

Final Progress Report

Vertical Lift Research Center of Excellence (2011-16)

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14. ABSTRACT The Alfred Gessow Rotorcraft Center (AGRC) at the University of Maryland (UM), in partnership with US Naval Academy (USNA), and further supported by researchers at the University of Texas at Austin (UT), the University of Wyoming (UW), and the North Carolina A&T State University (NCA&T) carried out a coordinated, five-year multidisciplinary research and education program that advanced fundamental understanding, predictive, and design optimization capabilities in a number of areas of science and engineering of great significance to the rotorcraft field. The analytical and experimental program consisted of 15 interconnected tasks, each covering at least one of nine research areas: aeromechanics; structures; flight dynamics and control; rotorcraft design and concepts; vibration and noise control; propulsion; affordability; safety and survivability; and naval operations.					
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“Vertical Lift Research Centers of Excellence (2011-16)”

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Abstract

The Alfred Gessow Rotorcraft Center (AGRC) at the University of Maryland (UM), in partnership with US Naval Academy (USNA), and further supported by researchers at the University of Texas at Austin (UT), the University of Wyoming (UW), and the North Carolina A&T State University (NCA&T) carried out a coordinated, five-year multi-disciplinary research and education program that advanced fundamental understanding, predictive, and design optimization capabilities in a number of areas of science and engineering of great significance to the rotorcraft field. The analytical and experimental program consisted of 15 interconnected tasks, each covering at least one of nine research areas: aeromechanics; structures; flight dynamics and control; rotorcraft design and concepts; vibration and noise control; propulsion; affordability; safety and survivability; and naval operations. The proposed research carried out by approximately 20 faculty and senior researchers, and over 25 graduate students, in close collaboration with industry and government laboratories. Overall, the research focused is on creativity, fundamental science, and potentially high-payoff revolutionary and disruptive concepts. The outputs of the program was directly useful in producing more energy efficient, highly-maneuverable, reliable, and cost effective advanced rotorcraft configurations, both manned and unmanned, such as those envisioned for the Joint Multi-Role (JMR) program; and which could successfully and safely operate in challenging conditions, from taking off and landing on small ship decks to operations in gusty wind conditions, and from carrying heavy slung loads, including partially or fully submerged loads, to safe day and night flying in degraded visual environments. The graduates from the program were infused into the U.S. helicopter industry, government laboratories, and academia, as a group of highly motivated young men and women, with deep specialized knowledge in a rotorcraft engineering-related research area, and a uniquely broad rotorcraft educational background.

Task	Title	Lead
A-1.1	High-Advance Ratio Aeromechanics of a Slowed Rotor up to a Full Retreating-Disk Reversal	Chopra (UMD)
A-1.2	Aerodynamics of a Rotor in Reverse Flow	Jones (UMD)
A-1.3	Simulation of Fundamental Viscous Flow Phenomena for Rotorcraft	Baeder (UMD)
A-1.4	Comprehensive Loads, Pressures and Performance Measurements for High-Speed Coaxial Compounds	Sirohi (UTA) Chopra (UMD)
A-1.5	High Resolution CFD for Interactional Aerodynamics of Coaxial Compounds	Baeder (UMD)
A-1.6	Fundamentals of Flight in Degraded Visual Environment (DVE)	Celi (UMD)
A-1.7	Innovative Numerical Algorithm for Fluid/Structure Simulation of Rotorcraft Transient Maneuvers	Sitaraman (UWYO)
A-1.8	Adjoint Methods for Numerical Optimization of Rotorcraft Performance, Vibration and Acoustics	Mavriplis (UWYO)
A-1.9	Total Fatigue Life Methodology for Damage Tolerance Design of Composite Rotorcraft Components	Shivakumar (NCAT)
A-1.10	Proximity Sensing of Degraded Visibility Missions	Humbert (UMD)
A-1.11	Collaborative Control for Autonomous Operation of Helicopters in Flight	Paley (UMD)
A-1.12	Flight Dynamics and Control of Rotorcraft Towing Submerged Bodies	Celi (UMD) Falls (USNA)
A-1.13	CAD-Based Structural Modeling for Advanced Rotorcraft	Chopra (UMD)
A-1.14	Conceptual Modeling of Novel Configurations for UAS Applications	Benedict (TAMU) Chopra (UMD)
A-1.15	Noncontact Torque Sensor	Flatau (UMD)

Task A-1.1 High Advance Ratio Aeromechanics of Slowed Rotors
PI: Inderjit Chopra chopra@umd.edu, (301) 405-1122

Background:

The objective of this task was to carry out comprehensive analysis (CFD/CSD) and Mach-scale wind-tunnel tests for fundamental understanding of performance, loads and vibration of a slowed (reduced RPM) rotor up to and beyond advance ratios of full-disk retreating side reversal ($\mu \approx 2.0$) on a variety of rotor geometries (of progressively increasing complexity) and a range of operating conditions (speed, RPM and shaft angles).

Slowed rotors – traditionally associated with autogyros and gyroplanes – have long been recognized as one potential solution for high-speed helicopters (200-300 kt). With the advancement of materials, controls, and propulsion/drivetrain technologies, slowed rotors have once again begun to emerge as a viable solution to high-speed, high-efficiency, heavy-lift helicopters of the future (along with tilt-rotors and lift-offset coaxial compounds). The intent of this task is the fundamental understanding of such rotors, using both analysis and experiment; at the very high-advance ratio reverse flow conditions they are envisioned to operate in ($\mu \approx 1.5$ -2.0 and beyond).

The only existing data set that includes performance, pressures and loads are the recent full-scale UH-60A tests – but this data is only up to $\mu = 1.0$. Model-scale tests performed recently either achieve higher advance ratios (up to $\mu = 2.2$) but all focused mostly on performance measurements and fall far short from being comprehensive. Similarly, discrepancies in analyses have still not been systematically addressed due to the scarcity of reliable and comprehensive test data. Thus, both lack of experimental data and validated analysis can become significant technical barriers towards effective and efficient use of slowed rotors in the development of next-generation high-speed compound rotorcraft. The intent of this task is to address these deficiencies directly.

Research Objectives:

The objective was to build upon the existing strength in Mach-scale experimentation of slowed RPM rotors and CFD/CSD coupled comprehensive analysis to focus activity towards basic research in slowed rotor aeromechanics. The research contained four major thrust areas: (1) understanding of basic physics – pitch link loads under reversed flow, flapping and cyclic control requirements at reduced RPM (including a better understanding of control reversals) and structural loads at reduced centrifugal force levels (2) understanding of efficient operations – shaft angle/collective combinations for minimum power or maximum range at various speeds and advancing tip Mach numbers; (3) generation of unique data set that includes cyclic control angles, and blade motion and loads up to $\mu = 2.0$; and (4) development of refined analyses with systematic validation addressing special challenges of high advance ratio operation – reverse flow region and wake modeling (related to lifting-line modeling), prediction of viscous drag (related to CFD modeling), and the potential for divergent airload sensitivities between lifting-line and CFD (implications on CFD/CSD analysis).

Approach:

The approach was to carry out both experiments and analysis to isolate basic phenomena and validate predictions. This approach was to generate benchmark data, help identify gaps in analysis

and rectify them, and provide a fundamental understanding of basic slowed rotor dynamic mechanisms.

(1) *Wind-tunnel test:* The research rotor was 4-bladed with pre-twist distribution, conventional rotorcraft airfoils (symmetric), and used an articulated rotor hub. Two rotor sets were built respectively incorporating different twist distributions. The operations focused on controlled RPM (starting from baseline hover tip Mach of 0.65 down to 40%) over a wide range of rotor advance ratios and shaft angles (-2° to 8° in steps of 1°) to identify autorotation states (minimum/zero power for rotor). In addition, the details of the power curves were measured in order to identify the speeds for best range and best endurance. In order to make observations concerning the basic physics, measurements included rotating and fixed frame loads (bending at r/R 0.5, torsion at 0.3, pitch link loads, and hub loads), blade flapping angles and elastic structural motions, and performance (torque). The tests were conducted in the Glenn L. Martin wind tunnel.

(2) *Analysis:* A baseline comprehensive analysis was to be first validated with the recent UH-60A slowed rotor data (from AFDD/NASA Ames) using both lifting-line and CFD/CSD (UMARC/UM-TURNS). The validated analysis was then be used to design the test plan for $\mu > 1.0$. For this purpose, the lifting-line analysis used airfoil properties extracted over $\pm 180^{\circ}$ (existing test data messaged using CFD), included leading-edge trailers to model the wake in reverse flow [2], and corrections for cross-flow effects. The obtained data set was finally used to quantify the limits of lifting-line prediction accuracy up to full-disk reversal. The CFD study first focused on drag prediction - each from zero to highest collective conditions - and then to coupled CFD/CSD analysis for prediction of pitch link loads (effect of a.c. movement in reverse flow), bending loads (due to changes in centrifugal force), and hub vibratory loads. The CFD analysis included an advanced turbulence model [see Task 1.2]. Also, the effect of scaled model Reynolds numbers on performance and loads evaluated systematically using test data.

(3) *Fundamental understanding:* Fundamental understanding was focused both on physical mechanisms as well as efficient vehicle operation. The physical mechanisms included: collective reversal and minimum power/drag operations, reverse flow induced dynamic stall phenomena on the lower surface of the inboard stations, reverse flow induced aerodynamic center movement and its impact on pitch link loads, impact of reduced centrifugal loading on chord bending loads, necessary refinements in reduced order lifting-line analysis, impact of reverse flow on CFD/CSD loose coupling trim convergence. Efficient vehicle operations included: trade-off between rotor efficiency (torque, lift-to-drag ratio) and vehicle efficiency (total power, propulsive force) as well as optimal lift and thrust sharing.

Accomplishments (Years 2011-16):

Four wind tunnel entries were performed in Years 1-4, with one wind tunnel entry in Year 4. The wind tunnel entries all consisted of Mach-scale rotors, roughly 6-ft in diameter, with baseline geometry of untwisted, rectangular blades with a NACA 0012 airfoil. The advance ratio envelope of the wind tunnel entries was increased, reaching to 1.5 in the Year 3 tests. The rotors were fully-controlled throughout and trimmed to zero 1/rev flap angles at each test condition. Comprehensive measurements were performed, including steady and vibratory hub loads, pitch link loads, blade structural loads, and blade surface pressures. A full dynamic calibration of the rotor hub balance was performed in Year 3 to measure accurate vibratory hub loads. This is a key measurement that has been missing in most of the high advance ratio tests in the literature. In Year-4, a dynamic test was conducted to test Endevco sensor vs Kulite sensor to verify whether they have a comparable performances up to 400 Hz. In Year-3 and Year-4, blade surface pressure sensors were also

included for three wind tunnel entries. Unsteady pressure sensors, from both Kulite and Endevco, were embedded at 0.30 R, 0.50 R and 0.86 R to measure phenomena associated with reverse flow at high advance ratio. From the pressure sensor data, the onset and development of dynamic stall peaks, originating at the trailing edge and passing towards the leading edge, was observed on the retreating blade. Hub and blade loads were correlated satisfactorily with UMARC comprehensive analysis, especially the vertical 4/rev hub loads at all advance ratios. Leishman-Beddoes dynamic stall model was modified for reversed flow to predict dynamic airload peak up to advance ratio of 0.6. Hybrid Method of CFD and Prescribed Wake Model (HCP) was also carried out in Year 4 and showed acceptable results compared with UMARC and UMD Year 3 test results. The work accomplished in Year 4 was published in four conference papers.

An extensive wind tunnel of 10 days was carried out in Year-5. A larger slipring was used to provide 150 data lines, including 12 lines were specially designed for high power transmission. We incorporated more pressure sensors in order to obtain integrated airloads at a specific spanwise location (30%R). Better fabrication methods using 3D-printing technology were used to develop superior identical blades as well as sensor holders. With the new trim strategy, a collective sweep test up to advance ratio of 1.5 with multiple pressure sensor stations was the goal of this wind tunnel and an advance ratio of over 1.0 was achieved safely step by step. At the same time, the reverse flow models in UMARC and CFD/CSD analyses was refined. The focus of the Year 5 was towards achieving the refined detailed test data at high advance ratios.

Graduated Students:

1. Benjamin Berry, "Fundamental Understanding of Rotor Aeromechanics at High Advance Ratio Through Wind Tunnel Testing," PhD, December 2016 (Engineer at Google).
2. Graham Bowen-Davies, "Performance and Loads of Variable Tip Speed Rotorcraft at High Advance Ratios," PhD, May 2015, (Contractor Army AFDD, Ames Research Center; now at Google).
3. Lauren N. Trollinger, "Refined Performance and Loads of a Mach-Scale Rotor at High Advance Ratios," MS, July 2017, (Arora Flight Sciences, Boston).

Publications:

1. Bowen-Davies, G. and Chopra, I., "Aeromechanics of a Variable-Speed Rotor," *67th Annual Forum of the American Helicopter Society*, Virginia Beach, VA, May 2011.
2. Berry, B. and Chopra, I., "Wind Tunnel Testing for Performance and Vibratory Loads of a Variable-Speed Mach-Scale Rotor," *67th Annual Forum of the American Helicopter Society*, Virginia Beach, VA, May 2011.
3. Bowen-Davies and Chopra, I., "Aeromechanics of a Variable-Radius Rotor," *68th Annual Forum of the American Helicopter Society*, Fort Worth, TX, May 2012.
4. Berry, B. and Chopra, I., "Performance and Vibratory Loads of a Slowed Rotor at High Advance Ratios," *68th Annual Forum of the American Helicopter Society*, Fort Worth, TX, May 2012.
5. Berry, B. and Chopra, I., "High-Advance Ratio Wind Tunnel Testing of Two Mach-Scale Rotor Geometries," *69th Annual Forum of the American Helicopter Society*, Phoenix, AZ, May 2013.

6. Bowen-Davies, G. and Chopra, I., "Validation of Rotor Performance and Loads at High Advance Ratio," *Fifth Decennial AHS Aeromechanics Specialists' Conference*, San Francisco, CA, January 2014.
7. Berry, B. and Chopra, I., "High-Advance Ratio Wind Tunnel Testing of a Model Rotor with Pressure Measurements," *Fifth Decennial AHS Aeromechanics Specialists' Conference*, San Francisco, CA, January 2014.
8. Berry, B. and Chopra, I., "Slowed Rotor Wind Tunnel Testing of an Instrumented Rotor at High Advance Ratio," *40th European Rotorcraft Forum*, Southampton, UK, Sept 2014.
9. Bowen-Davies, G. and Chopra, I., "Performance and Loads Correlation of the UH-60 Rotor at High Advance Ratios," *40th European Rotorcraft Forum*, Southampton, UK, Sept 2014.
10. Berry, B. and Chopra, I., "Wind Tunnel Testing of an Instrumented Rotor at High Advance Ratio," *AIAA SciTech Conference*, Kissimmee, FL, January 2015, Paper AIAA-2015-0950.
11. Bowen-Davies, G. and Chopra, I., "Aeromechanics of Slowed Rotor at High Advance Ratios," *AIAA SciTech Conference*, Kissimmee, FL, January 2015, Paper AIAA-2015-0951.
12. Bowen-Davies, G. and Chopra, I., "Investigation of the Unsteady Reverse Flow Airloads at High Advance Ratios," *41st European Rotorcraft Forum*, Munich, Germany, Sept 2015.
13. Trollinger, L., Wang, X. and Chopra, I., "Refined Measurement and Validation of Performance and Loads of a Mach-Scaled Rotor at High Advance Ratios," *43rd European Rotorcraft Forum*, Milan, Italy, September 2017.

Task A-1.2: Aerodynamics of a Rotor in Reverse Flow

PI: Anya Jones (arjones@umd.edu, (301) 405-7988)

PhD Students: Andrew Lind (alind@umd.edu), Luke Smith (lsmith1@umd.edu)

Background:

This work contributes to the development of high-speed helicopters by providing an improved understanding of the fundamental flow physics of a rotor blade in reverse flow. Reverse flow (i.e. flow from the geometric trailing edge towards the geometric leading edge) occurs when the forward flight speed of a helicopter exceeds the angular velocity of a portion of the retreating rotor blade. The affected portion of the blade undergoes rapid variations in local flow speed and direction, which has a profound effect on aerodynamic performance, blade loading, and pitch link loading. The blade experiences a high unsteady pitching moment due to the impulsive shifting of the center of pressure, and high pressure drag due to flow separation at low angles of attack. These adverse aerodynamic effects act to increase profile power requirements, vibrations, and component fatigue, directly limiting the maximum airspeed of the helicopter.

Research Objectives:

The objectives of this task are to experimentally characterize the flow features associated with reverse flow and quantify the resulting unsteady airloads. Specifically, this task aims to:

- Evaluate the performance merits of airfoil section characteristics (such as sharp or blunt geometric trailing edges) for use in reverse flow by quantifying time-averaged and unsteady airloads acting on static and oscillating airfoils.
- Identify relevant flow features such as boundary layer separation points and vortex shedding characteristics (e.g. strength, trajectory, and frequency) to inform the development of unsteady analytical models of reverse flow and flow control efforts.
- Assess the effects of scaling by varying Reynolds and Mach numbers.
- Evaluate flow three-dimensionality in the reverse flow region of a rotor disk.

Approach:

Experimental research efforts are being conducted in a 20x28" open-circuit wind tunnel (max speed 160 ft/s, located at UMD), a 42x60" closed-circuit wind tunnel (max speed 300 ft/s, located at the USNA), and the 7.75x11.04' Glenn L. Martin wind tunnel (max speed 337 ft/s, located at UMD). Time-averaged airloads are measured using force balance measurements. Unsteady airloads are obtained via integration of pressure captured using surface-mounted unsteady pressure transducers. Time-resolved particle image velocimetry (TR-PIV) measurements are synchronized with the unsteady pressure measurements to study boundary layer characteristics (e.g., separation point) and vortex development, growth, and shedding over the model rotor blades and in the wake. Collaborative efforts are ongoing to validate CFD codes with experimental results, both in conjunction with Task A-1.3 (James Baeder, UMD) and externally (Marilyn Smith, Georgia Tech).

Three separate research efforts are being conducted. First, the time-averaged and unsteady aerodynamics of static model rotor blades are being measured through 180 deg.

Second, the unsteady aerodynamics of airfoils subject to two types of pitching in reverse flow are being examined: sinusoidal and constant-rate. Sinusoidal pitching to mimics cyclic pitching kinematics and allows for comparison between reverse flow dynamic stall and classical dynamic

stall experiments. Linear (i.e., constant-rate) pitching experiments better capture the true angle of attack distribution in the reverse flow region of a coaxial high-speed rotor with lift offset. For both cases, unsteady pressure and flowfield measurements are being collected to characterize the evolution of reverse flow dynamics stall and its impact on unsteady airloads. Third, instrumented rotor blades with a blunt geometric trailing edge are being tested on a fully articulated hover stand and in forward flight to gain insight on the three-dimensional effects of the reverse flow region.

Accomplishments in Years 1-5:

Years 1 and 2 focused on sub-scale experiments at $Re = 110,000$ to characterize the effect of trailing edge shape on the time-averaged airloads and flowfields of static airfoils in reverse flow and at high angles of attack (through 360 deg). Unsteady wake regimes and corresponding vortex shedding frequencies were identified. In year 3, experiments on static airfoils through 180 deg were performed at the USNA at Reynolds numbers up to one million, representative of the flow conditions in the reverse flow region of a full-scale high-speed helicopter. Time-averaged airloads and unsteady surface pressure distributions were collected for four airfoils (NACA 0012, NACA 0024, 24% thick ellipse, and 26% thick ellipse with 4% maximum camber). A dynamic pitching rig was built and tested at UMD. Preliminary reverse flow dynamic stall results were obtained for the cambered elliptical airfoil.

In year 4, the fundamental features of reverse flow dynamic stall were characterized for a NACA 0012 and cambered elliptical airfoil undergoing sinusoidal pitching. Models were instrumented with 25-27 unsteady pressure transducers (Endevco and Kulite) at the mid-span allowing for calculation of unsteady airloads. The parameter space spanned Reynolds numbers up to 500,000, reduced frequencies up to 0.511, mean pitch angles up to 15 deg, and pitch amplitudes up to 10 deg. A NACA 0012 exhibits deep dynamic stall in reverse flow, although the type (i.e., number of dynamic stall and trailing edge vortices) varies with pitching kinematics. The unsteady airloads and flowfields are insensitive to Reynolds number due to forced flow separation at the sharp leading edge. The cambered elliptical airfoil exhibits light dynamic stall for a wide range of pitching kinematics due to its blunt aerodynamic leading edge, but can also undergo deep dynamic stall (similar to the NACA 0012) for high maximum pitch angles. Collaborative work was also conducted with Joachim Hodara and Marilyn Smith (Georgia Tech) to evaluate CFD tools that predict reverse flow dynamic stall features for an oscillating NACA 0012. The work was awarded Best Paper in the Aerodynamics session of AHS Forum 71 and the paper has since been accepted to the AHS Journal.

2D reverse flow dynamic stall experiments were continued in year 5 with a focus on more closely approximating the kinematics and flow physics of a spinning rotor. A series of linearly pitching blade experiments were completed using a NACA0012 airfoil and a set of blade kinematics extracted from UMARC, an in-house comprehensive rotor design code. The blade kinematics were intended to mirror the pitching motion experienced by a blade section passing through the reverse flow region on a Mach-scale rotor at advance ratios $\mu = 0.5$ and $\mu = 0.8$. The effect of starting pitch angle, pitch amplitude, and pitch rate on vortex strength were investigated via flowfield measurements and unsteady pressure transducers installed along the blade surface. Simultaneously, the dynamic pitching rig was modified to allow for model rotor blades to be oriented with a yaw (or sweep) angle relative to the tunnel freestream. Preliminary work regarding the effect of yaw on the convection behavior of dynamic stall vortices was completed in the Fall

of 2016; investigations into the effects of yaw were intended to lay the groundwork for an understanding of the 3D flow physics of vortex behavior in reverse flow. The linear pitching and yawed blade experiments were presented at the AHS Forum 72 and the 68th Meeting of the APS Division of Fluid Dynamics, respectively.

Year 5 also saw an assessment of modern dynamic stall models in their ability to predict unsteady loading in reverse flow. Results from the Leishman-Beddoes and ONERA dynamic stall methods were compared to unsteady airloads measured in previous 2D experiments of an oscillating wing in reverse flow. Although both models were able to predict basic trends in aerodynamic loads, each required adjustment based on the specific pitching kinematics, ultimately motivating the need for a more physics-based model for implementation in modern comprehensive rotor design codes.

Graduated Students

1. Andrew Lind, “An Experimental Study of Static and Oscillating Rotor Blade Sections in Reverse Flow,” PhD, December 2015 (currently an Assistant Research Engineer at the Glenn L. Martin Wind Tunnel)

Publications

1. Lind, A.H., Lefebvre, J.N., and Jones, A.R., “Experimental Investigation of Reverse Flow over Sharp and Blunt Trailing Edge Airfoils.” *31st AIAA Applied Aerodynamics Conference*, June 2013.
2. Lind, A.H., Lefebvre, J.N., and Jones, A.R., “Time-averaged Aerodynamics of Sharp and Blunt Trailing Edge Static Airfoils in Reverse Flow.” *AIAA Journal*, 52(12), December 2014.
3. Lind, A. H., Jarugumilli, T., Benedict, M., Lakshminarayan, V. K., Jones, A. R., and Chopra, I. (2014). “Flow Field Studies on a Micro Air Vehicle- Scale Cycloidal Rotor in Forward Flight.” *Experiments in Fluids*, 55 (12). doi: 10.1007/s00348-014-1826-1
4. Granlund, K., Ol, M. and Jones, A. R. (2015, January). “Stream-Wise Oscillation of Airfoils into Reverse-Flow.” AIAA Paper 2015-1065 presented at the 53rd AIAA Aerospace Sciences Meeting, Kissimmee, FL, USA.
5. Hodara, J., Lind, A.H., Jones, A.R., and Smith, M.J., “Collaborative Investigation of the Aerodynamic Behavior of Airfoils in Reverse Flow.” *71st Annual Forum of the American Helicopter Society*, Virginia Beach, Virginia, May 2015.
6. Jones, A. R., Hodara, J., Smith, M., Granlund, K., Mulleners, K., and Ol. M. (2015, May). Blade Sections in Streamwise Oscillations into Reverse Flow. Paper 2015-183 presented at the 71st American Helicopter Society Annual Forum & Technology Display, Virginia Beach, VA, USA.

7. Lind, A. H. and Jones, A. R. (2015). "Vortex Shedding from Airfoils in Reverse Flow." *AIAA Journal*, 53 (9), pp. 2621-2633. doi: 10.2514/1.J053764
8. Hodara, J., Lind, A., Jones, A. R., and Smith, M. (2016). "Collaborative Investigation of the Aerodynamic Behavior of Airfoils in Reverse Flow." *Journal of the American Helicopter Society*, 61(3), pp. 1–15. doi: 10.4050/JAHS.61.032001
9. Granlund, K., Ol, M., and Jones, A.R., "Streamwise Oscillations of Airfoils into Reverse Flow." *AIAA Journal*, 54(5), January 2016.
10. Lind, A.H., Smith, L.R., Milluzzo, J., and Jones, A.R., "Reynolds Number Effects on Rotor Blade Sections in Reverse Flow." *Journal of Aircraft*, 53(5), February 2016.
11. Lind, A.H. and Jones, A.R., "Unsteady Airloads on Static Airfoils through High Angles of Attack in Reverse Flow." *Journal of Fluids and Structures*, 63, May 2016.
12. Smith, L.R., Lind, A.H., Jacobson, K.E., Smith, M.J., and Jones, A.R., "Experimental and Computational Investigation of a Linearly Pitching NACA 0012 in Reverse Flow." *72nd Annual Forum of the American Helicopter Society*, May 2016.
13. Lind, A.H. and Jones, A.R., "Unsteady Aerodynamics of Reverse Flow Dynamic Stall on an Oscillating Blade Section." *Physics of Fluids*, 28(7), July 2016.

UM-1.3: Simulation of Fundamental Viscous Flow Phenomena for Rotorcraft
PI: Dr. James Baeder (UM); baeder@umd.edu; (301) 405-1107

Background:

Achieving significant increase in speeds and range capabilities for the rotorcraft has directed the attention of rotorcraft community towards the concept of slowed rotor. The requirement for reduction in rotor speed with increasing flight speeds results in high advance ratio operation where the retreating side of the rotor may be dominated by reverse flow region, characterized by low incoming Mach number with blades operating at high angles of attack. And, it is the retreating blade characteristics that end up limiting the maximum flight speeds attainable by rotorcraft. It is therefore imperative to understand the retreating flow physics and obtain accurate aerodynamics characteristics of rotorcraft blades in the reverse flow region if one aims to improve the performance of the rotorcraft. Therefore, the main focus of this work is to understand the fundamental viscous flow physics in reverse region and identify CFD methodologies suited to accurately capture the relevant flow features.

Modeling aerodynamic behavior of airfoil in the reverse flow regime is challenging for CFD because of the flow physics involved. At low angles of attack, the flow remains fully attached to the airfoil. This flow is nearly steady and two dimensional in nature; RANS equations can be used to model all scales of turbulence in attached flow and this modeling is generally accurate when flow has no transient components. At large angles of attack beyond the stall limit, the flow may be extensively separated comprising of three dimensional unsteady vortical structures. RANS will perform poorly because of its time averaged nature. However, moderately and massively separated flows are well suited for DDES (Delayed Detached Eddy simulation) method (which is a hybrid RANS-LES model) where adverse pressure gradient is strong enough to induce clear separation.

In the intermediate range of angles of attack where the flow experiences incipient separation, DES may fail however. It is because in the case of weakly separated flow, the thick RANS boundary layer enters the separated LES regions. Consequently, LES content is decayed by high levels of eddy viscosity convected from the RANS boundary layer resulting in excessive stress predictions. Further, due to direct dependency on grid spacing, DES requires more carefully generated grids to avoid inappropriate behavior. For instance, under fine wall-parallel grid refinement, the LES mode can become active inside the boundary layer. This leads to a depletion of the modeled turbulent stresses and a corresponding under prediction of skin friction causing grid induced separation. DDES predicts two separate logarithmic layers (one because of RANS model and other because of LES region) indicating its failure as WMLES in presence well refined grid. Therefore, for weakly separated flows a higher fidelity hybrid RANS-LES method like IDDES (Improved Delayed Detached Eddy Simulation) might be needed. IDDES combines functionality of DDES and Wall Modeled LES (WM-LES) formulation by defining an adaptive sub-grid scale. With the help of blending functions, there is a smooth transition between WMLES and DES approach, eliminating the log layer mismatch. The IDDES model is designed to allow the LES simulation of wall boundary layers at much higher Reynolds numbers than standard LES models

Research Objectives:

The objective of this research is to understand the physics of viscous flow associated with separated flows in the reverse flow regime. With this understanding, the next objective is to

identify and implement hybrid RANS-LES CFD methods that can be used to accurately predict the flow in the reverse flow region. The final objective then is to conduct detailed high advance ratio slowed rotor simulations and obtain accurate flow characteristics.

Approach:

Current CFD solver framework includes DDES and transitional modeling capabilities. IDDES method will be implemented into this framework to account for weakly separated flows. After this IDDES method will be validated against different benchmark cases. These benchmark cases are selected to test DDES and WMLES functionality of IDDES. After validation, numerical simulations of flow over SC1095 and NACA0012 airfoils will be conducted for wide range of angle of attacks with more emphasis on reverse flow angles of attack. Predictive abilities of IDDES and DDES will be assessed by comparing numerical predictions with experiments for these airfoils. Finally detailed rotor simulations will be conducted at high advance ratios with relevant hybrid CFD methods to obtain accurate flow characteristics.

Accomplishments (Years 2011-16):

Detailed 3D simulations were conducted for SC1095 and NACA0012 airfoils to evaluate and understand the relevance of transitional modeling and DDES mechanism. To account for small Mach number encountered in the reverse flow regime, a low Mach number fix was also incorporated in the simulations. A comprehensive literature review of DES type models was also conducted. Through this literature survey it was identified that IDDES: hybrid method of DES and WMLES has the potential to accurately predict the flow over airfoil in reverse flow as well as stall regimes. It was found that IDDES is capable of handling features which include flow that include flow reversal within the boundary layer, incipient flow separation as well as and re-attachment.

IDDES method was successfully validated within the DDES framework of the in-house GPU based Navier–Stokes solver. IDDES method has the capability to function as DDES and WMLES depending on flow characteristics. To validate WMLES mode of IDDES, a channel flow configuration was set up which comprised of RANS turbulent profile to act as modeled turbulence and added synthetic turbulence to act as resolved turbulence content. IDDES method was able to capture vortical structures at different channel heights in finer details when compared to DDES results. Further, the blending functions produced by IDDES matched closely with the corresponding functions predicted by Travin et al. IDDES method was also evaluated on a wall-mounted hump configuration for its ability to resolve weakly separated flows. IDDES method was able to capture fine turbulent structures in recirculation zone of wall-mounted hump.

Predictive abilities of RANS, DDES and IDDES methods were investigated along with the laminar-turbulent transition modeling and the correction for strong adverse pressure gradient. Detailed numerical simulations were conducted for forward and reverse flow over SC1095 airfoil in a broad range of angle of attack using GPU based Navier–Stokes solver. For the forward flow, in the attached flow regime, DDES and RANS methods predicted integrated lift coefficients that matched well with the experimental data. Correction for strong adverse pressure gradient (APG) significantly improved lift predictions at near-stall angles of attack by reducing the eddy viscosity levels near the boundary layer edge. IDDES method with APG correction predicted physically correct turbulent content and resulted in good agreement with experimental data when compared for integrated forces.

Unlike standard DDES method which uses maximum local grid spacing as the length scale governing the transport equation of eddy viscosity, IDDES formulation uses an adaptive length scale definition which is proposed by Shur et al. This adaptive length scale is substantially smaller to standard DDES length scale in the near-wall region and the outer part of the turbulent boundary layer. The improved prediction of modeled turbulence/eddy viscosity by IDDES method may be attributed to the usage of adaptive length scale along among other factors. Accurate prediction of eddy viscosity directly dictates the onset of flow separation in the near-stall flow regime and therefore controls the integrated forces and pitching moments.

It has been shown that the length scale used in the standard DDES method only works well for isotropic grid. The correct definition of length scale in a substantially anisotropic grid like the one used with airfoil remains a topic of investigation. Moreover, the shielding function in the DDES formulation depends implicitly on the length scale and other empirical parameters. Shielding function enforces RANS mode within the boundary and is vital in deciding the turbulence content at the edge of the boundary layer.

Therefore, it became imperative to investigate the impact of length scales on the prediction capabilities of DDES method. Consequently, different length scale definitions available from literature were investigated within the DDES framework. Based on the investigation, a hybrid length scale length is proposed. The proposed length scale depends on the length scale correction for anisotropy suggested by Scotti and the adaptive length scale of IDDES formulation. With the proposed length scale, the DDES method provided accurate drag and pitching moment predictions for SC1095 airfoil matching closely with the experiment. In the reverse flow regime of SC1095 airfoil, most of the CFD methods performed well in the angle of attack range of 160° – 180° . The predictions of the CFD deviated significantly from experimental data at angles of attack less than 150° even after employing correction for strong adverse pressure gradient.

To capture fine temporal scales, hybrid RANS-LES simulations were conducted with a small time step size and sizable number of iterations is required to attain statistical convergence. To achieve substantial savings in time, GPU based solver was used for the simulations. However, the size of the mesh that can be used with the solver has been limited by the video RAM size of the GPU being used. This limitation was eliminated by the addition of MPI capability to the GPU solver. Grid motion capability was also implemented into the solver successfully. This has now enabled the path for conducting highly resolved large scale dynamic simulations of rotor blade configuration spanning over multiple GPU cores.

Graduated Students:

1. Jimenez Ben, MS Scholarly Paper, May 2013 (Engineer at Whirlpool).
2. Shivaji Medida, “Assessment of Turbulence Length Scales in Hybrid RANS-LES Methods,” PhD, May 2014 (Engineer at Altair).
3. Nishan Jain, “Assessment of Turbulence Length Scales in Hybrid RANS-LES Methods,” PhD, May 2017 (Post-Doctoral Research at UMD/ARL).

Publications:

1. Medida, S., and Baeder, J. D., "Application of the Correlation-based γ -Re θ t Transition Model to the Spalart-Allmaras Turbulence Model", *20th AIAA Computational Fluid Dynamics Conference*, Honolulu, HI, June 2011.
2. Medida, S., and Baeder, J. D., "Numerical Investigation of 3-D Dynamic Stall using Delayed Detached Eddy Simulation", *50th AIAA Aerospace Sciences Meeting*, Nashville, TN, Jan 2012.
3. Medida, S., and Baeder, J. D., "Role of Improved Turbulence and Transition Modeling Methods in Rotorcraft Simulations", *AHS International 69th Annual Forum*, May 2013, Phoenix, AZ.
4. Medida, S., and Baeder, J. D., "Adverse Pressure Gradient Modification to Turbulence Models for Wall-bounded Flows", *21st AIAA Computational Fluid Dynamics Conference*, June 2013, San Diego, CA.
5. Medida, S., and Baeder, J. D., "A New Crossflow Transition Onset Criterion for RANS Turbulence Models", *21st AIAA Computational Fluid Dynamics Conference*, June 2013, San Diego, CA.
6. Baeder, J., Medida, S., and Kalra, T., "OVERTURNS Simulations of S-76 Rotor in Hover", *52nd AIAA Aerospace Sciences Meeting*, January 2014, National Harbor, MD.
7. Medida, S., Baeder, J., Nigam, N., and Chen, P., "Variable Surface Roughness Modeling for Skin Friction Estimation", *52nd AIAA Aerospace Sciences Meeting*, January 2014, National Harbor, MD.
8. Jain, N. and Baeder, J., "Investigation of Hybrid RANS-LES Methods to Understand their Predictive Capabilities in Flows with Separation", *AIAA Scitech 2015*, January 2015, Kissimmee, FL.
9. Medida, S., and Baeder, J., "Transition Prediction on Fixed Wings and Rotating Blades Using a Correlation-Based Model", *6th European Conference on Computational Fluids Dynamics*, July 2014, Barcelona, Spain.
10. Ghosh, D., Medida, S., and Baeder, J. D., "Application of Compact-Reconstruction Weighted Essentially Nonoscillatory Schemes to Compressible Aerodynamic Flows", *AIAA Journal*, Vol. 52, No. 9 (2014), pp. 1858-1870.
11. Medida, S., "Improved Turbulence and Transition Modeling Methods for Industrial CFD Simulations", Invited Talk, NASA LaRC, June 2013.
12. Baeder, J., "Recent Progress in Transition Model Development", Invited Talk, U. of Wyoming, Oct. 2013.
13. Jain, N., Baeder, J., "Investigation of hybrid RANS-LES methods to understand their predictive capabilities in flows with separation", *AIAA SciTech 2015*, Kissimmee, FL, Jan 2015.
14. Jain, N., Baeder, J., "Aerodynamic Characteristics of SC1095 Airfoil using Hybrid RANS-LES Methods Implemented into a GPU Accelerated Navier-Stokes Solver", *Aviation Forum 2015*, Dallas, United States, June 2015.
15. Jain, N., Baeder, J., "Comprehensive Aerodynamic Characteristics of SC1095 Airfoil using Hybrid RANS-LES Methods", *2015 ICMIDS Conference*, State College, PA, USA, June 2015.
16. Jain, N., Baeder, J., "Assessment of turbulence model length scales based on Hybrid RANS-LES modeling of unsteady flow over airfoil", *AHS International 72nd Annual Forum*, West Palm Beach, FL., May 2016.
17. Jain, N., Baeder, J., "Assessment of shielding parameters in conventional DDES method under the presence of alternative turbulence length scales", *AIAA Aviation*, Denver, Colorado, June 2017.

Task A-1.4: Comprehensive Loads, Pressures and Performance Measurements on Coaxial Rotors for High-Speed Compounds

PIs: Jayant Sirohi (UT-Austin); jayant.sirohi@mail.utexas.edu; and Inder Chopra (UMD) chopra@umd.edu (301) 405-1122

Background:

The coaxial compound helicopter has emerged as a potential candidate for the next-generation, high-speed, multi-role rotorcraft. Recently, the X2 Technology Demonstrator (X2TD), featuring a rigid, coaxial, counter-rotating (CCR) rotor and a pusher propeller, achieved a level flight speed over 250kts and proved the basic concept of the configuration. Further development of the CCR rotor, including optimization of its performance and minimizing vibratory loads requires refined analytical tools. Detailed experimental data is key in refining and validating these analytical tools, however, compared to a conventional rotor, limited experimental data sets exist for a coaxial rotor.

The goal of this research task is to obtain a comprehensive set of experimental data on a CCR rotor in hover and in forward flight, focusing on the effect of lift offset at high advance ratio. In parallel, a comprehensive analysis based on a modified version of UMARC will be developed to help design the experimental setup, define the test matrix and predict the behavior of the CCR rotor system.

Research Objectives:

The main objective of this research task was to measure the performance of the CCR rotor system under realistic combinations of lift offset and advance ratio that reflect the full-scale aircraft operating condition. Secondary objectives were to measure the vibratory loads, blade tip clearance, effect of rotor phasing and hover performance. Blade inertial and structural properties were carefully measured and documented to provide analysts with a complete data set for code validation. The UMARC for CCR rotor systems was developed in parallel with the experimental study.

Approach:

Experiments and analysis were carried out in parallel to define the test matrix as well as required blade design to achieve the desired test condition.

(1) Experimental study: A 80-inch diameter CCR rotor system was designed and fabricated. The nominal hover tip speed was designed to be 625 ft/s (1790 RPM). Rotor spacing was 14% of the rotor radius and the hubs were rigid (only pitch bearing), which is representative of coaxial, high-speed compound helicopters such as the X2TD. Each rotor hub was mounted on a load cell to enable measurement of individual rotor loads in the rotating frame. Pitch link loads were also measured to account for forces that bypass the hub-mounted load cells. The rotor blades had a chord of 3.15", were untwisted and untapered with a VR-12 airfoil profile. The CCR rotor system was driven by a 100 HP hydraulic motor, with synchronous toothed belts to ensure fixed phasing between the upper and lower rotors.

Hover tests were performed at the UT Austin rotor test facility, and forward flight tests were performed by installing the rotor system (including drive system and transmission) in the

University of Maryland Glenn L. Martin Wind Tunnel (GLMWT). In this way, the rotor hubs, load cell installation/ calibration and rotor disk blockage were common for both sets of tests.

The hover tests included measurements of performance on a two-bladed CCR rotor, a four-bladed single rotor (only one rotor installed on test stand) and a two-bladed single rotor. Comparison of these data yielded insight into the rotor interaction effects. Vibratory loads in hover, driven by the aerodynamic interaction during upper and lower rotor blade passage, were also measured. It was found that the performance was independent of rotational speed (Reynolds number) and so all tests were performed at 900 RPM to decrease loads and blade deflections.

Forward-flight experiments included measurements on a two-bladed single rotor as well as the two-bladed CCR rotor. In both configurations, the rotor system was tested up to an advance ratio of 0.5, a blade loading of 0.1 and a 20% lift offset. In addition, the effect of rotor speed (900 RPM and 1200 RPM), and rotor phasing (azimuth angle at which the blade cross each other) was measured. Quantities measured included: individual upper and lower rotor loads in the rotating frame (steady and vibratory), push-rod loads (steady and vibratory), blade pitch angles, upper-lower rotor blade tip clearance at the blade crossings and fixed-frame accelerations. A shaker test was performed on the load cells prior to the experiments; this test verified that in the frequency range of interest, the rotor vibratory loads was not contaminated by the test stand dynamic response.

(2) Analysis: A comprehensive analysis was developed from the baseline UMARC for coaxial rotor aeromechanics. The analysis included twin-rotor interactional aerodynamics and prescribed/free wake inflow, leading edge trailers in reverse flow, and blade airfoil tables (2D CFD up to $\pm 180^\circ$ blade angle of attack). The airfoil tables were generated at the Reynolds number at 75% rotor radius. The analysis was used to evaluate a number of blade structural designs to enable testing at the desired condition of 0.5 advance ratio and 20% lift offset, while maintaining a minimum blade tip clearance safety margin of 5% rotor radius.

Accomplishments (Years 2011-16):

Years 1-2 were dedicated to the development of the rotor test stand, including the swashplate mechanism, rigid rotor hubs and instrumentation. Each rotor was controlled by an individual swashplate; the lower rotor swashplate was located in a conventional position (above the fuselage) while the upper rotor swashplate was located under the fuselage with push-rods extending through the hollow inner shaft up to the upper rotor blade pitch horns. The large axial forces in these upper rotor push-rods, especially due to the small moment arm of the upper rotor blade pitch horns was one limiting factor in the achievable rotor speeds and blade loads of the test matrix. In parallel, the baseline UMARC was being modified to incorporate the unique geometry and aerodynamic interactions of the CCR rotor system.

In Year-3, a baseline set of uniform cross-section rotor blades were fabricated and hover testing was performed in three configurations: two-bladed isolated single rotor, four-bladed isolated single rotor and two-bladed CCR rotor. It was found that the two-bladed CCR rotor consumes around 6% less induced power than the four-bladed isolated single rotor at the same blade loading. The measurements were used to validate UMARC predictions. A methodology of non-contact blade deformation measurement (using Digital Image Correlation) and modal extraction was developed to further validate the blade deformation and fan plot predictions of UMARC. It was found that

the high Lock number and relatively low rotating flap frequency of the blades precluded forward-flight testing at a useful lift offset due to excessive blade flapping. The validated UMARC was then used to design another set of blades with a root reinforcement cuff. The new blades had a rotating flap frequency of 1.6/rev and were able to meet the flap bending limitations of the entire forward-flight test matrix.

In Year 4, two sets of wind tunnel tests were performed. During the first test, a failure occurred in the upper rotor electrical slip ring which prevented trimming of the coaxial rotor. Therefore, the first set of tests were limited to an isolated single rotor with lift offset. However, valuable lessons were learnt regarding the coaxial rotor trim procedure, pitch link load trends and acceptable play in the control system linkages. Based on these lessons, an upgraded control system including custom linear actuators and reinforced upper rotor control linkages was designed and fabricated. In the second set of wind tunnel tests, the two-bladed coaxial rotor as well as isolated upper and lower rotors were tested at advance ratio up to 0.5, blade loading up to 0.1 and lift offset up to 20%, covering the entire planned test matrix. The majority of tests were performed at a rotor speed of 900 RPM, with some points in the test matrix repeated at 1200 RPM and at different upper and lower rotor phasing angles. After the wind tunnel tests, hover testing of new blades was performed (at the wind tunnel RPMs), including tests of an inverted upper rotor to examine ground/fuselage interaction effects. Data reduction, analysis and validation with analytical predictions was performed in Year-5. It was found that at a lift offset of 20% at an advance ratio of 0.5 resulted in an increase in the rotor equivalent lift to drag ratio to around 9, from around 6 with no lift offset. The lift offset also resulted in a significant reduction in 2/rev vibratory thrust but also resulted in an increase in 4/rev vibratory loads due to the four blade crossings per revolution inherent in a two-bladed CCR rotor system. The UMARC predictions showed excellent agreement with measured quantities including steady and vibratory rotor loads, blade tip clearance and rotor power. The experimental data was shared with, and used to validate analyses by researchers from US Army ADD, US Army Research Laboratories and Technical University of Munich.

Graduated Students:

1. Christopher Cameron, "Comprehensive Aeromechanical Measurements of a Model-Scale, Coaxial, Counter-Rotating Rotor System", PhD, December 2016. Army Research Laboratories.
2. Joseph Schmaus, "Aeromechanics of a High Speed Coaxial Helicopter Rotor," May 2017, PhD, May 2017. Bell Helicopter.
3. Sergio Rizo-Patron, "Operational Modal Analysis of a Rotating Cantilever Beam using High-Speed Digital Image Correlation", MS, December 2015. SpaceX.
4. Michael Lawson, "Measurement of Deformation of Rotating Blades Using Digital Image Correlation", MS, August 2011. Sikorsky Aircraft Corporation.
5. Peter Oas, "Trim Analysis of Coaxial Rotor," MS, December 2017

Publications:

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2. Sirohi J. and Lawson M. S., "Measurement of Helicopter Rotor Blade Deformation Using Digital Image Correlation", *Optical Engineering*, Vol. 51, No. 4, 043603 (8 pages), April 2012.
3. Mula, S. M., Stephenson, J., Tinney, C. E., and Sirohi, J., "Dynamical and Evolutionary Characteristics of the Tip Vortex from a Four-Bladed Rotor in Hover", *AHS International 68th Annual Forum*, Fort Worth, TX, May 1-3, 2012.
4. Mula S. M., Stephenson J., Tinney C. E., and Sirohi J., "Dynamical Characteristics of the Tip Vortex from a Four-Bladed Rotor In Hover", *Experiments in Fluids*, Vol. 54, No. 10, pp. 1-14, October 2013.
5. Cameron C., Karpatne A. and Sirohi J., "Performance and Vibratory Hub Loads of a Mach-Scale Coaxial Rotor in Hover", *AHS International 70th Annual Forum*, Montreal, Canada, May 20-22, 2014.
6. Mula, S. M., Cameron, C., Tinney, C. E., Sirohi, J. "Low-Dimensional Characteristics of Tip Vortices from a Coaxial Rotor in Hover", *AHS International 70th Annual Forum*, Montreal, Canada, May 20-22, 2014.
7. Cameron C., Uehara D. and Sirohi J., "Transient Hub Loads and Blade Deformation of a Mach-Scale Coaxial Rotor in Hover", *AIAA Paper 2015-1412, 56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Kissimmee, Florida, 5-9 January 2015.
8. Singh R., Kang H., Bhagwat M., Cameron C. and Sirohi J., "Computational and Experimental Study of Coaxial Rotor Steady and Vibratory Loads", *AIAA Paper 2016-1787, 54th AIAA Aerospace Sciences Meeting*, San Diego, California, 4-8 January 2016.
9. Rizo-Patron S. S., and Sirohi J., "Operational Modal Analysis of a Rotating Cantilever Beam Using High-Speed Digital Image Correlation", *AIAA Paper 2016-1957, 54th AIAA Aerospace Sciences Meeting*, San Diego, California, 4-8 January 2016.
10. Cameron C., and Sirohi J., "Performance and Loads of a Model Coaxial Rotor Part I: Wind Tunnel Measurements", *AHS International 72nd Annual Forum*, West Palm Beach, Florida USA, 17-19 May 2016.
11. Cameron C., Karpatne A. and Sirohi J., "Performance of a Mach-scale Coaxial Counter-rotating Rotor in Hover", *Journal of Aircraft*, Vol. 53, No. 3, May 2016, pp. 746—755.
12. Feil R., Rauleder J., Hajek M., Cameron C. and Sirohi J., "Computational and Experimental Aeromechanics Analysis of a Coaxial Rotor System in Hover and Forward Flight" *42nd European Rotorcraft Forum*, Lille, France, 6–8 September 2016.
13. Schmaus, J. and Chopra, I., "Validation of Predicting Vibratory Loads of a Coaxial Rotor in High Advance Ratios with Wind Tunnel Data," *42nd European Rotorcraft Forum*, Lille, France, September 2016.
14. Schmaus, J. and Chopra, I., "Performance and Loads of a Model Coaxial Rotor Part II: Prediction Validations with Measurements," *72nd Annual Forum of the American Helicopter Society*, West Palm Beach, FL, May 2016.
15. Schmaus J. and Chopra, I., "Aeromechanics for a High Advance Ratio Coaxial Helicopter," *71st Annual Forum of the American Helicopter Society*, Virginia Beach, VA, May 2015.
16. Schmaus, J. and Chopra, I., "Performance and Loads Prediction for High Advance Ration Coaxial Rotor," *AIAA SciTech Conference*, Kissimmee, FL, January 2015, Paper AIAA-2015-1413.
17. Schmaus, J. H. and Chopra, I., "Aeromechanics of Rigid Coaxial Rotor Models for Wind-Tunnel Testing," *Journal of Aircraft*, Vol. 54, No. 4, July-August 2017, pp. 1486-1497.

Task UM-1.5: High Resolution CFD for Interactional Aerodynamics of Coaxial Compounds
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Background:

Performance and range requirements for next-generation rotary-wing aircraft have sparked renewed interests in the coaxial rotor configuration, augmented with lift and/or thrust compounding. Often, thrust augmentation is provided in the form of a propeller to counteract the airframe and rotor drag in high speed forward flight. This idea has been pursued in the past with the Advancing Blade Concept by Sikorsky with the XH-59 and more recently with the X2 Technical Demonstrator (X2TD). The compound coaxial lift offset configuration poses its own set of unique challenges. The aerodynamic environment is complex, with the rotor wakes interfering both with each other and with the airframe. The propeller thrust must also be carefully chosen based on a combination of rotor control mixing, expected lift offset, and airframe drag. While there has been previous work done in regards to compound coaxial helicopter configurations they have mostly focused on the integrated performance metrics using comprehensive analysis, such as CAMRAD, which rely on 2D look up tables and free wake models for the aerodynamics. Therefore, a new approach using high resolution CFD loosely coupled to CSD is applied to coaxial lift offset designs to obtain the interactional effects of compound coaxial lift offset vehicles specifically focusing on rotor-rotor and rotor-fuselage effects in forward flight.

Research Objectives:

The overall goal of this task is to gain further insight and understanding of the flow physics involved in compound coaxial lift offset vehicles and to provide better prediction capability in both low speed and high-speed forward flight. The projects objectives are:

- Develop a high resolution CFD/CSD coupling framework
- Build a notional X2TD vehicle simulation
- Compare and verify notional X2TD vehicle simulation to available test data
- Analyze interactional aerodynamic effects (rotor-rotor, rotor-fuselage)
- Quantify how design characteristics (such as rotor spacing, lift offset, shaft tilt, and fuselage design) affect wake structure, aerodynamic loads, and performance metrics
- Implement tail geometry and propeller model into the CFD model
- Verify the built CFD/CSD framework against experimental results from Task UM-1.4

Approach:

CFD is used to capture the finer details of the wake structure and interactional effects between various components. The “delta” loose coupling method is used to couple the CFD and CSD models. The CSD model is initially trimmed with a reduced-order aerodynamic model to obtain blade motions and approximate airloads. These blade motions are fed into the CFD solver to obtain accurate airloads. The difference between the CFD (“exact”) and CSD (“approximate”) airloads are applied as constant corrections to the CSD model during the next trim cycle. The process is repeated until the “delta” airloads (and hence deflections) converge. Having the CFD results updating the comprehensive analysis aerodynamics in this loose coupling framework will drive toward a deeper understanding of how vehicle components influence one another in the forward flight regime and provide more accurate solutions.

In the in-house CFD solver, all eight blades and a fuselage mesh are overset within two cartesian background meshes (a far field and a near rotor field). Using two nested cartesian background

meshes allows for finer resolution near the rotors ensuring that the CFD can capture with higher fidelity the effects between the two rotors while still minimizing the amount of overall points. The outer cartesian mesh serves as the far-field boundaries and encompasses the inner background mesh, blades, and fuselage. To capture the fuselage effects, the fuselage mesh is overset with the two background meshes. The fuselage mesh will transfer information to the background meshes just as the blade meshes transfer information to the background meshes. Implicit hole cutting (IHC) algorithm is used to maintain connectivity between the various overset meshes as they move in time and space.

As mentioned previously, an in-house comprehensive analysis is used to model the vehicle flight dynamics and rotor aeromechanics. The airframe is modeled as a rigid body with its own table look-up aerodynamics. The aerodynamic forces on the airframe will be augmented with the “deltas” obtained from the CFD analysis. The aerodynamics of the vertical and horizontal tail surfaces are modeled using their own table look-up values based on finite-span wing theory. Rotor-body couplings are modeled using a multibody-type rotations with exact kinematics. The rotor blades are modeled as flexible isotropic nonlinear Euler-Bernoulli beams with flap, lag and torsion using a geometrically exact formulation. The current configuration uses hingeless blades. The Ordinary Differential Equations governing the rotor-airframe dynamics are numerically reduced to algebraic equations and solved iteratively starting from an initial guess to obtain trim. Uniform inflow on isolated rotors is used to generate an initial guess for the trim controls and attitudes. Using these initial trim variables, a vortex wake model is used to model the rotor inflow with rotor-rotor aerodynamic interference. Alternate updates of wake geometry and trim controls are performed until convergence is achieved.

Accomplishments (Years 2011-16):

A framework for passing information between the in house comprehensive analysis and the in house CFD solver has been established and tested. A notional X2TD configuration was developed and modeled, blade and fuselage meshes were generated for CFD, and 2D airfoil tables for comprehensive analysis code calculated from 2D CFD. XH-59 structural properties were scaled and implemented into the comprehensive analysis model. The notional X2TD comprehensive analysis model was ran and validated against available X2TD test data. On the CFD side, the notional X2TD model, consisting of 8 blades and fuselage was tested in forward flight first with rigid blades, and then using deformations fed from the comprehensive analysis. A test case, forward flight speed of 55 kts is now being performed. The trimmed comprehensive analysis blade deflections were given to CFD and will be run for 3 revolutions before sending data back to CSD.

Several key points for exploration with CFD were chosen from the comprehensive analysis runs in order to further understand the changes in the rotor power curve that occur over the flight envelope. A couple of these key points to examine with CFD/CSD coupling are at very high speed (180+kts) as the rotor seems to operate in a state of autorotation.

Converged CFD-CSD coupling solutions for 55, 100, 150, and 200 knots have been completed for isolated coaxial rotors with full vehicle propulsive trim. The integrated rotor power was compared to test data and had a high level of correlation. From these cases, rotor-rotor interactional aerodynamics was quantified as a function of increasing forward flight speed. The results from the CFD-CSD analysis were also compared to the baseline CSD solution which incorporated a multi

rotor free wake aerodynamic model. This allowed for quantifying any shortcomings in the lower order comprehensive analysis' aerodynamic model. Three fuselage models with varying complexity were then incorporated into the CFD analysis and new CFD- CSD solutions at 55 and 150 knots were conducted. The objective was to quantify rotor-fuselage interferences as a function of increasing advance ratio. Lastly these results and the notional X2 model and CSD code was shared with ARL.

Graduated Students:

1. Shane Boyer, MS Scholarly Paper, December 2013 (Engineer).
2. Mathieu Amireaux, "Simulation of Coaxial Rotor Interactional Aerodynamics using Coupled CFD-CSD," PhD, May 2014 (Engineer at Corvid Technology).
3. Brad Passe, "Simulation of Coaxial Rotor Interactional Aerodynamics using Coupled CFD-CSD," MS, May 2015 (Engineer at Bell).

Publications:

1. van der Wall, B. G. and Lim, J. W. and Smith, M. J. Jung, S.N. and Bailly, J. and Baeder, J. D. and Boyd, D.D., Jr., "The HART II International Workshop: An Assessment of the State-of-the-Art in Comprehensive Code Prediction," American Helicopter Society 68th Annual Forum Proceedings, Fort Worth, TX, May, 2012.
2. Smith, M. J., Lim, J. W., van der Wall, B. G., Baeder, J., Biedron, R. T., Boyd, D.D., J., Jayaraman, B., Jung, S., and Min, B.-Y., "The HART II International Workshop: An Assessment of the State-of-the-Art in CFD/CSD Prediction," American Helicopter Society 68th Annual Forum Proceedings, Fort Worth, TX, May, 2012.
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4. Ghosh, D., Medida, S., and Baeder, J., "High-Order Non-Oscillatory Compact Reconstruction Scheme for Overset Grids", *11th Symposium on Overset Grids and Solution Technology*, Dayton, OH, Oct. 15-18, 2012.
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7. van der Wall, B. G. and Lim, J. W. and Smith, M. J. Jung, S. N. and Bailly, J. and **Baeder, J. D.** and Boyd, D. D., Jr., "The HART II International Workshop: An Assessment of the State-of-the-Art in Comprehensive Code Prediction," *CEAS Aeronautical Journal*, September 2013, Volume 4, Issue 3, pp. 223-252.
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9. Passe, B., Sridharan, A., Baeder, J., Jimenez, B., Singh, R. "Identification of Rotor-Fuselage Aerodynamic Interactions in a Compound Coaxial Helicopter using CFD-CSD Coupling," *AHS Technical Meeting on Aeromechanics Design for Vertical Lift*, San Francisco, CA 2015.
10. Passe, B., Sridharan, A., Baeder, J., "Computational investigation of coaxial rotor interactional aerodynamics in steady forward flight", *33rd AIAA Applied Aerodynamics Conference*, June 2015.

Task: A-1.6 Fundamentals of Flight in Degraded Visual Environment (DVE)
PI: Roberto Celi — (301) 405-1132 — celi@eng.umd.edu

Background:

Military and civilian rotorcraft operations in Degraded Visual Environments (DVE) continue to cause accidents and loss of lives and property. DVE can be caused by “brownout” or “whiteout” conditions, as well as by rain, haze, fog, or battlefield contaminants. Night flying over water can also cause DVE-like conditions even in good weather and clear air. The degradation of visual cues impairs the pilot’s ability to close control and navigation loops, and is especially dangerous during landing, and in hover and low speed flight near the ground.

Pilot behavior in DVE is not fully understood. Fundamental research was performed in the years leading to the publication of the ADS-33 HQ specification, but the assessment of DVE ratings was eventually based on qualitative, pilot-opinion based ratings of the availability of suitable visual cues. The solution to HQ degradation in DVE is today primarily based on suitable sensors and displays, together with Flight Control Systems (FCS) that give the aircraft favorable response types. It can be argued, however, that a better fundamental understanding pilot behavior in DVE, could also lead to improved safety, better training methods and tools, and more effective FCS. The proposed task addresses two fundamental and related questions: (a) how can DVE be measured and predicted?; and (b) how much visibility is needed to accomplish a given task?

Proposed Objectives

The general objective of the proposed task is to improve the fundamental understanding of flight in DVE. The specific objectives are: (a) to define visibility metrics that are objective, i.e., do not need a pilot assessment in every flying situation; can be measured; and can be modeled mathematically and predicted; (b) to understand how they affect pilot performance, and identify minimum thresholds required to accomplish given piloting tasks. A specific application was also chosen, to focus the entire research effort, namely, the measurement and prediction of the Usable Cue Environment (UCE) rating in ADS-33.

Approach:

The scope of the research is limited to the visual aspects of pilot control. The interactions between the visual and the vestibular system are neglected. Other sources of feedback, such as proprioceptive and aural feedback are also neglected. The research is primarily focused on the role of contrast and size of the visual cues. Contrast (or modulation) and size (or spatial frequency) are the two components of the Modulation Transfer Function (MTF), which is a widely used metric of optical degradation. In previous years we have demonstrated that the MTF can be extracted in DVE (specifically, brownout conditions) from processing of video images of very simple optical targets, e.g., a simple black-to-white edge. Other aspects, such as the role of perspective, optic flow, and color, are initially neglected, although they might be taken into account in later stages of the research.

The general approach has an experimental component and a theoretical component. The former consists of devising and carrying out computer-based experiments in which an operator (pilot) is asked to perform some task, such as controlling some object on the computer screen through a joystick, while the visibility of the object on the screen is progressively degraded. The theoretical component consists of formulating mathematical models that can describe, and ideally predict, the behavior of the operator in the computer-based experiments. Then, the theoretical and experimental results are analyzed, and the requirements for performing a certain task are proposed, typically in the form of ADS-33-like charts with different levels of performance.

Summary of key accomplishments for 2011-16

On the experimental side, we completed the analysis of a series of computer-based tests, intended to depict a highly idealized Lateral Reposition ADS-33 Mission Task Element (MTE). In these tests, the pilot was asked to keep centered, with a joystick, a circle on top of another, randomly moving circle, or target, as shown in Fig. 1. The target would initially move in the left portion of the computer screen, and then suddenly move to the right portion of the screen, and continue moving randomly there. The initially white background would progressively darken to gray, and the initially black target would progressively fade to gray, until the relative contrast between target and screen would go to zero. Combinations of target size and target/screen relative contrast were systematically explored. Through a careful analysis of the time histories of pilot joystick inputs, we were able to identify features of the time histories that could be reasonably associated with some of the (subjective) characteristics on which UCE assessment is built, such as “precision”, “confidence”, and “aggressiveness”. On the basis of these features, we could propose charts that quantify levels of precision, confidence, and aggressiveness as a function of the size and contrast of the visual cues (the size of the circles on the computer screen). A proposed “confidence” chart is shown in Fig. 2. Preliminary results were presented in the November 2013 VLRCOE review.

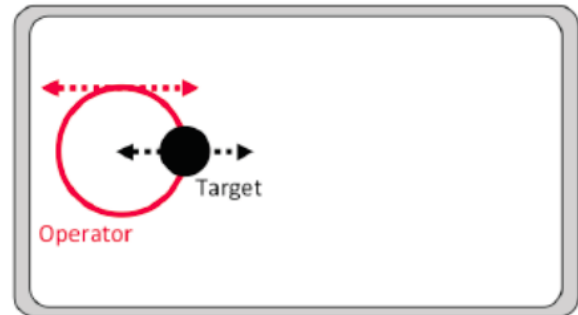


Figure 1 – Schematic of computer experiment.

The subsequent step was the development a mathematical model that could reproduce the experimental results described above. We decided to use the Optimal Control Model (OCM) as the starting point. The OCM is a well known mathematical model of a human pilot. It has been in use for over four decades, but to our knowledge it has never been used in a DVE context. Our approach was to

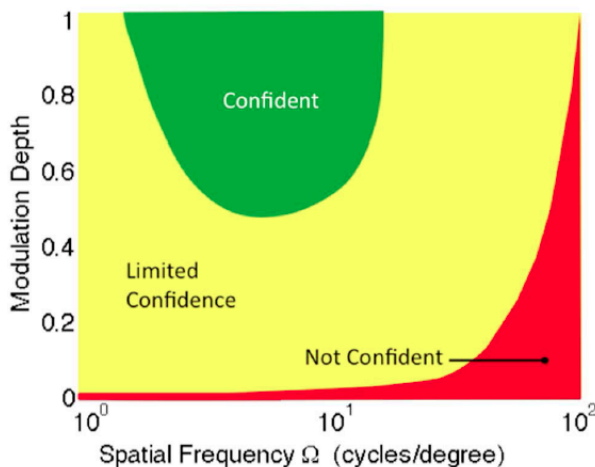


Figure 2 – Proposed "confidence" chart.

start by taking parameters of the OCM that are generally considered as fixed inputs, based on experience, and use them instead as free parameters to match the experimental results with the OCM predictions. In the end, the combination of three such parameters and two additional parameters coming from our extensions of the OCM, produced an excellent agreement for the confidence metric. The five parameters of the extended OCM were determined through a numerical optimization procedure. This optimization turned out to be mathematically challenging because of the presence of many local optima, but it could be easily solved using our in-house optimizer (based on adaptive response surfaces and special techniques to enhance global convergence). As a result, our extended OCM can now generate charts with levels of precision, aggressiveness, and confidence as a function of

visual cue size and contrast, which are in good agreement with those from the experiments. In principle, the extended OCM could already be coupled with a full flight dynamic simulation model, to form predictions or explain behavior of coupled pilot-vehicle systems in DVE conditions.

Task: A 1.7: Innovative Numerical Algorithm for Fluid/Structure Simulation of Rotorcraft Transient Maneuvers

PIs: Dimitri Mavriplis (University of Wyoming, mavripl@uwyo.edu), James Baeder (U of Maryland, baeder@umd.edu)

Background:

Rotorcraft transient maneuvers are characterized by the quasi-periodic nature of the governing physical fields (both fluids and structures). The objective of this task is to formulate, develop, test and validate an efficient numerical algorithm that exploits this physical mechanism by a combination of backward difference in time (BDF) and time spectral (TS) methods. The BDF/TS method can produce substantial reduction in computational time compared to traditional time-stepping simulations. Furthermore, the proposed algorithm provides a natural avenue for reaping larger amounts of parallelism, which is especially relevant as the scientific computing community is moving towards exascale computing in the next decade. The conventional approach to simulating a rotorcraft maneuver is a tightly coupled time integration of fluid and structural governing equation systems. In this case, practical time-stepping simulations can become very costly since the time step is limited by the accuracy consideration imposed fast periodic flow features (i.e. azimuthal steps of 0.25 degree of rotation or smaller are typical in traditional simulations). In particular, long time histories must be simulated to capture the slower transient effects. Inclusion of flight dynamics/trim to track a given trajectory also poses a technical challenge in this context because of the difference in time scales between the change in control angles (slow) and rotor periodic motions (fast). The hybrid BDF/time spectral numerical algorithm proposed here is formulated such that BDF type time integration is used to account for slow transients (hyperbolic part of the physical fields) and time-spectral type approach is used account for fast periodic content (elliptic part of the physical field). The time-spectral method itself is based on discrete Fourier analysis and involves usage of a few time-instances per period to resolve the periodic content (e.g. N locations in space of the rotor system per period can be used to resolve up to N/rev loading). The BDF/TS method does not constrain the number of time-instances to be the same in every revolution of a transient maneuver, which provides another avenue for maximizing efficiency, i.e. small number of time instances can be used when the physical fields are benign (i.e. pre-stall, non-BVI) and larger number of time instances can be used when the physical fields are complex (separation, stall, BVI etc). Larger amounts of parallelism can be obtained by partitioning the problem in both space and time. In contrast, time-stepping simulations are limited to only spatial parallelism. Another key advantage of the BDF/TS method stems from the ease of inclusion of flight dynamics and trim on a per revolution basis.

Approach:

This project focuses on the development and extension of the BDF/TS approach for transient rotorcraft maneuvers through: (1) extending the BDF/TS formulation, development, testing and validation for overset grid simulations; (2) formulating the structural dynamic system of equations for slow periodic flows; (3) developing an optimal parallel (in space and time) solver for BDF/TS discretizations and (4) demonstrating the efficient and accurate simulations for rotorcraft transient maneuvers on large high

performance computing environments. For problems where the periodic nature of the problem is less dominant and where rapid transient events may occur, finite-element in time and other related temporal discretizations that include high order accuracy and opportunities for temporal parallelism will also be considered. Finally, these temporal discretizations and associated solver will be configured in as a modular library designed to interface with existing CFD and CSD codes.

Accomplishments in 2014-2015:

In previous years we have derived and implemented the BDF/TS discretization and solver for both fluid dynamics (CFD) and structural dynamics (CSD) problems. We have also investigated and developed a sequence of progressively more efficient parallel solvers for the BDF/TS approach. Over the last year, this solver work has culminated in the development and demonstration of a fully implicit GMRES-based approximate factorization solver that delivers numerical convergence that is independent of the number of time instances used per period, and which scales (in parallel) linearly with the number of time instances. This solver is enabling much higher fidelity BDF/TS simulations with large numbers of time instances. The approach is modular since it is independent of the spatial discretization and can thus be used with existing CFD or CSD codes. The application of BDF/TS to structural dynamics problems began with the theoretical derivation, the application to a simple ODE, and the subsequent application to a beam structural model. In the past year, we have extended the BDF/TS formulation to a full finite-element structural dynamics model (using bricks and shell elements). In previous years we have also investigated the use of spectral-element in time (SEMT) methods, which are closely related to finite-element in time formulations, and enable the simulation of fast transients within periodic and non-periodic problems. In the past year we have extended these to finite-element (DG) in time methods, and fully implicit Runge Kutta methods, and demonstrated these within the context of a three-dimensional CFD solver.

Plans for 2015-2106:

In the coming year, work will continue on further improvements to the parallel solver which, although close to optimal in operation counts, still incurs excessive parallel communication costs when run a very large scale. In this final year of the project, we will consolidate the various temporal discretizations (TS, BDF/TS, FEM, FIRK) into a single modular library that can be used to integrate CFD and CSD discretizations in a time-parallel fashion with minimal modifications to existing disciplinary codes. At the same time we will incorporate adaptive time-step control for these temporal discretizations (on a per rev basis for TS and BDF/TS) using local temporal error estimates embedded in these methods. We will also demonstrate the ability to couple our developed time-parallel solver library with different existing CFD/CSD codes.

Task A-1.8 Adjoint Methods for Numerical Optimization of Rotorcraft Performance

PI: Dimitri Mavriplis (Wyoming University); mavripl@uwyo.edu

Background: With increasing computational hardware capabilities, the use of high fidelity numerical optimization is becoming increasingly feasible for rotorcraft aeromechanics problems. In most cases, gradient-based optimization represents the most viable strategy since the required number of high-fidelity simulations is minimized in this approach. However, gradient-based methods require the calculation of the sensitivities of the design objective with respect to all design inputs or parameters. Using a straight-forward approach (i.e. finite differencing) results in the requirement of performing one additional simulation for each design parameter. Although this approach may be acceptable for problems with small numbers of design variables, the more general case involving large numbers of design variables requires the use of an adjoint approach. Adjoint techniques are appealing because they enable the calculation of the sensitivity of a single objective with respect to any number of design variables at a cost of a single adjoint solution, which is generally equivalent to the cost of the original analysis simulation. A discrete adjoint formulation can be obtained by methodically linearizing and transposing all operations in the entire simulation process. Although adjoint methods have gained popularity for many aerodynamic design problems, these have mostly been for steady-state and single discipline problems. For time-dependent problems, solution of the adjoint equations requires a backwards integration in time, starting from the final time solution and proceeding to the initial conditions. This behavior is a result of the transposed nature of the adjoint equations, and for non-linear problems requires the storage of the entire time history during the analysis simulation. Because rotorcraft aeromechanics necessarily involve coupled aeroelastic effects, a meaningful adjoint-based optimization approach must involve the adjoint of the fully coupled aeroelastic problem. In previous work, we have implemented the discrete adjoint for three-dimensional time-dependent flow problems on dynamically deforming unstructured meshes and shown how the requirement of storing the solution time history can be handled effectively using local disk I/O on modern day parallel computer clusters. We have also developed a framework for implementing and solving the discrete adjoint for fully coupled aeroelastic problems in two dimensions. However, significant challenges remain in the development of a comprehensive rotorcraft aeromechanics adjoint-based optimization capability. Firstly, the coupled aeroelastic discrete adjoint implementation must be extended to three dimensions. This requires the formulation and implementation of the exact discrete adjoint of the fluid structure interface. Secondly, suitable objectives, constraints and optimization strategies must be developed for optimizing performance, vibration, and acoustics.

Research Objectives: The objectives of this project closely parallel the technical challenges described above:

1. Extension of fully coupled aeroelastic adjoint to three dimensions including fluid structure interface.
2. Formulation of objectives and constraints and optimization for performance and vibratory loads.
3. Extension of adjoint optimization strategy for acoustics problems

Approach: (1) *Extension of fully coupled aeroelastic adjoint to three dimensions including fluid structure interface:* A fully coupled fluid-structure discrete adjoint formulation must be developed for three-dimensional problems. This should be based on our previously developed two-dimensional coupled aeroelastic discrete adjoint formulation but requires the incorporation of the adjoint of the full structural model as well as the adjoint of the three-dimensional fluid-structure interface. This is to be implemented

using the modular adjoint framework previously developed and demonstrated for three-dimensional time-dependent problems.

(2) *Formulation of objectives and constraints and optimization for performance and vibratory loads:* The fully coupled aeroelastic adjoint capability is to be used to demonstrate the design optimization of rotorcraft configurations. This involves optimization for performance metrics, as well as optimization for vibratory loads. In both cases, suitable objectives and constraints need to be devised and investigated. For performance optimization, these will focus principally on aerodynamic quantities, whereas for vibration these will principally be targeted towards structural quantities. However, in both cases, aerodynamic and structural design parameters may be used simultaneously to drive the optimization procedure.

(3) *Extension of adjoint optimization strategy for acoustics problems:* The developed adjoint capability is also to be used to perform optimization of acoustic signatures for rotorcraft configurations. This requires coupling the high-fidelity adjoint-enabled Navier-Stokes solver to a lower fidelity acoustic propagation code and incorporating the adjoint of the acoustic propagation component of the simulation. Suitable objectives and constraints must also be devised and demonstrated for acoustic noise reduction through optimization.

Accomplishments (Years 2011-16):

Over the 5 year period of the project, the three principal technical objectives have been met and demonstrated. This was done in a progressive building block approach, where single discipline optimization problems such as a rigid rotor in hover were first demonstrated, followed by more complex multidisciplinary optimization problems. In the first year of the project, the formulation for adjoint sensitivities for rigid rotors in hover was derived and implemented. An optimization of a Hart2 rotor in hover was then demonstrated where the power was reduced at constant thrust condition. In the second year, an adjoint optimization capability for a fully coupled aero-elastic rotor was developed, based on the inclusion of a beam model for the rotor structure. This was followed by the demonstration of the optimization of a flexible rotor in forward flight, which required the incorporation of cyclic pitching into the analysis and optimization framework, along with the capability to compute the sensitivities of aerodynamic performance objectives with respect to the cyclic pitching parameters. Based on this newly developed capability, the optimization of both rigid and flexible rotors in forward trimmed flight was demonstrated. In this case, an optimization was first performed using the current framework to obtain the cyclic pitching parameters required to trim the initial baseline rotor. Next the rotor was optimized for reduced power with trim constraints implemented as penalty functions added to the power objective. Finally, the optimized rotor was re-trimmed using a final trim optimization run. Overall, a net reduction of rotor power of the order of 2-3% was demonstrated between the baseline initial rotor and the final optimized and re-trimmed rotor through shape changes to the rotor. In the final years of the project, a far-field acoustic module was added to the multi-disciplinary optimization capability, including the adjoint of this model, in order to compute sensitivities to aeroacoustic objective functions. Aeroacoustic optimization of a flexible rotor in forward flight was demonstrated in a paper which was awarded the Best Paper prize at AHS Forum 72.

Graduated Students:

1. Enrico Fabiano, "Multidisciplinary Adjoint-based Design Optimization Techniques for Helicopter Rotors", PhD, May 2017, (Boom Aerospace, Denver CO)

Publications:

1. E. Fabiano and D. Mavriplis, "Adjoint-based Aeroacoustic Design-Optimization of Flexible Rotors in Forward Flight", Paper presented at AHS Forum 72, West Palm Beach FL, May 2016. AHS Forum 72 Best Paper Award.

2. E. Fabiano, A. Mishra and D. Mavriplis, "Time-Dependent Aero-acoustic Adjoint-based Shape Optimization of Helicopter Rotors in Forward Flight", AIAA Paper 2016-1910, January 2016.
3. A. Mishra, D. J. Mavriplis and J. Sitaraman, "Multipoint Time-Dependent Aero-elastic Adjoint-based Aerodynamic Shape Optimization of Helicopter Rotors", AHS Forum 71, Virginia Beach VA, May 2015.
4. A. Mishra, D. J. Mavriplis and J. Sitaraman, "Time-dependent Aero-elastic Adjoint-based Aerodynamic Shape Optimization of Helicopter Rotors in Forward Flight ", AIAA Paper t2015-1130, presented at SciTech 2015, Kissimmee FL, January 2015.
5. E. Fabiano, D. Mavriplis and J. Sitaraman, "Adjoint-Based Aeroacoustic Design Optimization for Blade Vortex Interaction Noise", AIAA Paper 2015-1801, presented at SciTech 2015, Kissimmee FL, January 2015
6. A. Mishra, K. Mani, D. J. Mavriplis and J. Sitaraman, "Time-depedent Adjoint-based Aerodynamic Shape Optimization Applied to Helicopter Rotors", Presented at AHS Forum 70, Montreal, Canada, May 2014.
7. D. Mavriplis and K. Mani, "Unstructured Mesh Solution Techniques using the NSU3D Solver AIAA Paper 2014-0081, Presented at the 52nd AIAA Aerospace Sciences Conference, National Harbor, MD, January 2014

Task A-1.9 Total Fatigue Life Methodology for Damage Tolerance Design of Composite Rotorcraft Components

PI: Kunigal Shivakumar (NCA&T) kshivaku@ncat.edu

Background:

Susceptibility to delamination is a major weakness in composite laminates. Knowledge of material's resistance to interlaminar fracture and fatigue is essential to establish design allowable and damage tolerance guidelines for structures. TOGAA committee report recommended FAA for implementation of damage tolerance requirements for metal (FAR29.571) and composite (FAR29.573) rotorcrafts. Fracture mechanics-based delamination growth models are required to predict fatigue life and establish suitable inspection intervals so that a delamination damage can be predicted, found and repaired long before it becomes critical. Fatigue delamination growth laws that cover the threshold, the stable growth and the unstable fracture domains are needed for total life estimation. Such growth laws were proposed for metallic materials and are becoming developed/accepted in damage tolerant design of fixed wing structures. Such models don't exist for rotorcraft composite structural components. This research was focused on development of total life methodology for shearing stress (Mode-II) state that includes damage onset, growth and fracture.

Research Objectives:

The overall objective of the research was to develop Mode-II stress state (shearing stress) total life damage tolerance design methodology for composite rotorcraft structural components. Focus the research on aircraft/rotorcraft composite materials, namely, IM7/8552 carbon/epoxy composite. The specific objectives are: (1) Review and understand the Mode-II test specimen and testing and modify test specimen and test procedure as needed; (2) Measure Mode-I, II and I-II fracture toughness; (3) Establish mixed mode (I-II) fracture criteria; then (4) through extensive Mode-II fatigue tests and data reduction establish Mode-II total fatigue life model.

Approach and Accomplishments (Years 2011-2014):

Each of the objectives were accomplished by four tasks and the approach followed is briefly summarized below. Because of non-availability of IM7/8552 composites, the initial work was started with AS4/8552, a same matrix system but different diameter fibers (9 μm versus 7 μm

Task 1: Reviewed all Mode-II fracture test procedure followed in the literature found standard edge notched (ENF), revised ASTM standard and Japanese JIS-K-7083 standard. The loading was slightly different in each case. A detailed finite element analyses of specimen and loading were conducted and the results revealed that JIS standard is not a pure Mode-II test specimen instead it includes about 6% of Mode-I component. All standard ENF specimen has about 1.5% effect on G_{II} due to friction effect between top and bottom beam contact.

Task 2: Conducted Mode-I, II and at several ratios of I-II stress state fracture tests using the standard DCB, ENF and Mixed-mode bending apparatus, respectively for AS4/8552 and

IM7/8552 unidirectional composite laminates. The test results revealed that mixed-mode total fracture toughness is related to G_{II}^m/G_T ratio in the form of power law.

Task 3: Conducted a thorough investigation of Mode I-II fracture criteria in the literature and then developed a simplified power law equation fracture criterion. Later, we showed that one need not have to perform the complicated mixed-mode fracture tests using the mixed-mode test apparatus instead a single leg beam fracture toughness value along Mode-I and II fracture toughness would be sufficient to develop mixed-mode fracture equation.

Task 4: In this task we conducted an extensive Mode-II fatigue tests, data analysis to capture the fatigue crack growth rate in on-set, Paris and fracture domains. From that data and innovative data analysis we developed a total fatigue life model of the form $da/dN = 0.8(G_{II\max}/G_{IIc})^{5.8} ((1 - (G_{IIth}/G_{II\max})^{12})/(1 - (G_{II\max}/G_{IIc})^3))$ for IM7/8552 composite laminate in Mode-II loading. If the time permitted we could have validated this model.

Graduated Students:

1. Samuel Williams Jr., MS, June 2014; “Mixed Mode Fracture Criteria for IM7/8552 Composite Laminate”
2. Sidharth Reddy Karnati, MS, July 2014; “Mixed Mode Fracture Criteria for AS4/8552 Composite Laminate”
3. Torrence Marunda, MS, May 2015; “Mode II Interlaminar Fatigue Characterization of AS4/8552 Carbon/Epoxy Composite Laminate”

Supported Post-Graduates and Staff:

1. Raghu Panduranga, Research Associate
2. Matthew Sharpe, Composite Fabrication Engineer
3. John Skujins, Test Engineer

Publications:

1. Kunigal N. Shivakumar, Raghu Panduranga, John Skujins, and Sidharth K. Reddy, “Assessment of Mode-II Fracture Test methods,” American Society for Composites 29th Technical Conference, September 8-10, 2014, San Diego, California, USA.
2. Kunigal Shivakumar, R. Panduranga, M. M. Sharpe, and S. G. Miller, Compatibility “Assessment Between Interleaving Polymer Nanofibers and Composite Laminate Resin,” Proceedings of the 19th International Conference on Composite Materials, July 28 – August 02, 2013, Montreal, Canada.
3. Shivakumar K, Panduranga R, Skujins J, Miller S. Assessment of Mode-II fracture tests for unidirectional fiber reinforced composite laminates. *J. Reinforced Plastic Composite* 2015;34(23):1905–25.
4. Sidharth Reddy and Kunigal N. Shivakumar, “Mixed Mode Interlaminar Fracture Criteria for Composite Laminates” (Submitted to International Journal of Fracture).

5. Raghu Panduranga and Kunigal N. Shivakumar, "Mode II Interlaminar Fatigue Model for IM7/8552 Carbon/Epoxy Composite Laminate", International Journal of Fatigue, Vol. 94, 2017.
6. Raghu Panduranga and Kunigal N. Shivakumar, "Finite Element Analysis of JIS and Standard End Notch Flexure (ENF) Test Specimens for Mode-II Testing", (Submitted to Engineering Fracture Mechanics)
7. Kunigal Shivakumar, "Fatigue Data Reduction methods for Composite Laminates," SciTech-2018, Orlando Fl.

Department of Defense Laboratory Visits by NC A&T Faculty:

1. Army Research Laboratory, Aberdeen, MD, April 2, 2013
2. NAVAIR, Patuxent River, MD, April 3, 2013

Summer Internship at Army Research Laboratory, Aberdeen, MD:

Samuel Williams, Jr. Summer Interned at ARL (2013), Mentor Dr. Asha Hall

ARL/NAVAIR Scientists/Engineers Visit Participation

Dr. Robert Haynes visited NC A&T SU on July 1, 2014

- Toured Center for Composite Materials Research
- Reviewed Progress made in the project
- Member of M.S. thesis defense committee of Mr. Samuel Williams, Jr M.S.

Dr. Anisur Rahman, NAVAIR, April 9-10, 2015

- Member of M.S. thesis defense committee of Mr. Torrence Marunda's M.S.
- Toured Center for Composite Materials Research
- Presented a talk on "NAVAIR Overview with focus on Airframe Technology"

Task A-1.10: Proximity Sensing for Degraded Visibility Missions

PI : Sean Humbert; sean.humbert@colorado.edu

Background:

Adverse visibility conditions and atmospheric obscurants, including fog, rain, smoke, dust, low light, and darkness, significantly limit the operational capabilities and combat effectiveness of rotorcraft. These conditions result in a reduction of visual cues that typically assist pilots in mission-critical tasks such as landing, hovering, and terrain following. Several technologies have been employed to assist in overcoming these operational barriers, including the Forward Looking Infrared sensors (FLIR), Terrain Following/Terrain Avoidance (TF/TA) radar and Low Light Level Television (LLTV). Instruments such as the LANTIRN, as equipped on the heavy-lift vehicle MH-53 Pave Low, combine these sensors to provide useful visual imagery to the pilot in low-visibility conditions so that obstacles can be monitored (FLIR), or navigational cues to the vehicle's control system for terrain following (TF/TA radar).

The FLIR sensor provides the pilot with an infrared image of the environment, which typically outperforms visible imaging in degraded visibility conditions. The apparent motion cues, available from the moving infrared imagery (or *optic flow*), can help the pilot make critical decisions regarding obstacle avoidance. However, directly observing an estimated motion field to interpret proximity is inefficient as it increases pilot workload disproportionately to the benefit attained. Alternatively, the estimated optic flow can be combined with knowledge of the self motion of the vehicle to provide an estimate of environmental structure within the imaged area, which would be a useful addition to aid a pilot's situational awareness. A direct estimate of environmental structure (proximity), in the form of a processed "depth" image, would allow the pilot to position the vehicle relative to observed obstacles as necessary, even in white-out or brown-out conditions, so long as the imager is able to penetrate the obfuscations. Furthermore, this approach would permit automated or assisted landing capabilities even in GPS-denied environments. This visual approach complements other concurrent research at UMD involving the use of a laser range finder for environmental mapping [1].

Research Objectives:

The overall objective is to develop and implement an algorithm that generates a 3D map of the local environment using infrared imagery. The resulting proximity information will be used to develop a 3D map of local obstacles under conditions of degraded visibility. Wide-field infrared sensing will be assumed, similar to the FLIR sensing capabilities on current rotorcraft configurations. The ability to compute optic flow from infrared imagery will be investigated. A nonlinear, continuous time structure from motion observer will be investigated as a robust approach to provide proximity information during degraded visibility conditions. The quality of the structural estimate obtained by the observer will be compared to the quality of the 3D estimates that resulted from the AFDD's precision autonomous landing adaptive control experiment (PALACE) program [10,11] where a stereo camera setup and scanning laser combination was used to generate a 3D map for automated landing purposes. The observer will be demonstrated operating on a flying quadrotor platform with an integrated IR camera. This demonstration will ensure the

feasibility of the observer as a standalone proximity detection solution. As part of the external interaction, the usefulness of integrating the proposed structural observer into the AFDD's safe landing determination (SLAD) algorithm and terrain obstacle avoidance display (TOAD) will be investigated.

Approach:

(1) Investigations of optic flow derived from infrared imagery in degraded visibility conditions: Infrared and visual imagery will be recorded for prescribed platform motions in outdoor environments for a range of lighting conditions (morning, midday, evening, open areas, shaded areas). Optic flow computation algorithms that have been developed in the Autonomous Vehicle Laboratory will be adapted and used to assess the feasibility of infrared imagery as a basis for optic flow estimation. The methodology will be evaluated by comparing the accuracy of optic flow computed using infrared imagery versus visual imagery to assess the quality and accuracy of optic flow based on outdoor infrared imagery.

(2) Design and analysis of a nonlinear structure from motion observer based on infrared imagery: We will investigate and implement a nonlinear structure from motion observer based on infrared imagery. Figure 2 shows the proposed observer design where the structure of the environment has been slightly redefined as the inverse distance to objects in the viewing area, given by the nearness estimate. The intuition behind this observer is that the estimated nearness as a function of viewing angle is continuously driven towards the actual nearness by minimizing the error between the observed optic flow field and the optic flow estimated from the known self-motion and the current structural estimate. The adaptation law governs how the nearness estimate changes as a function of this error. The presence of the "egomotion" input captures the fact that we assume knowledge of the vehicle's kinematics. The resulting algorithms will be demonstrated on a rotary wing research helicopter platform using infrared cameras as the sensors.

(3) Comparison of Structure Estimate Quality: The resulting 3D structural estimate obtained by the proposed FLIR-based observer will be compared to the quality that is obtained from the AFDD's precision autonomous landing adaptive control experiment (PALACE) program, which utilizes a stereo camera setup with a scanning laser range finder. The AFDD's safe landing determination (SLAD) algorithm selectively uses the stereo camera and scanning laser data to determine a landing trajectory. The scanning laser range finder is remarkably accurate, however it is an active sensing method and not sufficient when stealth is a priority. The stereo camera arrangement is most likely computationally comparable to the FLIR-based observer, and both are passive sensing methods, however the FLIR imagery will be better in certain conditions.

(4) Demonstration of the structural observer on a flying platform: To demonstrate the feasibility and practicality of the observer, the observer will be demonstrated on a flying quadrotor platform using an IR imager. The kinematics of the vehicle will be assumed to be known, thus allowing the observer to determine range uniquely. A persistency of excitation condition will be associated with the desired flight patterns of the vehicle, thus ensuring the convergence of the structural estimate, so long as the optic flow can be computed from the IR imagery.

(5) Evaluate Observer Usefulness for Integration into SLAD and TOAD: The ability of the observer to assist the SLAD algorithm in degraded visibility conditions will be determined. This will require the development of a method to assign reliability

measures to each method of sensing, as in some cases, the visible light stereo camera arrangement will be best and in other cases, the FLIR-based imagery will be most useful. Additionally, we will evaluate the usefulness of integrating the improved structural estimate into the AFDD's terrain obstacle avoidance display (TOAD), thus allowing the FLIR-based structural estimator to assist in manned helicopter degraded visibility landing scenarios as well.

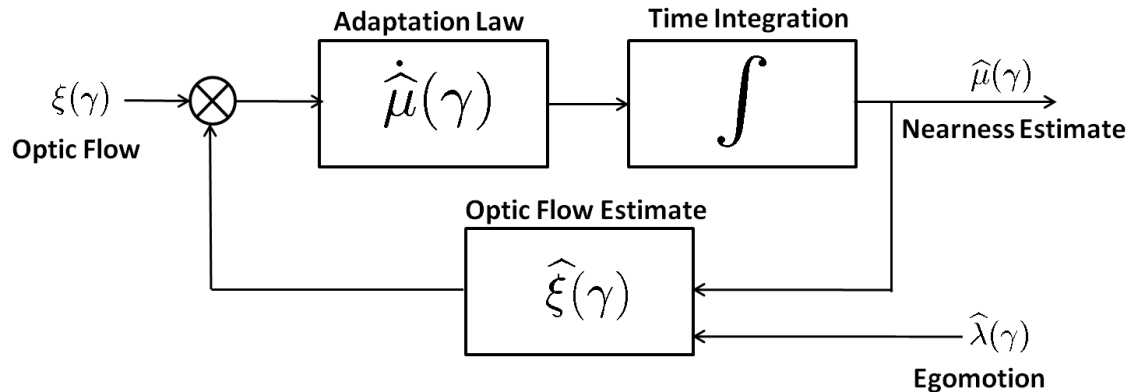


Figure 2: Proposed Structure from Motion Observer

Accomplishments (Years 2011-16):

In Year 1, a testbed for comparison of IR versus visual based optic flow was completed. We showed the quality of optic flow is maintained for IR imagery across a variety of conditions (day/night, natural/man-made). The state of the art for structure from motion algorithms with IR and visual imagery was also investigated, and it was found that IR imagery outperforms visual imagery across lighting conditions, and visual imagery was slightly better for well-lighted natural scenes. In Year 2, we developed, implemented and performed a preliminary evaluation of a planar (3 DOF) structure from motion nonlinear observer for FLIR imagery. Body velocity estimation was accomplished using a micro-IMU, and a real-time implementation was realized in hardware that ran at 15 Hz. We also demonstrated that illumination and lighting does not significantly affect the performance of the IR-based system. In Year 3, the nonlinear observer formulation was extended for full 6 DOF motions in 3D environments. Video streams and IMU time histories from the autonomous Blackhawk platform supplied by the AAFD Autonomous Rotorcraft Program (Matthew Whalley) was used to evaluate the 6 DOF observer formulation. In Year 4, we developed conditions of excitation and quantified observer performance under different persistency of excitation conditions. In Year 5, we finalized a provably stable observer design and performed an analysis versus state-of-the-art algorithms. We demonstrated observer performance for both dense depth map and sparse feature depth extraction applications.

Graduated Students:

1. Kedar Dimble, "Electrollocation Based Obstacle Avoidance and Autonomous Navigation in Underwater Environments," PhD December 2013

2. Jishnu Keshavan, "A H-infinity Loopshaping Framework for Bio-Inspired Sensorimotor Control," PhD, May 2012, Assistant Professor, Mississippi State University.

Publications:

1. Dimble KD, Escobar-Alvarez HD, Ranganathan BN, Conroy JK and Humbert JS, "3D Depth Estimation for Helicopter Landing Site Visualization in Environments with Degraded Visibility," *6th AHS International Specialists Meeting On Unmanned Rotorcraft Systems*, Chandler, AZ, January 2015
2. Keshavan J, Escobar-Alvarez H and Humbert JS, "An Adaptive Observer Framework for Accurate Feature Depth Estimation Using an Uncalibrated Monocular Camera," *Journal of Control Engineering Practice*, Vol. 46, pp. 59-65, 2016, DOI: 10.1016/j.conengprac.2015.10.005
3. Keshavan J, Escobar-Alvarez H, Dimble KD, Humbert JS, Goerzen, CL and Whalley MS, "Application of a Nonlinear Recursive Observer for Accurate Visual Depth Estimation from UH-60 Flight Data," *AIAA J. of Guidance, Control and Dynamics*, Vol. 39, No. 7, pp. 1501-1512, 2016, DOI: 10.2514/1.G001450
4. Keshavan J and Humbert JS, "An Optical Flow-Based Solution to the Problem of Range Identification in Perspective Vision Systems," *Journal of Intelligent and Robotic Systems*, Vol. 85, No: 3-4, pp. 651-662, 2016, DOI: 10.1007/s10846-016-0404-6
5. Keshavan J and Humbert JS, "An Analytically Stable Structure and Motion Observer Based On Monocular Vision," *Journal of Intelligent and Robotic Systems*, Vol. 86, No. 3-4, pp. 495-510, 2017, DOI: 10.1007/s10846-017-0470-4.
6. Keshavan, J and Humbert JS, "Range Identification Using an Uncalibrated Monocular Camera," *American Control Conference*, Seattle, WA, May 2017
7. Keshavan J and Humbert JS, "Robust Structure and Motion Recovery for Monocular Vision Systems with Noisy Measurements," *International Journal of Control*, 2017 DOI:10.1080/00207179.2017.1291997.
8. Keshavan J and Humbert JS, "Structure-Independent Motion Recovery from a Monocular Image Sequence with Low Fill Fraction", *International Journal of Robust and Nonlinear Control*, 2017, DOI:10.1002/rnc.3879

A-1.11: Collaborative Control for Autonomous Operation of Helicopters in Flight

PI : Derek A. Paley, dpaley@umd.edu 301-405-5757

Background:

The coordination of multiple autonomous helicopter promises the same general benefits of collaborative control over any type of platform, but it presents a set of control challenges that are unique to rotorcraft aerodynamics and how they are affected by gusty environments. The approach taken for this research has been to focus on these topics as they relate to small rotorcraft UAVs. Like all flying vehicles, small rotorcraft are adversely affected by flow-field disturbances but are more vulnerable due to their size. Unlike fixed wing vehicles, the aeromechanics of rotary wing vehicles are more complex and current control frameworks that use oversimplified models adequate in low-advance ratio flight conditions may not provide the control performance needed to realize collaborative control in the presence of wind. Another control challenge specific to rotary-wing platforms is that the downwash they generate can induce significant flow field disturbances for other vehicles operating nearby, adding further potential complications when applying conventional collaborative control frameworks to rotorcraft.

Research objectives:

This research aims to identify challenges in collaborative control for helicopters that are specific to rotary-wing platforms and to develop platform-level techniques and strategies to advance the state of the art. Specifically, we seek fundamental improvements to the flight control capabilities of autonomous helicopters in complicated flow environments, which will inform future efforts that will explore the concept of autonomous rotorcraft coordination during collaboration with other types of vehicle platforms, such as when landing on a surface vessel.

Technical approach

Our methodology can be summarized as follows:

- Apply tools from nonlinear dynamics to devise reduced-order models of individual rotorcraft with a focus on modeling the aeromechanic effects of external wind.
- Conduct ground-based and flight tests that provide insight and drive theoretical advancement
- Develop sensing packages and strategies that estimate local wind fields and incorporate those estimates into the feedback control framework.

Summary of Results

Between years 1 and 2, simulations of flyby and ship landing maneuvers in unknown, turbulent wind fields were conducted. Multi-vehicle flight tests were conducted identifying wind as a key challenge to practical collaborative control. Year 2 saw the development of a high-fidelity, quadrotor dynamic model including aerodynamic effects of blade flapping and induced thrust. A feedback-linearization based controller for flight was demonstrated in estimated wind fields through simulation. In Year 2, an on-board flow instrumentation and data-acquisition concept for small rotary wing UAVs was developed and preliminary flight tests were carried out to validate the system. In Year 3, the theoretical framework for onboard flow sensing was extended through the insight gained from experimental efforts. The onboard flow instrumentation system saw further

development through improved calibration techniques and avionics. Flow-field surveys in the downwash region of small rotorcraft drove the development of a Bayesian downwash detection and localization framework that leveraged onboard flow measurements. These technologies were combined with previous flight control developments, leading to the first “flow-aware” collaborative flight control result: a downwash de-confliction capability demonstrated through multi-vehicle flight testing indoors. A small autonomous quadrotor helicopter was able to successfully detect and localize the downwash of a second overflying vehicle. This was achieved by assimilating spatially distributed flow measurements around the vehicle with predictions from the Bayesian estimation framework. By redirecting its trajectory based on these in-flight estimates, the vehicle was able to safely reach its destination despite the presence of an unknown and potentially hostile rotorcraft generating a hazardous downwash region overhead.

In Years 3-4, we developed a dynamic height controller for rotorcraft hovering and landing in ground effect, based on flow field sensing and estimation. The rotor downwash in ground effect is represented using a ring-source potential flow model selected for real-time use and validated experimentally. In the experiment, flow field pressure measurements were assimilated into a grid-based recursive Bayesian filter to estimate height above ground. Height control in ground effect using the estimated height was implemented with a dynamic linear controller. The experimental results demonstrated that height estimation and control are possible with only two sets of differential pressure probes situated in the rotor downwash.

We analyzed a simplified set of analytically tractable blade-flapping equations and predicted a phase delay of 81 degrees for a small, stiff propeller in a steady and uniform wind. The system was also modeled using blade-element momentum theory, and the model results were compared to existing experimental data, finding agreement with both the simplified model and experimental data. The force due to drag was found to be stronger than the force due to blade flapping. Equations of motion were also derived for another experimental testbed: a two-degree-of-freedom rotor-gyropendulum, which affixes a spinning propeller to the end of a spherical pendulum. We also used experimental results to develop a dynamic model that captures the aerodynamic effects of wind on a small multi-rotor platform that uses differential thrust for attitude control. We examined a single degree-of-freedom tandem-rotor platform and designed an attitude controller that used onboard measurements of airspeed to feedback linearize the system in the presence of wind. Numerical simulation and experimental results have shown improvements in attitude control through onboard flow sensing.

In Year 5, the current blade-element momentum-theory model was updated to include the blade pitching moment and account for the parameters specific to the Gemfan 5030 propeller used in experiment. A rotor-gyropendulum test stand was built to explore the response of a small, stiff propeller to wind. The Collective Dynamics and Control Laboratory’s motion-capture facility was used to ensure that the dynamics of the system were identified with sufficiently high spatial and temporal resolution. The results were compared to a simulation of the full rotor-gyropendulum dynamics. Blade flapping was also investigated using high speed cameras in a wind tunnel. The cameras were calibrated and positioned to accurately capture the blade flap at different angles in

steady and uniform wind, and have yielded data on the magnitude of blade-flapping at higher speeds than had been previously obtained.

Graduated Students:

1. Nitin Sydney, "Rotorcraft Flight Dynamics and Control in Wind for Autonomous Sampling of Spatiotemporal Processes", PhD 2015 (Autonomous Systems Engineer, MITRE)
2. Chin Gian Hooi, "Height Estimation and Control of a Rotorcraft in Ground Effect Using Multiple Pressure Probes", MS 2015 (Software Engineer, Rockwell Collins)

Publications:

- [1] W. Craig, D. Yeo, and D. A. Paley. "Dynamics of a Rotor-Pendulum With a Small, Stiff Propeller in Wind," Proc. 2016 ASME Dynamic Systems and Control Conf., pages 1-10.
- [2] C. G. Hooi, F. D. Lagor, and D. A. Paley. "Height estimation and control of rotorcraft in ground effect using spatially distributed pressure sensing," *J. American Helicopter Society* 61(4), pages 1-14, 2016.
- [3] C. G. Hooi, F. D. Lagor, and D. A. Paley. "Flow Sensing for Height Estimation and Control of a Rotor in Ground Effect: Modeling and Experimental Results," Proc. American Helicopter Society Forum 71, Virginia Beach, Virginia, 5–7 May 2015.
- [4] C. G. Hooi, F. D. Lagor, and D. A. Paley. "Flow Sensing, Estimation and Feedback Control for Rotorcraft Landing in Ground Effect," Proc. IEEE Aerospace Conference, pages 1–8, Big Sky, Montana, March 2015.
- [5] N. Sydney, B. Smyth, and D. A. Paley. "Dynamic Control of Autonomous Quadrotor Flight in an Estimated Wind Field," Proc. IEEE Conf. Decision and Control, pages 3609–3616, Florence, Italy, December 2013.
- [6] D. Yeo, N. Sydney, D. A. Paley, and D. Sofge. "Onboard flow sensing for downwash avoidance with a small quadrotor helicopter," *Autonomous Robots*, DOI: 10.1007/s10514-015-9542-0.
- [7] D. Yeo, N. Sydney, D. A. Paley, and D. Sofge. "Onboard Flow Sensing For Downwash Detection and Avoidance with a Small Quadrotor Helicopter," Proc. AIAA Guidance, Navigation and Control Conf., number AIAA 2015-1769, pages 1–11, Orlando, Florida, January 2015.
- [8] D. Yeo, E. Shrestha, D. A. Paley, and E. Atkins. "Experimental Development of a Rotorcraft UAV Downwash Model for Real-Time Disturbance Localization and Avoidance," Proc. AIAA Atmospheric Flight Mechanics Conf., number AIAA 2015-1685, pages 1–14, Orlando, Florida, January 2015.

- [9] D. Yeo, N. Sydney, and D. A. Paley. "Onboard flow sensing for rotary-wing UAV pitch control in wind," 2016 AIAA Guidance, Navigation and Control Conf., AIAA 2016-1386.

Task: A-1.12 Flight Dynamics and Control of Rotorcraft Towing Submerged Bodies
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Jaye Falls — (410) 293-6437 — falls@usna.edu

Background:

Naval rotorcraft can operate while towing submerged bodies, such as sonar and minesweeping devices. The towed devices can affect the flight dynamics and control (FD&C) characteristics of the rotorcraft in ways that are similar to, but more complex than those of a slung load. Trim and maneuverability are affected during operation of the towed device. Additionally, the towed device may introduce low frequency load modes that can couple with fuselage and rotor modes and affect the aircraft stability margins, and could potentially trigger aeroservoelastic instabilities in the presence of high gain flight control systems. These effects have not been studied systematically, and currently there are significant gaps in the fundamental understanding of the underlying dynamic phenomena.

The problem is intrinsically multidisciplinary and requires integration of rotorcraft FD&C and ship dynamics. If the towed body is not fully immersed in the operational phases of interest, the interaction of air- and water-generated forces must be correctly modeled as a function of time, and carefully coupled with the rotorcraft dynamics. The interaction of any control system present on the towed device with the rotorcraft Flight Control System (FCS) must also be carefully studied to prevent adverse couplings or, conversely, to take advantage of both types of control system to improve the coupled dynamics.

Proposed Objectives:

The primary objective of the proposed task is to improve the fundamental understanding of the coupled dynamics of a rotorcraft and a towed body that is fully or partially submerged. The task will identify and study the key physical mechanisms that affect the trim state of the helicopter, its dynamic stability, the frequency response to pilot inputs, and the behavior in transients of operational and environmental origin. Finally, the task will determine the most important design parameters (both of rotorcraft and towed load) and the key flight and operational conditions affecting the coupled dynamics.

Technical Approach:

A sophisticated rotorcraft flight dynamic simulation model has been developed at the University of Maryland. Rotorcraft configurations with any number of rotors and lifting surfaces at arbitrary locations can be modeled. Nonlinear beam finite elements are used to model the blades, and flexible wings and fuselage models are currently being implemented. A slung load model is included. The model can calculate the trim state in straight flight and steady turn, extract linearized models for stability and frequency response analyses, simulate the free flight response to arbitrary pilot inputs, and perform trajectory optimization and inverse simulation. The model has been extensively validated through comparisons with flight test data for single main rotor (UH-60) and tilt-rotor (XV-15) configurations.

The technical approach consists of the following elements:

- (a) Development of an initial coupled rotorcraft/towed body model, consisting of: a single main rotor helicopter configuration, a fully submerged body broadly representative of a towed sonar, including full 6-DOF rigid body dynamics, and a straight, axially flexible cable. Study effects of design parameters, and flight conditions on trim, poles/zeros, frequency response to pilot inputs (including ADS-33 handling qualities assessments), and maneuvers under tow.
- (b) Refine the simulation by including an improved flexible cable dynamics FEM, assuming that the cable is partially in air and partially in water. Repeat fundamental studies for refined configurations.
- (c) Validate cable/submerged body model experimentally in the towing tanks at USNA. Test matrix will include a range of steady state speeds, wave characteristics (height, speed and direction) and water depth. Planar motion mechanism (PMM) controlling the carriages of 380 ft towing tank currently allows control of sway (lateral translation) and yaw. Planned towing tank modifications include allowing for oscillatory motion control. This capability will allow validation of the rotorcraft/towed body dynamic coupling. Shallow water operations and beaching will be examined in the coastal engineering tank.

- (d) Study the flight dynamics of the rotorcraft following an engine failure while under tow, and determine the optimum control strategies and flight paths for recovery, if possible, or damage minimization.
- (e) Develop the equivalent of a FCS for the towed body, and study the best control strategies to minimize required power in trimmed conditions, and to minimize pilot workload during maneuvers.

Accomplishments in 2014-2016

During those two year the UMD research has focused on two areas, namely: (i) the study of trajectories and piloting strategies following an engine failure, and (ii) the study of the dynamics with a controlled towed load.

The trajectories and piloting strategies following the engine failure have been studied as an optimization-based inverse simulation problem, in which the design variables define the time histories of the pilot controls, and the aircraft trajectory is not specified *a priori* but is an outcome of the optimization. The first step has been the solution of the problem, for the non-towing case, for two different scenarios, i.e., (i) a flyaway maneuver, and (ii) a landing. Engine failure was simulated by reducing the fuel flow to one engine. The aircraft model was broadly representative of a UH-60. With the remaining power, trimmed level flight was possible between approximately 40 and 100 kts. The failures for the flyaway maneuvers were assumed to occur below 40 kts. For the flyaway case, the optimization was formulated so as to minimize the maximum loss of altitude following the failure. For the landing case, the optimization was formulated so as to minimize the violation of maximum limits on velocities and attitudes at landing.

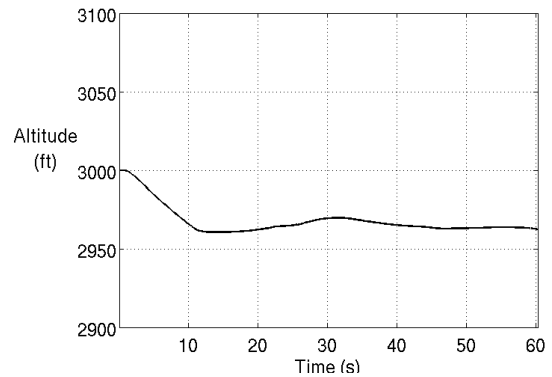


Figure 1 - Flyaway (not towing)

The optimizer successfully determined flyaway trajectories (see Fig. 1 for an example). This is significant because the formulation of the problem did not include in any way the knowledge that by accelerating through a nose down maneuver it would be possible to reach a speed where the residual power would allow trimmed flight. The optimizer also determined landing trajectories (not shown) that would correspond to survivable OEI landings. Initial calculations for failures while towing were also performed, under the (favorable) assumptions that the failure would be immediately detected and the tow cable would also be immediately cut. Somewhat unexpectedly, the optimization indicated that this would be a rather benign failure mode, and a flyaway maneuver could be easily accomplished, as can be seen in Fig. 2. The reason, according to the simulation, is that before failure, to overcome the hydrodynamic drag of the towed load, the rotor is generating thrust well in excess of what would be needed in non-towing conditions. When the engine failure occurs and the cable is severed, this excess thrust, coupled with the nose-down initial attitude, allows an initial climb and forward acceleration that are short-lived, but sufficient to allow a flyaway-type recovery.

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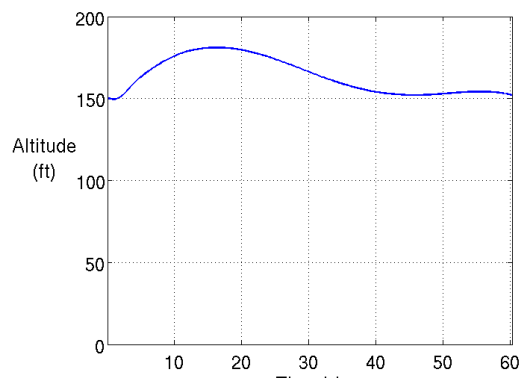


Figure 2 - Engine failure under tow

All calculations were performed using an in-house optimization methodology, which was originally developed for brownout mitigation through landing trajectory optimization, and preliminary design of advanced rotorcraft configurations with refined aerodynamics. The two classes of problems have in common that they are computationally intensive and with local optima. Gradient-based methods and genetic algorithm-type methods are problematic because they may not converge to the global optimum, and because they are too

problematic because they may not converge to the global optimum, and because they are too

computationally intensive, respectively. The methodology used in the present task maintains good global convergence with reasonable computing requirements by coupling genetic algorithms with specially derived, adaptive, response surfaces. With 16 design variables, the problems solved in the present task are twice the size of the problems previously studied with this methodology. This is significant because response surfaces are subject to the “curse of dimensionality”. If the methodology maintains its good properties for up to 25-50 design variables, it would be a good practical optimization tool for very difficult, computationally intensive problems.

The study of the towing dynamics with a controlled load was carried out with a highly idealized model, rather than the full nonlinear simulation. Aircraft and load were modeled as point masses connected by a straight, axially flexible cable. The motion of the aircraft was prescribed and its position perfectly known. The position of the load was also assumed to be known. The load was required to follow a trajectory prescribed relative to the aircraft. Active fins provided lateral and vertical control of the load. Magnitude and direction of the propulsive force of the load was determined by tension and spatial orientation of the cable. A U-shaped trajectory was studied, with two straight segments and a 180-degree turn. The unknown control gains of the load “flight” control system (FCS) were determined through optimization techniques.

Under the highly idealized conditions of the model, the results show that good trajectory-following accuracy could be obtained even with a simple, proportional-plus-integral controller. A multiobjective optimization with a Pareto frontier for minimum trajectory accuracy and minimum cable tension, with the addition of the altitude of the towing aircraft as a design variable, showed that significant reductions in required cable tension (and by implication, rotor power required) could be possible by carefully considering the flight conditions of the towing aircraft, and the overall interplay of the forces acting on the aircraft and the submerged towed load.

Accomplishments — Years 1-5

Year 1 — (a) Development of the initial coupled rotorcraft/cable/towed body simulation, with a simplified cable model, assumed to be straight and only axially flexible; (b) Extension of the trim procedure to the coupled configuration, for straight flight conditions and steady turns; (c) Extensive parametric studies on the effects of design parameters and flight conditions on trim characteristics and power required.

Year 2 — (a) Refinement of the coupled simulation with a fully flexible (nonlinear, coupled bending torsion dynamics), finite element-based model of the tow cable; (b) Extension of the trim procedure to include the finite element cable model; (c) Validation of the refined cable model with experimental results; (d) Extension of the parametric studies of Year 1 to account for cable flexibility; (e) Initial development of maneuver modeling, and application to a teardrop maneuver.

Year 3 — (a) Completed the development of the maneuver model; (b) Development of the methodology to extract a high-order linearized model of coupled rotorcraft/cable/towed body dynamics; (c) Calculation of poles and frequency responses to pilot inputs (Bode plots), and analysis of the handling qualities implications (bandwidth/delay, potential coupling of cable dynamics with FCS).

Year 4 — (a) Formulated and solved trajectory optimization problem for recovery or damage mitigation in the case of engine failure without towing, and obtained initial results for the towing case; (c) Developed a simple FCS for the towed body, and studied effects of flight condition on accuracy of trajectory and cable tension using a simplified towing model.

Year 5 — (a) Refined the coupled simulation by including experimentally derived hydrodynamic characteristics of the towed body; (b) Completed trajectory optimization problem for recovery; (c) Incorporated the simple FCS for the towed body in the full accuracy simulation.

Task UM_1.13 CAD-Based Modeling of Advanced Rotary-Wing Structures

PM: Inder Chopra chopra@umd.edu (301) 405-1122

Background:

The goal of this research project was to develop advanced 3-D structural analysis models of rotors for integrated CSD-CFD analysis. In the previous two decades, CFD has proven itself as a viable tool to improve aerodynamic predictions in comprehensive analyses of rotorcraft. Computational structural dynamics (CSD), on the other hand, has not kept pace in terms of dimensionality and discretization. Current rotor structural analyses use multibody, but blades are simply modeled as a one-dimensional slender beam undergoing flap-lag bending, elastic twist, and axial deformation, with chordwise bending neglected. Static stress analysis is performed using three-dimensional FEM, but only for isolated components. Although accurate for many current applications, these methods do face certain limitations, such as the inability to handle structural discontinuities, advanced hubs with non-slender elastically deforming components, and morphing structures. Furthermore, these methods cannot determine the critical stresses which drive the weight of rotor components in an integrated manner. Next generation dynamic analyses are envisioned to utilize fully integrated 3-D CSD and CFD. This will allow modern rotor designs to be analyzed with high fidelity and will enable engineers to determine stresses at the design stage, allowing for lighter rotor components. Integrated 3-D is more computationally intensive than current methods but will be enabled by continued improvements in high performance computing. Such an advanced solver, combining multibody structures with full 3-D finite element analysis (FEA) for flexible components, has been developed by Army AFDD. This high fidelity 3-D CSD requires the development of a new kind of description for the rotor geometry, starting from CAD models and ending in a full-featured structural analysis model (SAM).

Research Objectives:

The objective was to develop an unique and brand new set of simulation tools for 3-D CAD based geometry, meshing, and modeling capability of advanced rotor blades that can be used by the Army's NexGen 3-D Rotor Structural Dynamics/Aeroelastic solver – X3D. The tool sets developed will then be used to carry out comprehensive analysis of a modern helicopter rotor at a critical flight condition to predict blade stresses/strains as a demonstration test case.

Approach:

The approach was to work toward this new breakthrough capability jointly with the Computational Aeromechanics group at the US Army ADD at Ames Research Center (Dr Anubhav Datta and Dr Roger Strawn) and the Aeromechanics group at the NASA Ames Research Center (Dr Wayne Johnson and Dr William Warmbrodt). NASA release detailed internal drawings and material properties of the TRAM rotor specifically for this task. The US Army provided full access to X3D specifically for this task.

Accomplishments (Years 2011-16):

The accomplishments were far more than what originally promised. The tool set was developed successfully. A detailed report was submitted to the US Army with thorough description of the new methodology including step by step procedure to CAD, mesh, and material model a new rotor system. The tool was the enabler, driver, and led to the first demonstration of a new kind of aeromechanics analysis described as “Integrated-3D” or in short “I3D”. It was defined as 3-D Structures coupled to 3-D Aerodynamics and trim solution for helicopter rotors. It was demonstrated and validated with TRAM. This worked revealed the intricate stress/strain patterns at the complex root end of the tiltrotor for the very first time. It was also used to study RPM-driven twist morphing of an UH-60A like rotor to increase high speed efficiency. This worked demonstrated a 20% increase in aircraft L/D might be possible even with only a 15% reduction in rotor RPM at high speed. This UMD tool integrated with Army's X3D for detailed analysis of NASA's TRAM was a showcase problem for a collaborative production of a leap-ahead technology. In total there

were 13 publications: 1 restricted Army report, 3 journal papers (documenting final results), and 9 conference papers (documenting progress in research; AHS-5 papers, ERF-2 papers, AIAA-2 papers).

Graduated Students:

1. William Staruk, "CAD Based Modeling of Advanced Rotary Wing Structures for Aeromechanics Analysis," PhD, December 2017 (Contractor, Army ADD, Ames Research Center).
2. Elizabeth Ward, "Aeromechanical Behavior of Twist-Morphing, High-Speed Slowed RPM Rotors," PhD, January 2018, (Engineer at Bell Helicopter).

Publications:

1. Staruk, W., Chopra, I., and Datta, A., "Final Report: CAD-Based Modeling of Advanced Rotary-wing Structures," US Army ADD Report, July 2016. Restricted to US Army.
2. Staruk, W. and Datta, A., "Gimbaled Tiltrotor Conversion Flight Loads Prediction Using Three-Dimensional Structural Analysis," *Journal of Aircraft*, v 56, (2), Mar-Apr 2019, pp. 758-770.
3. Staruk, W., Datta, A., Chopra, I., and Jayaraman, B., "An Integrated Three-Dimensional Aeromechanics Analysis of the NASA Tilt Rotor Aeroacoustic Model," *Journal of the American Helicopter Society*, v 63, (3), April 2018, pp. 1-12.
4. Ward, E., Chopra, I., and Datta, A., "Rotation-Frequency-Driven Extension-Torsion Coupled Self-Twisting Rotor Blades," *Journal of Aircraft*, v 55, (5), Sep-Oct 2018, pp. 1929-1941.
5. Ward, E., Chopra, I., and Datta, A., "Aeromechanics of Self-Twisting Blades in High-Speed Slowed Rotor Flight," European Rotorcraft Forum 43, Milan, Italy, September 12--15, 2017.
6. Staruk, W., Chopra, I., and Datta, A., "Loads Prediction for a Gimbaled Tiltrotor in Conversion Flight Using CAD-Based 3-D Structural Analysis Models," American Helicopter Society Annual Forum 73, Fort Worth, TX, May 2017.
7. Staruk, W. and Datta, A., "Fundamental Understanding, Prediction, and Validation of Tiltrotor Dynamic Loads in Transition Flight Using RANS/FEA," AIAA Science and Technology Forum and Exposition 2017, Grapevine, TX, January 2017.
8. Ward, E., Chopra, I., Datta, A., "RPM Driven Extension-Torsion Coupled Self-Twisting Rotor Blades," American Helicopter Society Forum 73, Fort Worth, TX, May 2017.
9. Ward, E., Chopra, I., Datta, A., "Design of Self-Twisting Rotor Blades for High-Speed Compound Rotorcraft," Paper AIAA 2017-0292, AIAA SciTech Forum, Adaptive Structures Conference, Grapevine, TX, January 2017.
10. Ward, E., Chopra, I., Datta, A., "RPM Driven Extension-Torsion Coupled Self-Twisting Rotor Blades," American Helicopter Society Forum 72, West Palm Beach, FL, May 2016.
11. Staruk, W., Chopra, I., Datta, A., and Jayaraman, B., "Validation of Aeromechanics Predictions for a Full 3-D Structural Analysis Model of the Tilt Rotor Aeroacoustic Model (TRAM) Proprotor," European Rotorcraft Forum 42, Lille, France, September 2016.

12. Staruk, W., Chopra, I., and Datta, A., ``Coupled Aerodynamics and 3-D Structural Dynamics of the Tilt Rotor Aeroacoustic Model (TRAM) Proprotor," AHS International Technical Meeting on Aeromechanics Design for Vertical Lift, San Francisco, CA, January 2016.
13. Staruk, W., Chopra, I., and Datta, A., ``Three-Dimensional CAD-Based Structural Modeling for Next Generation Rotor Dynamic Analysis," American Helicopter Society 70th Annual Forum, Montreal, QC, May 2014.

Task UM-1.14: Conceptual Modeling of Novel Configurations for UAS Applications

PIs: Dr. Inderjit Chopra, University of Maryland, College Park (chopra@umd.edu)
Dr. Moble Benedict, Texas A&M University, College Station (benedict@tamu.edu)

Motivation

Increased demand for unmanned aerial systems for both military and civilian applications has sparked interest in novel configurations using conventional rotors as well as out-of-the-box solutions such as cycloidal-rotors and flapping wings. However, most of these novel vehicle prototypes are developed through extensive experimentation and not utilizing traditional aircraft design techniques. Based on our preliminary research, even quad-rotors, the most popular UAV configuration today, are heavily over-designed with poor rotor performance leading to very low endurance. The reason for this is primarily the lack of design tools for these types of small-scale unconventional systems. Proper modeling techniques and systematic design of these vehicles can help to build more efficient next generation small-scale vehicles. A good example for this is the 45 gram quad-rotor helicopter developed by the PIs demonstrating 31 minutes of hover endurance, which is more than double the endurance of any micro-helicopter at this scale.

Research Objectives

The objective is to develop a design methodology, which will provide the capability to model some of the novel UAS concepts, namely (1) Multi-rotor, shrouded-rotor helicopters, (2) Cyclocopter, and (3) Flapping-wing aircraft, over a range of scales (30 to 500 grams).

Technical Approach

Developing such a design code would involve developing analytical methods to predict thruster (conventional rotor, cyclorotor, flapping wing) average performance (lift, thrust and power), blade aerodynamic/structural loads and hub loads, methods to calculate component weights and geometry, modeling of propulsion system and further, utilize these analyses to understand scalability, both in terms of performance and component weights/geometry.

Thruster model: Accurate performance/loads prediction for a given thruster geometry would require a comprehensive aerodynamic model coupled with a structural model. The structural model needs to be fully non-linear in order to handle large deflections. For a conventional rotor, the aerodynamic model could be a BEMT-based analysis with linear unsteady aerodynamics and uniform/dynamic inflow model. However, on cyclorotors and flapping wings, the large amplitude, high reduced frequency pitching/flapping motion results in highly complex unsteady aerodynamics. A two-fold approach will be used to model these unconventional systems:

(1) Novel physics-based lower-order modeling techniques will be developed to model the different flow features (such as dynamic stall, leading edge vortices, wing-wake interactions, etc.) along with the inflow distribution for hover and forward flight. However, for such complex systems, developing lower-order physics-based models valid over a range of operating conditions could be extremely challenging, and hence the second approach.

(2) Extend our present high-fidelity CFD/CSD-based modeling capability for accurate simulation of cyclorotors/flapping wings. This analysis will be systematically validated with in-house experiments. Once validated, the results from the high-fidelity analysis will be used to refine the

lower-order physics-based models or develop semi-empirical/reduced-order models which can accurately predict forces and performance over a range of scales and operating conditions.

Control and trim calculation: Once the thrusters are accurately modeled, the total forces and moments acting on the aircraft can be obtained from the fixed-frame forces produced by each of the thruster and respective geometric locations where the forces are transferred to the fuselage. Once the total force and moments acting on the aircraft from all the components are obtained, a trim routine would solve for the controls and aircraft motion that produce equilibrium in the specified flight state (hover, forward flight, etc.).

Weight estimation: The goal is to develop fundamental structural principles-based models to estimate the weight of the load-bearing components. Each of these structures would be idealized as beams or plates and the stresses and strains would be calculated using simple beam theory or classical plate theory depending on the forces acting. The weights obtained using the basic structural models will need to be corrected using the actual weights of the few existing aircraft. Now, for estimating the weights of other components such electronics (servo-motors, motor-controllers, sensors, autopilot, wiring, etc.), and propulsion system (motor + batteries/fuel cells, engines and transmission), statistical models will be developed based on existing data.

Accomplishments in 2014-16 (3-year task):

Conventional micro-rotor (UMD): To predict the performance of MAV scale conventional rotor, a BEMT-based aerodynamic model is developed. Since the linear lift to angle-of-attack relationship is not valid for the low Reynolds number operating regime of MAV scale rotors, necessary modifications are made to develop the BEMT model. For this purpose, a look-up table based on XFOIL and 2-D CFD (TURNS2D) is generated for a range of Reynolds numbers. The developed model is systematically validated with data obtained from in-house experiments.

A detail design framework for MAV scale quadrotor is developed. Initially primary quadrotor component groups are identified and the empirical trends, which drive their weights are investigated. These trends have been quantified and organized in multivariable regression equations. Finally, a complete sizing algorithm of different system components are formulated, and its detail validation is presented.

Cycloidal rotor (TAMU): The primary objective of the project is to develop a lower-order, high-fidelity analytical model of cycloidal rotor (or, cyclorotor) which could be utilized to develop a computational design framework of cyclorotor based MAVs. Towards this, a nonlinear aeroelastic model of cyclorotor is developed by coupling an unsteady aerodynamic model with a structural framework. For this purpose, aerodynamics of cyclorotor is investigated thoroughly and several phenomena behind the force production of cyclorotor such as nonlinear dynamic virtual camber, effects of near and shed wake, leading edge vortices are rigorously modeled. To capture complex inflow characteristics of cyclorotor, a modified double multiple streamtube (D-MS) model is developed which relaxes the unrealistic assumptions of uniform inflow and traditional D-MS model. The developed model is validated with in-house experimental data. The inclusion of detail modeling of several aerodynamic phenomena led to thorough validation of not only time-averaged forces but also time-history of instantaneous forces as the blade goes through different azimuth locations. Once validated, the developed model is utilized to understand the physics behind thrust production of cyclorotor.

It is observed from in-house experiments that cyclorotor blades go through large bending and torsional deflections. To capture the effect of blade deflections on rotor performance, systematic experiments are carried out with moderately and highly flexible rotor blades. Experimental results showed increase in power requirement and decrease in thrust generation as the flexibility of the rotor blades are increased, which in turn decreases power loading of flexible rotors. To further investigate these phenomena, an aeroelastic model of cyclorotor is developed by coupling the aerodynamic model with structural framework. Towards this, two structural model of cyclorotor is developed: 1. 2nd order nonlinear model (Hodges-Dowell), 2. fully nonlinear geometrically exact model. The aeroelastic model is validated with in-house experiments. It is observed that the inclusion of geometrically exact model is extremely important to accurately predict the performance of flexible cyclorotors.

The aeroelastic model of cyclorotor is utilized to develop a coupled-trim framework of the complete vehicle (cyclocopter) based on cyclorotor. For this purpose, control strategy of a twin cyclocopter is formulated for different flight conditions (i.e. hover, forward flight) and coupled trim simulation is carried out by simultaneously solving the thruster model and vehicle trim model. Once systematically validated with in-house experiments, the coupled trim model is utilized to understand the effect of different design parameters (i.e. longitudinal location of center of gravity, gross weight, pitch amplitude) on the performance of the vehicle.

In the final step, a sizing model of cyclocopter is developed which can estimate weights of several sub-systems of the vehicle. The major load bearing components (i.e. rotor shaft, pitch link etc) of the cyclorotor is identified and modeled based on simplified beam and plate theory. The weight of these load bearing components are estimated using inertial loads and aerodynamic loads obtained from thruster model. To estimate weight of the electronic subsystems, a machine learning based approach is taken. For this purpose, a semi-empirical model based on artificial neural network (radial basis function network) is developed which is trained utilizing existing data of weights of electronic components.

Flapping wing (TAMU): Geometrically exact nonlinear finite element beam and shell model were developed for structural analysis of the flapping wing structure. This model was validated both statically and dynamically with commercial FEA Software Abaqus. A potential flow based unsteady aerodynamic model was developed, which capture the effects of leading edge vortex, shed wake and dynamic inflow. Systematic validation was carried out for the aerodynamic model with both experiments and in-house CFD results on rigid flapping wings.

The structural solver and aerodynamic solver were explicitly coupled to generate aeroelastic framework. Instantaneous lift force and wing deflection predictions from coupled aeroelastic simulation were compared with the force and deflection measurements (using Digital Image Correlation, DIC) obtained from in-house flapping wing experiments at both moderate and high flapping frequencies.

A coupled trim model is developed to predict the control inputs required for achieving force and moment equilibrium in hovering flight. Coupled trim analysis is performed by simultaneously solving wing response equations and vehicle trim equations until trim controls, wing response, inflow and circulation converge all together. The dependence of control inputs on weight and center of gravity (cg) location of the vehicle are studied for hovering flight case.

Graduated Students:

1. Justin Winslow, “Understanding of Low Reynolds Number Aerodynamics and Design of Micro Rotary-Wing Air Vehicles,” MS, 2016 (Flight Test Engineer at NAVAIR).
2. Atanu Halder, “Nonlinear Aeroelastic Coupled Trim Modeling of Cycloidal Rotor Based Micro Air Vehicle,” defended PhD in Feb’ 2019.
3. Xuan Yang, 5th year PhD student (Expected graduation: May 2020).

Journal Publications:

1. Benedict, M., Winslow, J., Hasnain, Z., and Chopra, I., “Experimental Investigation of Micro Air Vehicle Scale Helicopter Rotor in Hover,” *International Journal of Micro Air Vehicles*, Vol. 7, No. 3, October 2015, pp. 231–255.
2. Winslow, J., Benedict, M., Hrishikeshavan, V., and Chopra, I., “Design, Development and Flight Testing of a High Endurance Micro Quadrotor Helicopter,” *International Journal of Micro Air Vehicles*, Vol. 8, No. 3, September 2016, pp. 155–169.
3. Halder, A., Walther, C. M. & Benedict, M., “Hydrodynamic Modeling and Experimental Validation of a Cycloidal Propeller,” *Ocean Engineering*, Vol. 154, 15 April 2018, Pages 94–105.
4. Halder, A., and Benedict, M., “Role of Blade Flexibility on Cycloidal Rotor Hover Performance”, *Journal of Aircraft*, Vol. 55, No. 5 (2018), pp. 1773-1791.
5. Yang, X., Sudhir, A., Halder, A., and Benedict, M., “Nonlinear Aeroelastic Analysis for Highly Flexible Flapping Wing in Hover”, *Journal of the American Helicopter Society* (In review).

Publications in Conference Proceedings:

1. Benedict, M., Winslow, J., Hasnain, Z., and Chopra, I., “Performance and Flow field Measurements of a MAV-Scale Helicopter Rotor in Hover,” Proceedings of the 70th Annual National Forum of the American Helicopter Society, Montreal, Quebec, Canada, May 20–22, 2014.
2. Winslow, J., Benedict, M., Hrishikeshavan, V., and Chopra, I., “Design, Development and Flight Testing of a High Endurance Micro Quadrotor Helicopter,” Proceedings of the 6th American Helicopter Society International Specialists' Meeting On Unmanned Rotorcraft Systems, Chandler, AZ, January 20-22, 2015.
3. Halder, A., and Benedict, M., “Understanding the effect of Blade flexibility on Cycloidal Rotor Performance in Hover,” Proceedings of the American Helicopter Society Specialists' meeting on Aeromechanics, San Francisco, CA, Jan 20-22, 2016.
4. Yang, X., Sudhir, A. and Benedict M., “Nonlinear Aeroelastic Model for Highly Flexible Flapping Wings in Hover,” AHS 72nd Annual Forum, West Palm Beach, Florida, May 17–19, 2016.
5. Halder, A., and Benedict, M., “Nonlinear Aeroelastic Coupled Trim Analysis of a Cyclopter in Hover,” Proceedings of 73rd Annual Forum of the American Helicopter Society, Dallas, TX, May 9-11, 2017.
6. Yang, X., Sudhir, A., Halder, A., and Benedict, M., “Aeroelastic Analysis for Highly Flexible Flapping Wing in Hover,” Proceedings of 73rd Annual Forum of the American Helicopter Society, Dallas, TX, May 9-11, 2017.
7. Halder, A., Walther, C.M. & Benedict, M., “Unsteady Hydrodynamic Modeling of a Cycloidal Propeller”, Fifth International Symposium on Marine Propulsion, SMP’17, Espoo Finland, June 12-15, 2017.

8. Halder, A., and Benedict, M., "Nonlinear Aeroelastic Modeling of Cycloidal Rotor in Forward Flight," Proceedings of the AHS Technical Meeting on Aeromechanics Design for Transformative Vertical Lift, San Francisco, CA, Jan 16-18, 2018.
9. Yang, X. and Benedict M., "Nonlinear Aeroelastic Coupled Trim Analysis of Flapping Wing MAV in Hover," AHS International Technical Meeting, Aeromechanics Design for Transformative Vertical Flight, Jan. 2018, San Francisco, CA
10. Halder, A., and Benedict, M., "Nonlinear Aeroelastic Coupled Trim Analysis of a Cyclocopter in Forward Flight," Proceedings of 74th Annual Forum of the American Helicopter Society, Phoenix, AZ, May 14-17, 2018.

Task A-1.15 Noncontact Torque Sensor (2015-2017)

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Background:

It is desirable for torque measurement systems to meet certain demands such as being non-contact and passive to the shaft, compact and easy to install, accurate, sensitive and cost effective. Other factors include the ability to provide real-time measurements and minimal signal conditioning requirements. Most commercially available torque measurement systems require direct contact with rotating frame of reference and slip rings or wireless transfer from the rotating frame of reference to a fixed frame of reference. This project builds on preliminary studies of non-contact magnetic torque sensors. UMD has been pioneering use of sensors made using smart materials, and in particular of stress and strain sensors that use structural magnetostrictive materials and can be applied to composite shafts as well as traditional metal shafts. Magnetostrictive sensors provide a non-contact approach for detection and monitoring of torque-induced stress/strain states in a shaft, such as for a helicopter tail rotor or drivetrain and/or a ground vehicle driveshaft. Vibration signatures from gearboxes would also be sensed through this sensor; potentially reducing the number of sensors required (replacing existing or potential accelerometers and torque sensors).

The magnetostrictive alloys Galfenol (FeGa) and Alfenol (FeAl) show great promise for use in magnetostrictive torque sensors and would require only bonding of a thin patch of magnetostrictive material to a load bearing shaft, or potentially just applying a layer of paint containing flakes of these magnetostrictive alloys to a shaft. The output signal from a magnetostrictive sensor is obtained from a conventional, robust but low-cost magnetic field detector in a fixed frame of reference that tracks changes in the magnetic flux in the air above the rotating shaft where the magnetostrictive patch/paint has been applied. This is caused by stress/strain-induced changes in magnetic state of the magnetostrictive material when the shaft the material is bonded to is subjected to static and/or dynamics torque loads.

Research Objectives:

The objective was to further develop a concept for non-contact torque sensing system using rolled sheet magnetostrictive alloys, building on recent advances in structural magnetostrictive alloys, and to investigate how improved usage monitoring and sensing of multiple components can be accomplished. Here-to-fore, quasi-static tests of this concept have demonstrated that magnetic flux lines that leak into the air above a magnetostrictive layer will change in response to the torque-induced magnetic state change within the magnetostrictive material. Consistency of the data from test to test as well as acquisition of dynamic data were not been the focus of that work, and were the primary objectives of this task. A third focus was the exploration of a concept in which flakes of magnetostrictive material were mixed with epoxy to form a magnetostrictive paint. For this objective, we sought and successfully achieved a preliminary proof-of-concept experiment.

Approach:

The approach was to carry out both experiments and analysis. This involved generating benchmark data to help identify areas for improvement in the experimental method, analysis of the data and rectify them, and assimilation of experimental and analytical/computational results to provide a fundamental understanding of basic transduction mechanisms. Experimental studies were conducted on iron-gallium rolled sheet, in the shape of a rectangular patch and as a cylindrical sleeve forming an ~inch wide ring around the shaft, on iron-aluminum rolled sheet, also as a

rectangular patch and as a cylindrical sleeve/ring, and on a rectangular patch made of epoxy mixed with micron-sized flakes of wet ball-milled iron-gallium that was used to create a magnetostrictive paint. Analytical models of magnetostriction and stress, strain and magnetic field modeling using the finite element code COMSOL Multiphysics were used to aid in the interpretation of the performance of the non-contact magnetostrictive sensors.

(1) Measurement consistency: Based on variability in the measurements acquired from a prior student, time was devoted to establishing a reproducible bonding protocol that reliably produced good transfer of torque from the shaft surface to all of the magnetostrictive layer for the loads considered. The prior student had used the adhesive known as Crystalbond because it dried quickly and bonded patches could easily be removed with a heat gun. The VLRCOE-supported student examined the performance of six commercial adhesives, including Crystalbond, with Loctite 648 maximizing strain transfer in bending tests of bonding steel patches to a sheet of steel. In addition, the application protocol included the need to rough-up the shaft surface lightly with sand paper, to use a syringe to control the amount and “dot” size for application of Loctite 648 to the patches, and to the torque applied to the hose clamp used to affix the patch to the shaft during the two-hour long cure. The recommended bonding protocol is described in Chapter 3 of Mr. Muller’s MS thesis.

(2) Quasi-static and Dynamic System Analysis:

A baseline study was conducted to assess sensor output from randomized quasi-static loadings of +/-50, 100, 150 and 200 in-lb of torque. A similar range of loads were applied for a fully randomized study of output at rotation rates of 500, 1000, 1500 and 2000 rpm. The responses to quasi-static loads increased linearly for all cases except for the counterclockwise loading of the FeGa paint, which showed no response to loads. There was a slight asymmetry in the slope of the linear responses to clockwise and counterclockwise loading of a given sample, with the only the FeGa paint and the FeAl ring exhibiting a steeper slope, i.e. greater sensitivity, to clockwise loading/positive torques. The output from the FeGa paint was roughly one order of magnitude smaller than the output from the rolled sheet, and output from both FeGa and FeAl rolled sheet was similar, with the FeAl patch exhibiting slightly more output than the FeAl ring and the FeGa patch and ring. With the benefit of modeling, this asymmetry was attributed to slight variations in the initial magnetic bias states of the different samples. This explanation is further supported by recent experiments as part of an undergraduate honors thesis in which the use of a weaker biasing magnet produced an order of magnitude greater output in FeGa paint when loaded with a positive torque, now similar to the output of rolled sheet, and with slightly weaker sensitivity in response to counter-clockwise loads. Dynamic testing achieved greater output than in the past, but exhibited more noise than the quasi-static tests. These results are presented in Chapters 4 and 5 of Mr. Muller’s MS thesis, as well as our recent (2019) AIP paper.

(3) Fundamental understanding: FeGa alloys are almost twice as magnetostrictive as much lower cost FeAl alloys (saturation magnetostrictions of 380 microstrain in FeGa and 180 microstrain in FeAl). However, their saturation magnetization values are similar; with saturation magnetization of ~1.6 Tesla in FeGa and of ~1.4 Tesla in FeAl. Even though FeAl alloys have not received much attention in the field of smart materials, this work successfully demonstrated similar performance from both alloys when operating as a non-contact torque sensor, illustrating for sensor and in turn energy harvester designs choice of material selection should be saturation magnetization, and not

saturation magnetostriction as is often done. The post-doctoral research, Dr. Na, worked on fabrication and characterization of FeAl alloys (our 2017 AIP paper) and developed the procedure for making micron-thick oriented flakes of FeGa alloy and then developing and testing paints with a range of fill ratios of flakes in toluene epoxy. The 1:1 fill ratio was painted into a rectangular patch on the shaft for torque sensing studies.

Accomplishments (Years 2015-17):

In year 4 of the effort a reliable and reproducible protocol for bonding rolled sheet to shafts was developed. Fundamental advances in the fabrication of rolled sheet FeAl alloys were made, and the successful demonstration of a novel FeGa-flake-based paint was demonstrated. Testing of non-contact torque sensing under quasi-static loading conditions was undertaken, and software for efficient gathering of data using matlab scripts was put in place. The focus of the Year 5 effort was on dynamic testing, and material characterization studies that included testing under a range of compressive and shear/torsion load conditions.

Supported Students:

1. Brooks Muller, "Characterizing the quasi-static and dynamic response of a non-contact magneto-elastic torque sensor," MS, May 2017 (Systems Engineer at Orbital ATK).
2. Dr. Souk Min Na, Post-Doctoral Researcher (Metallurgist/Research Engineer at the Naval Surface Warfare Center/Carderock Division)

Publications:

1. Muller, B. "Characterizing the quasi-static and dynamic response of a non-contact magneto-elastic torque sensor," MS thesis, Univ. Maryland, (2017) <http://hdl.handle.net/1903/19808>
2. Downing, J.R., Na, S-M. and Flatau, A, "Compressive pre-stress effects on magnetostrictive behaviors of highly textured Galfenol and Alfenol thin sheets," *AIP Advances* **7**, 056420 (2017) <https://doi.org/10.1063/1.4974064>
3. Muller, B., VanOrder, M, Na, S.-M. and Flatau, A., "Alfenol Patch-, Galfenol Patch- and Galfenol Paint-Based Torque Sensor Characterization Studies," *AIP Advances* **9**, 045113 (2019) <https://doi.org/10.1063/1.5080140>