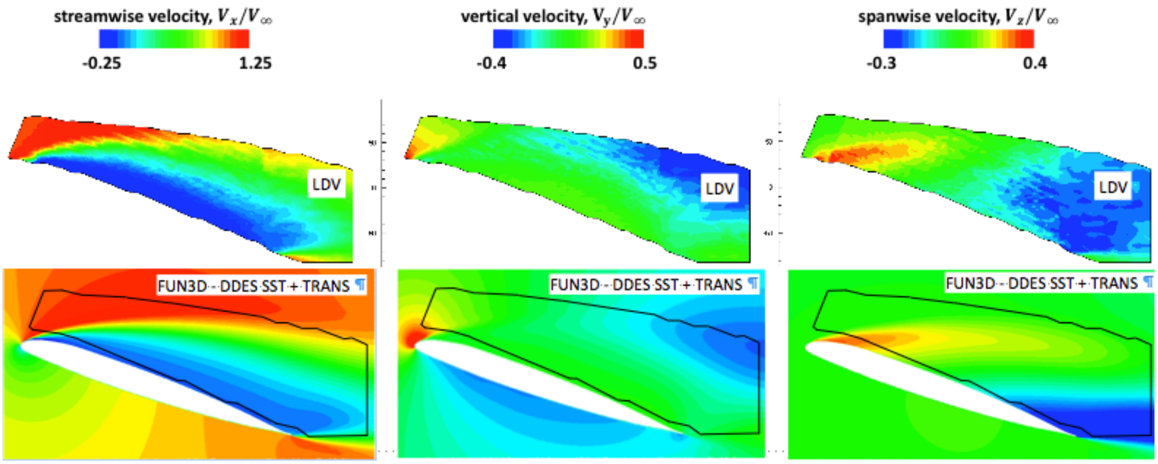

Figure 2: OA209 Wing CFD correlation with PIV Velocity Field at 80% R, α= 19.4^o, downstroke

Full rotors were then analyzed using the best practices found in the prior research. The articulated 7A ONERA rotor was chosen and a team (GIT, Army, ONERA) of researchers began analysis of the rotor. The separated flow regions, which have been overall classified as dynamic stall, are overwhelmingly not the result of "classic" dynamic stall, as most researchers have been focusing their efforts upon. Instead, they are primarily from a mix of blade-vortex interactions and blade mechanics. These differing origins explain in part why the prior computations have mixed success. The primary findings from a recent joint paper (29) are summarized.

The separated flow regions that are due to blade vortex interactions appear overall to be comparably predicted with a two-equation URANS model and DDES models, when sufficient meshes, based on best practices for separated flows, are present in the boundary layer and the wake regions. A one-equation URANS turbulence model does not as accurately predict separation and other wake behavior so that BVI events in particular may not be correctly captured.

Transition is a minimal influence on the separated flow regions on the 7A rotor. Modeling the rotor with a rigid blade captures most of the behavior; strong BVI responses may be missed. Separation and stall due to transonic effects at the tip may be sensitive to the control angles if the angles are close to their aerodynamic stall values.

Beyond this project, two additional rotors are being assessed and will be reported on in Grubb's dissertation (expected in late 2019). In addition, several additional influences are being assessed. The URANS turbulence model simulations were performed on a much smaller mesh than the DDES-based turbulence simulations. It is not clear how much of the observed differences are attributable to the turbulence closure or the influences of the mesh. The unstructured mesh computations were based on prescribed motions from a structured CFD/CSD simulation. Given the sensitivity of the stall events in some regions, it is important to determine the solver's sensitivity to these motions via a fully coupled aeroelastic simulation. The sensitivity of the separation and subsequent stall events to the location and strength of the vortices during BVI events will be quantified to determine what role these play for mesh and turbulence selections.

4.3. Engineering Modeling Best Practices

The current state of the art in modeling dynamic stall with Computational Fluid Dynamics (CFD) is now acknowledged by the majority of the community to require detached or large eddy simulations and three-dimensional simulations. Two-dimensional simulations of dynamic stall where there is separation are not sufficient; in some circumstances, the simulations may appear to match experiments, but these are likely due to numerical errors such as mesh dependencies or turbulent viscosities.

For reverse dynamic stall, additional data (after the 2015 work) on the upstroke from Jones has been studied. The behavior of the rotor blade is not the traditional dynamic stall, but blends a “gust-like” (ramp) behavior with the traditional angle of attack changes. The physics are interesting as they are large angle of attack excursions that occur rapidly. This research has yielded several important results. First, as these are single “ramps”, the flow simulations are difficult to be modeled as periodic flows as the experiments usually have longer recovery times before the next event. So, long computational times can result. Instead, a single “span-averaged” three-dimensional airfoil (with periodic boundary conditions) simulation can be correlated with the “phase-averaged” behavior of the experiments. With LES wake turbulence closures, the flows are highly three-dimensional due to the airfoil motion, even though they nominally are defined as attached. Analyses indicated that while the results are not identical, the 30-50 span stations, when analyzed are similar to their temporal experimental counterparts and can be utilized to provide an estimate of the extent of the simulation variation. Periodic and aperiodic features are similar across the two analyses.

Extension of the CFD approaches to a finite wing case (OA209) indicated that the three-dimensional behavior near the wing tip due to the interaction with the tip vortex provides mitigation of the refined mesh requirements needed to capture the performance metrics in the downstroke. Initial evaluations (first by GIT, then by ADD-A) on the use of unsteady adaptive mesh refinement (AMR) within the OVERFLOW structured code are able to reduce mesh requirements significantly, although the cost in the AMR itself mitigated the benefits. There was no such mitigation of the temporal requirements.

Follow-up on high temporal resolution requirements indicated that the timestep could be changed during the attached and separated portions of the cycle without loss of accuracy or loss of the conservation metrics. Analysis of simulations across a series of symmetric and cambered airfoils in both 2D and 3D indicated that the most consistent metric that identifies the onset of dynamic stall is the behavior of the stagnation point. As an airfoil increases (or decreases) the angle of attack, the stagnation point will move aft (or forward) along the chord in an approximately linear fashion. It was noted that as the nonlinear lift peak due to the formation/release of the leading edge vortex occurs, the location and magnitude of the stagnation point remained relatively constant, although the angle of attack continued to increase. This behavior could be captured via a sensor as the airfoil behavior on a rotor blade will be known on a vehicle. It appears that there could be sufficient time, given the sensor, to communicate the onset of dynamic stall to the pilot or control system to avoid it.

A potentially more accurate mathematical indicator is the behavior of the residuals, as illustrated in Figure 3. During the upstroke when the flow is attached, the residuals are much lower than during separated flows, which also indicate the time when the time step should be reduced. A limit threshold could be set at which the time step will be lowered in the calculation, but then increased during the remainder of the simulation.

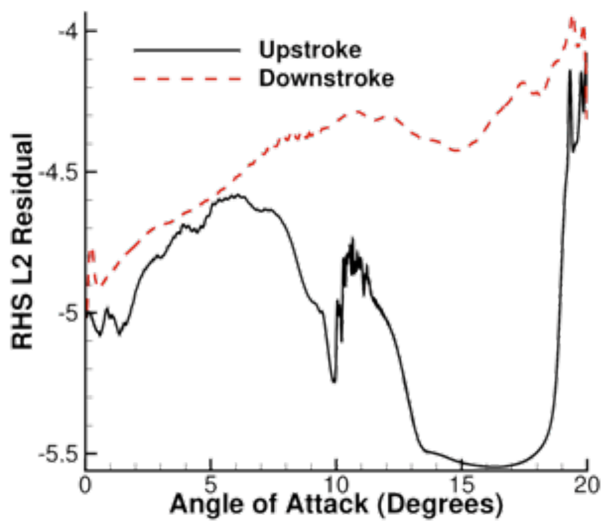

Figure 3: Evaluation of residual behavior over a dynamic stall event.

4.4. Reduced Order Model Development

For use in design and rotorcraft comprehensive codes, the objective of the low fidelity modeling and simulation portion of this project sought to enhance existing finite-state, semi-empirical stall models to be able to give quantitative, predictive results in real time, including the secondary stall event, and to be quantitatively predictive for dynamic stall in the rotating environment with yawed flow and unsteady free-stream.

The physics for the presence of a secondary stall event were identified, and a successful model was developed and validated with success across multiple airfoils.

The analysis of the effect of yawed flow was completed, and a model developed and validated. For a number of different airfoils and reduced frequencies, the Peters model was demonstrated to be valid and provide good correlation for a variety of sweep angles. This was a fundamental step to creating a model that can handle finite rotor blades that are rotating.

The Modarres dynamic stall model (30) for modelling pitching moment and drag for two datasets: steady freestream, wind tunnel testing of a Boeing VR12 airfoil section, and steady freestream, water-tunnel testing of a Boeing VR7 airfoil section. VR12 data (31) was compared to the results from Ahaus (32), who compared pitching moment and drag to the dynamic stall model, but only optimized parameters for lift. Additional data from the VR7 (33) included a wide range of reduced frequencies (k=0.002 to 0.25), which were used to develop a stall parameter function dependent on pitch rate. Both datasets were used to verify the Modarres secondary stall model for pitching moment.

Examples that illustrate the effectiveness of the approach are provided to substantiate these findings. *Figure **4*** and *Figure* **5** show pitching moment coefficient versus blade pitch angle for the VR-12 airfoil tests at a reduced frequency of 0.05 and at Mach numbers of 0.2 and 0.4, respectively. Each plot contains the experimental data, the model with primary stall only, and the model with both primary and secondary stall models. The red curve is the experimental data, the green curve is with primary stall only, and the blue curve adds secondary stall. At M=0.2, the model with secondary stall only differs from the primary stall curve in the relatively small region where secondary stall occurs, and the blue curve is barely visible. However, at M=0.4, in which secondary stall plays a bigger effect, one can see a large effect of the secondary model on the results over a wider range of angles. The results with primary stall show only qualitatively good correlation; but that model is unable to match the secondary peaks that are apparent in the data. Once the secondary stall model is added, however, the theory shows close correlation with the data including the secondary oscillations at both Mach numbers. The model with secondary stall shows clearly improved correlation with the data over the primary stall model.

Figure **6** gives pitching-moment correlation for the VR-12 at k=0.1 and M=0.2. At these conditions, there no second peak in the pitching moment data; and no secondary stall correction is needed. Notice that the model picks up all three loops of the stall curve. Since the central loop represents negative pitch damping, it follows that the present model can predict pitch damping even in the presence of dynamic stall. *Figure **7*** applies the primary stall model to dynamic drag. The correlation is qualitatively accurate and much better than the drag results presented by Ahaus (32). This is because the present model uses stall parameters different from those for lift and also allows the stall parameters to be different on the upstroke and downstroke. The data do indicate some secondary stall peaks in the response, indicating the need for a secondary stall drag model for drag. Such a model has yet been tested for drag in our work, but that will be a next step in the research. Correlation will definitely improve when the secondary drag is added.

Current results include only steady freestream, un-skewed VR-7 water tunnel data (34). Correlation was observed for the primary stall model when compared to data with reduced frequencies of 0.05 - 0.25. Close qualitative agreement with the experimental results can be seen; and, while the data includes secondary peaks in the moment curves, the secondary stall model is not shown in the figures. The results have a stability constraint placed on the

η parameter, restricting the solutions to positively damped parameter sets only. The optimization routine without this constraint often finds solutions that allow the solution to become briefly unstable, so this constraint is necessary to remove those possibilities. The constraint is implemented by a simple cost of 1000 to the 2-norm error of a test for any parameter set not satisfying $0 < \eta_0 + \eta_2 max(\Delta Cl^2)$ (2-norm errors for these tests are on the order of 0.1 - 0.2). Additionally, with various weighting functions applied, solutions that select one set of parameters works effectively for all reduced frequencies in the set. Even though data sets are not available for all Mach numbers or reduced frequencies, it is possible to provide a simple quadratic or cubic fit of the parameters that give reasonable results for conditions either interpolated and extrapolated from the training data set.

One can see from example figures and the papers that a single parameter functionality does an excellent job of matching the value of the peaks and the general qualitative nature of the pitching moment response. The same correlation is found for the drag data. The damped oscillations of the data set that can be seen in some cases have already been shown in to be well modelled by the addition of the secondary stall terms. This has been extended to unsteady freestream conditions as well.

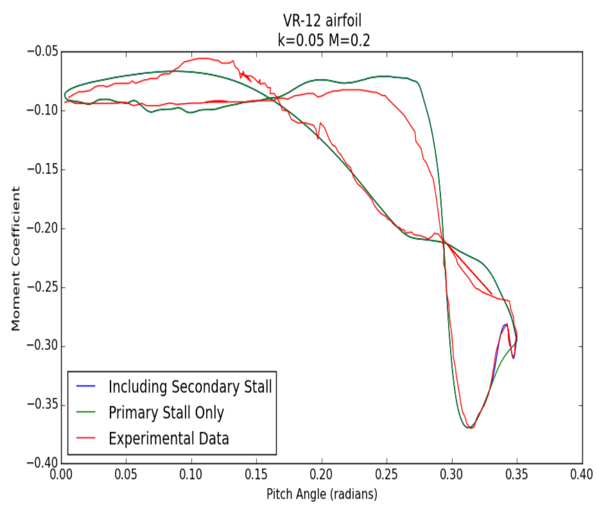

Figure 4: Correlation of pitching moment data for VR-12, k=0.05, M=0.2.

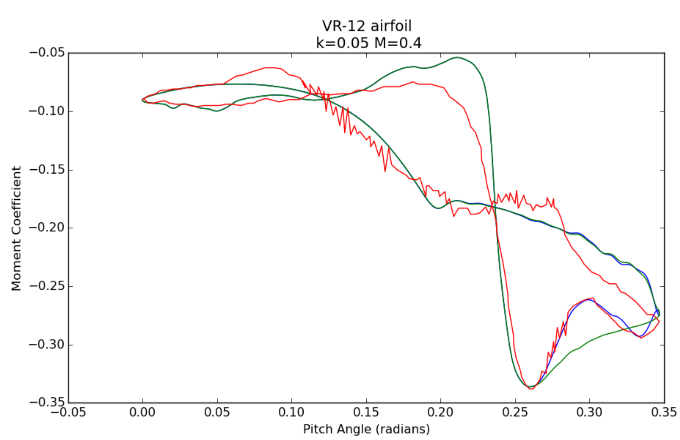

Figure 5: Correlation of pitching moment with data, VR-12, k=0.05, M=0.4.

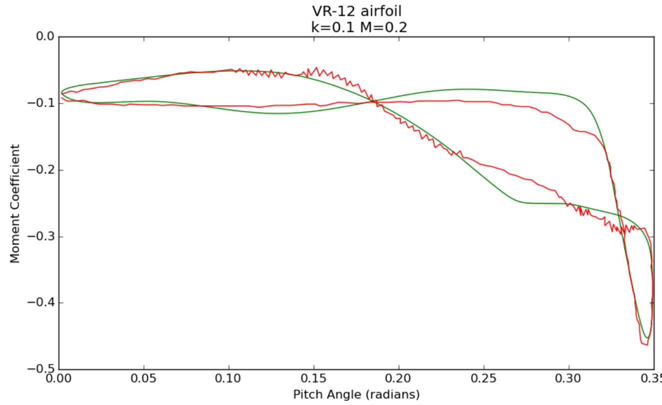

Figure 6*: Primary stall model compared to VR-12 data without any secondary peak.*

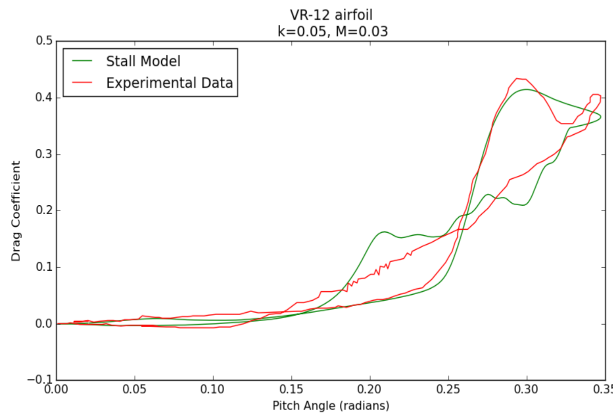

Figure 7: Correlation of drag data, VR-12, k=0.05, M=0.3.

5. Technology Transfer

The Peters reduced order model advancements have been/are being implemented into the flight simulation tool, FlightLab by ART. It has also been shared with Dr. Hong Xin, Sikorsky Arlington, GENHEL; Dr. Bill Welsh, Sikorsky Hartford, GENHEL; Prof. James Gregory, OSU, experiments; Indrajit Mukherjee, IISC, for hummingbird flight.

The new turbulence and transition methodologies developed by the GT VLRCOE for dynamic stall have been implemented into the NASA FUN3D solver, which is also a near-body solver for the CREATE-AV Helios framework.

Peters' reduced order dynamic stall model served as the inspiration of the Georgia Tech Aerodynamics of Bluff Bodies (GTABB) reduced order model developed under the GT VLRCOE. This model has been adopted by the US Army, industry and academia for modeling of slung loads, airdrops, towed loads, and maneuvering UAVS.

The CFD knowledge and the reduced-order developments are being utilized in the NATO AVT-282 Technical Working Group on Gusts, as well as a task on transients for UAVs in the 2016-2021 GT VLRCOE.

A Dynamic Stall Workshop at Georgia Tech will be held in September 2019 to gather researchers from across the globe.

5.1. Student Training

Summer presentations at Georgia Tech on this research (2014, 2015, 2016) to University of Alabama Aerospace Engineering NSF REU program.

Joachim Hodara completed his PhD Dissertation under 50% funding of this task in 2016.

Amanda Grubb performed two summer internships at ADD-Ames in Mountain View, CA during 2016 and 2017 at AED, CCDC in Huntsville, AL. Her PhD Dissertation (expected in 2019) is a direct result of this research.

6. Honors and Awards

71st American Helicopter Society Forum Best Paper, Aerodynamics: Hodara, Lind, Jones, Smith

Professor Marilyn J. Smith
2018 – present: Deputy Technical Director, Aeromechanics for Vertical Flight Society
2017: NASA Group Achievement Award, FUN3D Rotorcraft Development
2017 – present: Director, Southern Region of Vertical Flight Society (formerly AHS)
2016: Fellow, American Institute of Aeronautics and Astronautics
2015: Technical Fellow, American Helicopter Society
2014: Agusta-Westland International Fellowship Award, American Helicopter Society for the US/French Partnership Agreement (US Army, ONERA, DGA, NASA, GIT). Participation by GIT in Dynamic Stall task has been part of analysis and collaborative effort in this project

Professor David A. Peters
Technical Director of American Helicopter Society, 2014-2016
2017: Honorary Fellow, AHS

Student Awards
2016-2017 Vertical Flight Foundation Fellowship:
Amanda Grubb, GIT (PhD)
Michael Malick, WU (PhD)

2014-2015 Vertical Flight Foundation Fellowship:
Joachim Hodara, GIT (PhD)

2015-2016 Vertical Flight Foundation Fellowship
Amanda Grubb, GIT (MS)
Ramin Modarres, WU (PhD)

7. Publications

7.1. Refereed Journal Publications

1. Jain, R., Le Pape, A., Grubb, A., Costes, M., Richez, F., and Smith, M. J., "High-resolution CFD Predictions for the Static and Dynamic Stall of a Finite-span OA209 Wing," *Journal of Fluids and Structures*, Vol. 78, April, 2018
2. Modarres, Ramin and Peters, David A., "Real-Time Simulation of Dynamic Stall with Unsteady Free-Stream Velocity," *Journal of the American Helicopter Society*, Vol. 62, No. 3, July 2017, pp. 1-10.
3. Hodara, J. and Smith, M. J., "Hybrid Reynolds-Averaged Navier-Stokes/Large-Eddy Simulation Closurefor Separated Transitional Flows," *AIAA Journal*, Vol. 55, No. 6, pp. 1948-1958, 2017, doi: 10.2514/1.J055475.
4. Modarres, Ramin and Peters, David A., "Dynamic Stall with Circulation Pulse and Hysteresis for NACA 0012 and VR-12 Airfoils" *Journal of the American Helicopter Society,* Vol. 61, No.4, October 2016.
5. Hodara, J., Lind, A., Jones, A., and Smith, M. J., "Collaborative Investigation of the Aerodynamic Behavior of Airfoils in Reverse Flow," *Journal of the American Helicopter Society, Vol. 61, No. 3,* 2016.

7.2. Conference Publications

1. Grubb, A., Castells, C., Jain, R., Richez, F., and Smith, M. J., "High Fidelity CFD Analyses of Dynamic Stall on a Four-Bladed Fully Articulated Rotor System," in Proceedings of the 2018 AHS 74th Annual Forum, Phoenix, AZ, May 14-17, 2018.
2. Malick, Michael and Peters, David A., "Simulation of Pitching Moment and Drag by a State-Space Dynamic Stall Model—Experimental Correlation," Proceedings of the 73rd Annual National Forum of AHS International, Ft. Worth, Texas, May 9-11, 2017.
3. Jain, R., Le Pape, A., Grubb, A., Costes, M., Richez, F., and Smith, M. J., "High-resolution CFD Predictions for the Static and Dynamic Stall of a Finite-span OA209 Wing," Proceedings of the 2017 AHS 73rd Annual Forum, May 2017.
4. Grubb, A. and Smith, M.J., "Temporal Adaption Methods for Computationally Intensive Rotorcraft CFD Simulations," AIAA Aviation, June 2017, Denver CO.
5. Smith, L., Lind, A., Jacobson, K., Smith, M. and Jones, A., "Exp. and Comp. Investigation of a Linearly Pitching NACA0012 in Reverse Flow," American Helicopter Society 72nd Annual Forum, West Palm Beach, FL, May, 2016.
6. Cross, P., Hodara, J. and Smith, M., "Evaluation of Transitional Effects in Rotorcraft Applications," American Helicopter Society 72nd Annual Forum, West Palm Beach, FL, May, 2016.
7. Modarres, Ramin and Peters, David A., "Reduced-Order Dynamic Stall Model with Unsteady Free-Stream—Experimental Correlation," AHS International Technical Meeting on Aeromechanics Design for Vertical Lift, San Francisco, California, January 20-22, 2016.
8. Hodara, J. and Smith, M. J., "Improved Turbulence and Transition Closures for Separated Flows," 41st European Rotorcraft Forum, Munich, Germany, September 1–4, 2015
9. Smith, M. J., Jain, R., Grubb, A., and Jacobson, K., "Time-and-Spatially Adapting

Simulations for Efficient Dynamic Stall Predictions,"41st European Rotorcraft Forum, Munich, Germany, September 1–4, 2015
10. Hodara, J., Lind, A., Jones, A., and Smith, M. J., "Collaborative Investigation of the Aerodynamic Behavior of Airfoils in Reverse Flow," American Helicopter Society 71st Annual Forum, Virginia Beach, VA, May, 2015
11. Modarres, R., Peters, D.A., and Gaskill, "Dynamic Stall with Circulation Pulse and Hysteresis for NACA 0012 and VR-12 Airfoils, American Helicopter Society 71st Annual Forum, Virginia Beach, VA, May, 2015
12. Hodara, J. and Smith, M. J., "Improvement of Crossflow Aerodynamic Predictions for Forward Flight," in Proceedings of the 40th European Rotorcraft Forum, Southampton, UK, Sept. 2–4, 2014

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