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14. ABSTRACT
The MURI team has started to undertake a carefully planned program of research, including the development of efficacious predictive models for the physical elements that may contribute to the brownout problem. This goal will be achieved by better understanding rotor and airframe aerodynamics when operating in ground effect, as well as how the interaction of rotor wake vortices with the sediment bed occurs, the particulate uplift processes, and the two-phase fluid transport physics. The topic of the present MURI also specifically addresses piloting problems, so proper characterization of brownout clouds will be undertaken based on their optical properties. As the research progresses, brownout mitigation processes using rotorcraft design optimization techniques will then be undertaken using the validated computational methods.

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"Rotorcraft Brownout: Advanced Understanding, Control, and Mitigation"

1st Progress Report
August 1, 2008 – November 31, 2008

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This multidisciplinary research investigation has been designed to accelerate the understanding and mitigation of "brownout" for rotorcraft operations in austere environments. This progress report represents the first report since the award was made by AFOSR in August 2008. The next progress report will cover the period December 1, 2008 through March 31, 2009, and quarterly reports will follow thereafter. In this MURI project, the University of Maryland (Departments of Aerospace Engineering and Mechanical Engineering) is partnered with researchers at Arizona State University, Iowa State University, and Dartmouth College.

The problem of brownout is characterized by heavy dust suspension that is uplifted during rotorcraft operations in austere environments. Brownout can obscure the pilot's view, and significantly degrades or eliminates visual cues. The uplift and suspension of a sediment dust cloud is known to differ substantially from rotorcraft to rotorcraft; it is a fundamentally complex physical phenomenon because it can potentially be affected by several interdependent parameters, including but not limited to, disk loading, blade loading, number and placement of rotors, number of blades, blade twist, blade tip shape, fuselage shape, as well as surface type and condition.

The MURI team is now starting to undertake a carefully planned program of research, including the development of efficacious predictive models for the physical elements that may contribute to the brownout problem. This goal will be achieved by better understanding rotor and airframe aerodynamics when operating in ground effect, as well as how the interaction of rotor wake vortices with the sediment bed occurs, the particulate uplift processes, and the two-phase fluid transport physics. The topic of the present MURI also specifically addresses piloting problems, so proper characterization of brownout clouds will be undertaken based on their optical properties. As the research progresses, brownout mitigation processes using rotorcraft design optimization techniques will then be undertaken using the validated computational methods.

In this MURI, a comprehensive interdisciplinary research program with 12 sub-tasks (see table on next page) led by specialist researchers, is being undertaken to provide advances in the state of the art of understanding brownout problems, and in the development of a rational methodology to predict the effects of brownout. The team is undertaking the planned research with the following overall goals: 1) A detailed physical understanding of vortex wake-induced sediment uplift and two-phase flow physics; 2) Rigorous methods for quantifying rotorcraft brownout problems, including optical metrics; 3) A systematic design methodology for rotorcraft brownout mitigation and control; 4) Proper identification of the key rotorcraft design parameters for achieving reduced brownout signatures; 5) A detailed physical understanding of the overall mechanisms of action of these parameters, including mutual interactions. Mitigation requires the synergistic use of multiple solution techniques and numerical methods, and the team will begin to develop a methodology that is capable of integrating these solutions and highlighting their physical couplings. Finally, while focusing on brownout mitigation as the major objective, additional requirements such as performance, vibrations, aircraft handling qualities, etc., will be examined using existing rotorcraft analyses developed at the University of Maryland. The team will conduct systematic validation of predicted results for actual rotorcraft when encountering brownout flight conditions, and will demonstrate the efficacy of the computational models that are developed.

The following pages give a brief update of progress thus far on each sub-task. Notice that shortly after the award, Dr. Piomelli took a faculty position at Queen's University in Canada (but will continue to work on his task), and Dr. Ramasamy took a position as a Research Scientist at NASA Ames Research Center. As a result, there has been some minor restructuring of the research tasks.

Primary Research Tasks	Research Sub-Tasks	Interactions	Task Leaders	Graduate Students
Part 1. Fundamentals of Rotor and Airframe Aerodynamics in Ground Effect Operations	1.1 Measurements of Rotor and Fuselage Aerodynamics in Ground Effect	1.2, 1.3, 2.2, 2.3	Leishman, Ramasamy	1
	1.2 High Fidelity Vorticity Generation and Preservation in Ground Effect	1.1, 1.3, 2.3, 2.4, 2.5	Baeder, Chopra	1
	1.3 Fuselage Configuration Effects on Rotorwash and Brownout	1.1, 1.2, 2.2	Rajagopolan, Baeder	1
Part 2. Fundamentals of Particle Suspension	2.1 Non-Uniform, Near-Bed Flow Field Associated With Impinging Rotor Wash	2.2, 2.3, 2.4, 2.5	Dade, Cushman-Roisin	1
	2.2 Dual-Plane Stereoscopic PIV in Two-Phase Near-Wall Bounded Turbulent Flows	2.1, 2.3, 3.1	Ramasamy, Leishman, Kiger	1
	2.3 Fundamental Two-Phase Measurements in Brownout Fluid Mechanics	2.2, 2.4, 2.5	Kiger, Ramasamy, Leishman	2
	2.4 Large-Eddy Simulation of the Interaction Between Wake Vortices and Ground	1.2, 2.1, 2.2, 2.3, 2.5	Piomelli	1
	2.5 Two-Phase Large-Eddy Simulation Based on the Mesoscopic Eulerian Formalism	1.2, 2.1, 2.2, 2.3, 2.4	Squires	1
Part 3. Brownout Synthesis Mitigation and Validation	3.1 Optical Characterization of Brownout Clouds	3.2, 3.3, 3.4	Celi, Leishman	1
	3.2 Development of Numerically Efficient Airborne Sediment Tracking Algorithms	3.1, 3.3, 3.4	Leishman, Celi, Baeder	1
	3.3 Understanding Brownout and Developing Mitigation and Control Strategies	All	Celi, Leishman, Baeder, Chopra	2
	3.4 ABATE Simulation Framework and Validation	All	Baeder, Celi, Chopra, Leishman	1

Task 1.1 – Measurements of Rotor and Fuselage Aerodynamics in Ground Effect

Investigator(s): **Dr. J. Gordon Leishman**
Institution/Department: **University of Maryland, Dept. of Aerospace Engineering**
Graduate Student(s): **Joe Milluzzo, Bradley Johnson, Timothy Lee**
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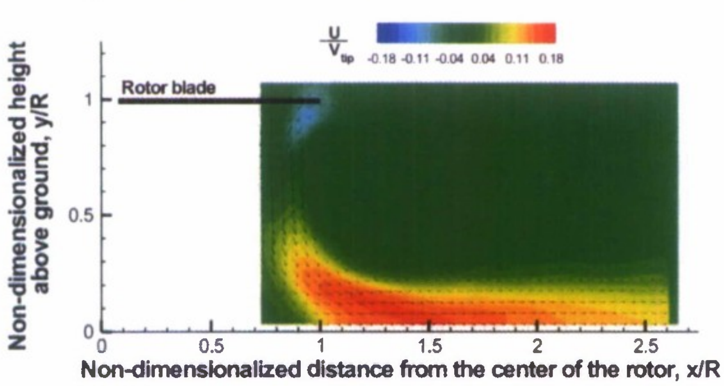
Background and Technical Challenges: As helicopter rotors come within two diameters of solid boundaries, the velocities in the rotor flow are altered, and the embedded wake vortices undergo a series of complex interactions as they convect down and reach these boundaries. These vortices may merge to produce regions of flow recirculation with high average flow velocities. The magnitude of the velocities at the ground level (i.e., the "groundwash") is related to rotor disk loading and to the strengths and structure of the blade tip vortices, which in turn, depends on average rotor blade loading. It is also known that the flows inside the tip vortices are affected by blade twist and tip shape. In all cases, when the tip vortices reach the ground boundaries and interact, these zones of recirculation form inside a radially expanding "jet-like" turbulent boundary layer, which may contain peak velocities that are several times higher than the average flow velocity below the rotor. A key issue in understanding the phenomenon of brownout is in understanding the fluid dynamics of the blade tip vortices as they impinge on the ground, and relating the resulting effects (velocities, turbulence, surface shear, etc.) to the rotor design parameters.

Technical Approach: The goals of this research are to: 1) Measure the effects of key rotor design changes on the blade tip vortex structures, including the turbulence and Reynolds stresses within the vortex cores; 2) Understand the details of the flow as these vortices interact and impinge on the ground plane surface. There have been no previous flow measurements of this problem, and the outcomes will further the physical understanding of ground effect aerodynamics and give an unprecedented set of measurements for validation (i.e., with free-vortex wakes, LES, RANS, etc.)

Progress in Last Quarter: Preliminary experiments have been conducted using flow visualization and phase-resolved particle image velocimetry (PIV) to examine the fluid dynamics of a rotor wake as it interacts with a horizontal ground plane. The experiments were conducted using a small rotor with a plane that could be moved to as close as 25% of the rotor radius to the rotor plane.



Visualization of the rotor wake and the wake/ground interactions was performed by illuminating a smoke seeded flow using a Nd:YAG laser sheet, phase-locked to the rotational frequency of the rotor. Two-component PIV measurements were obtained at four rotor heights off the ground. Measurements at several wake ages were obtained to examine the dynamic features of the wake/surface interaction process. The initial results have shown that the overall downwash induced by the rotor initially becomes an unsteady radial wall jet that is defined between the ground and the rotor wake boundary. The viscous processes of diffusion, vortex straining, and turbulence generation have been shown to be significant factors in understanding the fluid dynamics of the resulting flow. At the higher rotor heights, the vortices were seen to diffuse before they reached the ground. At the lower rotor heights, vortex stretching countered the effects of diffusion but turbulence in the developing wall jet sheared the vortices, accelerating their diffusion. The tip vortices still created substantial unsteady shear stresses on the ground, in some cases exceeding twice the time-averaged values. An intermediate rotor height was found to produce the highest flow velocities at the ground. Corresponding measurements of performance showed the expected reduction in rotor power and an increase in its thrust for in-ground-effect operations.

Anticipated Progress in Next Quarter: We will continue to make measurements of rotor wakes near a ground plane. To this end, we have begun to examine the methods of controlling surface reflections by using a rhodamine dye, which is painted onto the ground plane. The rhodamine has allowed PIV measurements to be performed well into the boundary layer, and offers good prospects for giving improved PIV measurements. A paper on this topic is under preparation, which will include some preliminary measurements of sediment uplift, and will be presented at a conference in 2009 (see below).

Papers Published:
1. Lee, T. E., Leishman, J. G., and Ramasamy, R., "Fluid Dynamics of Interacting Blade Tip Vortices With a Ground Plane," Presented at the 64th Annual Forum of the American Helicopter Society, Montreal, Canada, April 29–May 1, 2008. (Accepted for publication in the Journal of the American Helicopter Society.)
2. Johnson, B., and Leishman, J. G., "Measurements of Rotor Wake Flows and Sediment Uplift at Planar Interfaces Using PIV," For publication and presentation at the 65th American Helicopter Society Annual Forum & Technology Display, May 27–May 29, 2009, Gaylord Texan Convention Center, Grapevine, Texas.

Technical Interactions: Technical interactions with members of the MURI group.

Task 1.2 – High Fidelity Vorticity Generation and Preservation in Ground Effect

Investigator(s): **Dr. James Baeder, Dr. Shreyas Ananthan**
Institution/Department: **University of Maryland, Dept. of Aerospace Engineering**
Graduate Student(s): **Sebastian Thomas**
Contact email(s): ***baeder@umd.edu, sthomas2@umd.edu***

Background and Technical Challenges: The key to a better understanding of the brownout problem is the capability to accurately predict the induced velocity field near the ground plane below the rotor disk. To obtain reliable predictions of the velocity field, the vortices shed and trailed from the rotor blades need to be accurately tracked and convected from the rotor plane all the way to the ground plane. Furthermore, the distortions of the vorticity field in the presence of the helicopter fuselage, empennage, and the tail rotor, etc. all need to be accounted for to provide a realistic description of the shape, trajectory, and the induced velocity field of the blade vortices. While Lagrangian free-vortex methods can track vorticity to long times and distances, most vortex-based computational methods are essentially inviscid in nature, and, therefore, cannot account for the generation, evolution, and rollup of the vortex sheet behind the rotor into rotor tip and root vortices. A first-principled based CFD methodology is necessary to compute the viscous boundary layer near the rotor blade to determine the strength of the vortex sheet trailed behind the rotor blades. This near-blade flow solver must be coupled with a blade computational structural dynamics (CSD) solver to determine the positions of the vortex sheets trailed from the blades. The CSD solver accounts for the geometric deformation of the rotor blades primarily from flap, lag, and torsion. High-fidelity computation of the vorticity field associated with a lifting blade requires accurate prediction of the viscous boundary layer near the blade surface. The computational complexity of the problem increases quickly with the increasing number of grid points, and can become uneconomical unless some clever strategies are not adopted to reduce these costs. With the advent of cheap parallel computing clusters, parallel solvers using Message Passing Interface (MPI) has become an attractive option for CFD solvers capable of solving flow fields on several millions of grid points.

Technical Approach: High-fidelity vorticity generation and preservation computational methods need to be capable of predicting: 1. The vortex sheet creation and evolution near the blade surfaces; 2. The blade geometric deformations from elastic flap, lag, and torsion bending; 3. The convection and diffusion of the wake vortices under the self- and mutually-induced velocity field of the wake. These individual solvers need to be coupled consistently in a time-accurate manner at each time step to model a rotor system in ground effect, and so to determine the effects of the three-dimensional unsteady transonic elastic rotor aeromechanics on the resulting unsteady downwash at the ground. The effect of the rotor wake vortices will be included in the near-blade solution using a field velocity approach. The blade deformations will be accounted for by deforming the blade computational mesh such that the computational surface geometry conforms to the deformed blade geometry as computed by the CSD solver. The coupling is achieved using the ABATE framework (Task 3.4) where the individual solvers are "Python-wrapped" into individual modules that can be then coupled using a solver script written in Python. The advantage of this approach is that the solvers can be developed and validated individually without affecting the other participating solvers. The primary bottleneck in the rotor aeromechanic computations is the time required to calculate the near-blade flow solution using grid-based Navier-Stokes solvers. As mentioned previously, parallelizing the solvers using MPI allows scalable performance for several millions of grid points. The objective in this approach is to split the computational domain into smaller sub-domains, and solve these sub-domains on different processors. Periodically (typically at the end of each time step or sub-iteration), the information between the processors is *communicated* to the other processors to allow for the evolution of the flow field. The computational costs associated with this communication step can result in diminishing returns with an increasing number of processors. To achieve scalability across number of processors and grid points, sufficient care must be taken during the domain decomposition process to allow for proper *load balancing* between the processors. Furthermore, it is preferable that the domain decomposition process happens without much user intervention; not just from an end-user perspective but also because this can allow future enhancements using strategies such as adaptive grid refinement and dynamic load re-balancing.

Progress in Last Quarter: The objective of the recent research has been to develop a scalable, parallel version of the Reynolds-averaged Transonic Unsteady Rotor Navier-Stokes (TURNS) CFD solver. TURNS uses a structured mesh around the blade to solve for the near-body flow field. Currently a C-O mesh hyperbolic mesh topology, with approximately 4.3 million grid points (257x257x65) is used to model the blade and its surrounding region. Different domain decomposition (mesh splitting) strategies are being studied to understand the trade-offs involved between the computational time spent in the solver as well as the time required for MPI communications. Two different strategies: 1. Splitting along the blade span, and 2. Splitting along the blade chord, have been investigated. It was observed that the decomposition along the blade span provided a nearly linear speed up of the problem (up to 8 processors) in comparison to the runtime necessary for a single processor, without any loss of accuracy in the final solution. With a larger number of processors the cost of MPI communications across processors was found to more than offset the gains from solving lower number of mesh points per processor. Similar trends were observed for the splitting along the chordwise direction on a 2-D mesh geometry.

Anticipated Progress in Next Quarter: Based on the results of the spanwise and chordwise domain decomposition studies, it is obvious that the scalability of 1-dimensional decomposition is limited to the number of mesh points along that direction. This scalability can be improved by splitting the mesh along both directions, thereby allowing the use of a larger number of processors. However, with this multi-dimensional decomposition strategy, the data structures necessary to track the neighboring mesh blocks and the resulting data transfer logistics, can get complicated and must be carefully designed. Future research will concentrate on combining the spanwise and chordwise domain decomposition strategies, and in developing an automated domain decomposition strategy that can perform load balancing at runtime without much user intervention.

Papers Published: None yet.

Technical Interactions: Normal technical interactions with members of the MURI group.

Task 1.3 – Fuselage Configuration Effects on Rotorwash and Brownout

Investigator(s): **Dr. R. Ganesh Rajagopalan**
Institution/Department: **Department of Aerospace Engineering, Iowa State University**
Graduate Student(s): **Sayan Ghosh**
Contact email(s): **rajagopa@iastate.edu**

Background and Technical Challenges: Rotorcraft brownout is an in-flight visibility restriction caused by clouds of sand and dust particles during landing, take off and near ground flight operations in arid desert terrain. This complex phenomenon is caused by entrainment of dust, sand and ground particles by rotor downwash and is compounded by fuselage geometry and its orientation with respect to the ground. Nonlinear forces and moments on the fuselage and highly unsteady wind velocities are common in near ground operations and play a significant role in the behaviour of the particulate clouds that create the brownout condition.

Technical Approach: The main objective is to develope an efficient CFD based tool for predicting and analysing the dust cloud formation and the kinematics in the vicinity of a single or multiple rotor aircraft operating near the ground. The proposed research is novel, in that it integrates the rotor downwash and the ground interference in a coupled viscous solution procedure wherein the rotor blades are modeled as unsteady momentum sources. The emphasis of this simulation approach will be on the global flow field rather than on the flow near the rotor blades themselves. To reduce the burden on the grid generation on complex geometries, Cartesian grids and its simplicity will be exploited. Initially, the single zone structured grid will be used to expedite the understanding of the issues involved with the physics of the simulation, followed by a more accurate representation of the geometry by using an unstructured Cartesian grid topology. Similarly, the fluid representation will follow a two pronged approach. Initially the coupling between the rotorwash and the particles will be assumed to be one-way, in that the particle loading is small enough that the rotor downwash will not be affected by the presence of the particles. In the ensuing phase of the simulation, the coupling will be considered as a two phase fluid, where the particle-particle interactions near the ground may dominate the process and dictate the outcomes of the simulation. The flow field of an unsteady, turbulent, flow is governed by the Reynolds-averaged Navier-Stokes equations. The action of the rotor blades are modeled by the source terms of the momentum equations. The numerical algorithm for solving the governing equations of the flow is based on the SIMPLER algorithm. In a specific number of computational cells through which the rotor blades pass, the source terms from to the rotor are evaluated and added to the discretized momentum equations. The turbulent viscous flow field generated will be processed to obtain the shear stress field on the ground, and used as an input to the algorithms for determining particulate lofting, particulate concentration, particulate trajectory and cloud formation.

Progress in Last Quarter: A simplified three-dimensional unsteady, incompressible, laminar, Navier-Stokes solver has been developed in a Cartesian coordinate system. The solver will be used as a platform for implementing and testing different models of turbulence, rotor source effects, multiphase granular flow, and particle dynamics. This test bed will be to help facilitate selecting appropriate models for the rotor brownout problem. In the solver, the governing flow equations are solved using a finite-volume based method known as SIMPLER. In this algorithm, the flow field is determined by solving for primitive variables, namely the static pressure and the velocity vector, directly from the mass and momentum conservation equations. The discretized conservation equations are solved by line-by-line method that is a combination of a TriDiagonal–Matrix Algorithm and the Gauss Seidel iterative method. The overall steps of SIMPLER algorithm can be summarized as:

1. Guess velocity field,
2. Calculate the momentum and pressure equation coefficient,
3. Solve pressure equation,
4. Solve momentum equation,
5. Solve pressure correction equation and correct the velocity field.

The steps are repeated until convergence is reached. To validate, the solver has been used to simulate three-dimensional flows inside a lid driven square cavity for a range of Reynolds numbers. Excellent agreement has been obtained in comparing the steady state solution with the results available in the literature.

Anticipated Progress in Next Quarter: Implementing and testing rotor source modeling in the 3-D flow solver. Implementing and testing turbulence modeling in the 3-D flow solver.

Technical Interactions: A short course on 'Particle Entrainment – Physics and Modeling' is being presented by Dr. James Iversen, Professor Emeritus of Department of Aerospace Engineering, Iowa State University. *Dr. Iversen started working in the field of Particle Entrainment in 1971, when the Mariner 9 spacecraft started orbiting Mars. Dr. Iversen authored many papers related to particle transport and is considered as an international expert in the field.* The short course has been a great help in learning and understanding the basic physics of particle entrainment. Further guidance and technical aid is being expected from Dr. Iversen in the problems related to rotorcraft brownout. His experience in the field of Particle Entrainment will be valuable in formulating the process, algorithm and modeling of particulate lofting, particulate concentration, particulate trajectory and cloud formation.

Task 2.1 – Non-Noniform, Near-Bed Flow Field Associated with Impinging Rotor Wash

Investigator(s): **Brian Dade, Benoit Cushman Roisin**
Institution/Department: **Dartmouth College/Earth Sciences**
Graduate Student(s): **(in recruitment stage)**
Contact email(s): **W.B.Dade@dartmouth.edu**

Background and Technical Challenges: Micrometer-sized particles make up the dust in potential brownouts expected in some settings of strategic interest. Such materials are significantly smaller than the sand-sized particles now under study, and are subject to cohesive behavior even in the absence of significant soil moisture. We aim to extend our ongoing laboratory research to the study of fine-grained soils comprising silt and cohesive clays systematically subjected to known moisture contents. The goals of our research are thus: i) To provide heretofore unavailable observations of the non-uniform, near-bed flow field associated with impinging rotor or jet wash for the validation of numerical models of rotor- and jet-wash flows; ii) To provide relevant boundary conditions for sediment entrainment under such flows to constrain numerical models of rotor- and jet-wash generated brownout.

Technical Approach: The wind-tunnel facility to be used in our research is located at CRREL, in close proximity to Dartmouth College. Using this facility, we are now assessing the non-uniform spatial structure of near-bed mean flow speed, Reynolds stress, and associated erosion of an underlying sediment bed. Evaluation of the spatial structure of an impinging flow of known source intensity is achieved with a 3D hot-wire anemometer. Following exposure of a bed to a flow for a known amount of time, changes in topography of a granular bed of known properties is evaluated to yield the spatial pattern of sediment entrainment and transport at the bed. These measurements arc made to better than millimeter-precision with a laser profilometer. Both profiler and anemometer are mounted on an automated gantry positioned over the test bed. All equipment is in place, and experiments have been successfully run. Physics-based relationships between flow properties and sediment flux are now being evaluated for sand-sized material, and a manuscript for peer-reviewed publication is in preparation. We will undertake complementary studies of cohesive clay and silt beds subjected to known moisture contents. Initially, we propose to examine beds comprising well-sorted silica silt (with median grain size $d_{50} = 50$ μm), well-sorted kaolinite clay ($d_{50} \leq 10$ μm) and well-characterized mixtures of these two end-member materials. Each bed would be subjected to systematic and well-characterized moisture contents (e.g., 0%, 10%, 20%, etc, by weight). Natural soils from one-or-more field sites of interest could easily be accommodated within the scope of this research and as opportunities develop. Assessment of the properties of all fine-grained beds considered, including their granulometry, clay contents and mineralogical compositions, moisture contents and bed surface rheology, will be carried out using Dartmouth facilities already in place.

Progress in Last Quarter: Initial milestones the experimental component of this project include:

i) Recruitment and initial training of a student to undertake proposed laboratory research,
ii) Purchase of a computer for student analysis of experimental data,

iii) Altering the wind tunnel facility at ACE CRREL to serve our experimental aims,
iv) Purchase of equipment to upgrade the wind-tunnel anemometry system,
v) Purchase of materials (particles) for use in wind tunnel experiments.

Work in the wind-tunnel facility will commence in January 2009, and a computer will be purchased in December in anticipation of his arrival. Discussions with our colleagues at CRREL toward achieving milestones (iii)-(v) are now in progress, and we are working toward completion by end of the calendar year.

Anticipated Progress in Next Quarter: We aim to successfully recruit and initiate training of student undertaking laboratory research during Winter 2009.

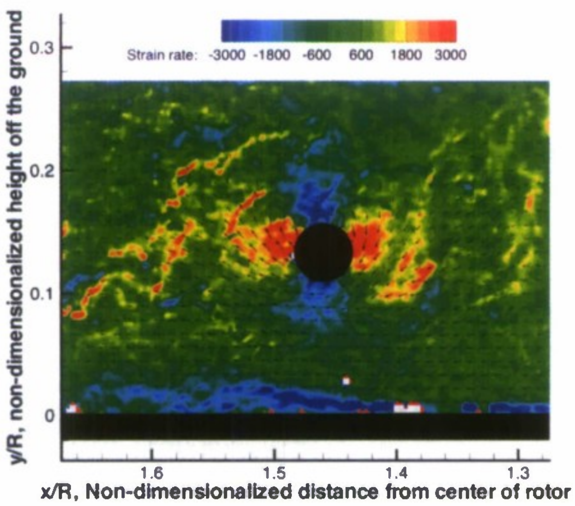
Papers Published: None.

Technical Interactions: A representative of the Dartmouth College team plans to attend an initial meeting with the MURI team.

Task 2.2 – Dual-Plane Stereoscopic PIV in Two-Phase Near-Wall Bounded Turbulent Flows

Investigator(s): **Dr. Manikandan Ramasamy, Dr. J. Gordon Leishman**
Institution/Department: **University of Maryland, Dept. of Aerospace Engineering**
Graduate Student(s): **Bradley Johnson, Joe Milluzzo**
Contact email(s): ***leishman@umd.edu***

Background and Technical Challenges: The understanding of helicopter wake vortices becomes more difficult when they approach and impinge on the ground. The resulting flow has steeply embedded velocity gradients associated with individual tip vortices, vortex bundling, and flow recirculation. The two-phase fluid nature of the problem becomes important because sediment can be quickly uplifted by the scouring action of the vortex-induced flows. This is a primary two-phase fluid mechanics mechanism that can lead to brownout. The ability to understand this process is fundamental for understanding how to mitigate the problem of brownout through changes to the rotor or airframe design, such as by downwash minimization and/or by tip vortex alleviation.



Technical Approach: The objectives of this task are to use particle image velocimetry (PIV) to understand how the turbulent evolutionary properties of vortices change as they approach and interact with a ground surface. Measurements in both single-phase (carrier flow only) and two-phase flow (with uplifted particles) will be performed using an existing small-scale rotor over a wide range of rotor operating conditions and wake ages to obtain the mean velocity components in the vortex flows, their gradients, and their turbulent fluctuations. In the proposed work, about half of the vortex turbulence measurements will be performed in the dust chamber (Task 2.3) using the same spectrum of particle sizes, with the other experiments being performed in the rotor test cell. The idea is that the interrogation of the images using appropriate PIV analysis software allows for the discrimination and simultaneous resolution of the velocities of both the suspended sediment particles and the background carrier flow.

Progress in Last Quarter: The feasibility of studying the characteristics of the blade tip vortices generated by a hovering rotor were studied using dual-plane particle image velocimetry (DPS-PIV) system as well as time-resolved PIV. The DPS-PIV method is based on coincident flow measurements made over two differentially spaced laser sheet planes. A polarization-based approach was used in which the two laser sheets are given orthogonal polarizations, with filters and beam-splitting optical cubes placed so that the cameras image Mie scattered light from only one or other of the laser sheets. The digital processing of the images used a deformation grid correlation algorithm optimized for the high velocity gradient and small-scale turbulent flows found inside blade tip vortices. A paper has been published on these studies. We have also begun to look into time-resolved PIV. Some initial results showing the uplift of sediment from a planar bed have been obtained using the time-resolved PIV system.

Anticipated Progress in Next Quarter: There are numerous issues in making these types of PIV measurements, and we will continue to look at the methods and their value for studying the brownout problem.

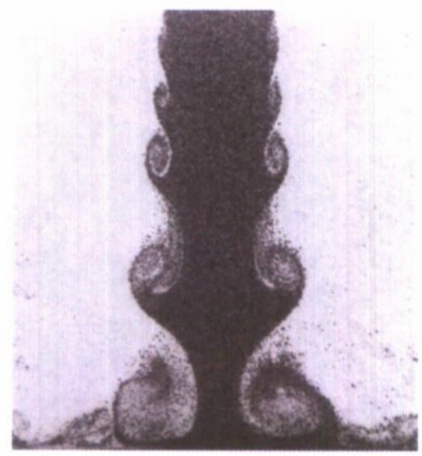
Papers Published:
1. Ramasamy, M., Johnson, B., Leishman, J. G., "Turbulent Tip Vortex Measurements Using Dual-Plane Digital Particle Image Velocimetry," Presented at the 64th Annual National Forum of the American Helicopter Society, Inc., April 29–May 1, 2008, Montreal, Canada. (Accepted for publication in the AIAA Journal.)
2. Johnson, B., and Leishman, J. G., "Measurements of Rotor Wake Flows and Sediment Uplift at Planar Interfaces Using PIV", For publication and presentation at the 65th American Helicopter Society Annual Forum & Technology Display, May 27–May 29, 2009, at the Gaylord Texan Convention Center, Grapevine, Texas.

Technical Interactions: None at this point.

Task 2.3 – Fundamental Two-Phase Measurements in Brownout Fluid Mechanics

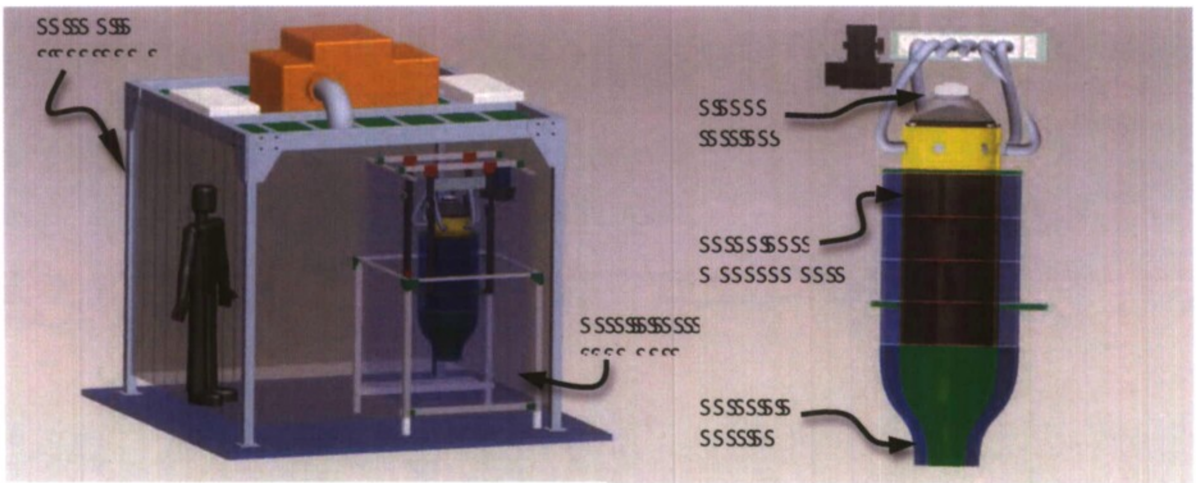
Investigator(s): **Ken Kiger**
Institution/Department: **University of Maryland/Department of Mechanical Engineering**
Graduate Student(s): **Daniel Fornia (Intern from Fachhochschule Mannheim), Jayson Geiser (undergraduate)**
Contact email(s): ***kkiger@umd.edu***

Background and Technical Challenges: Important fundamental issues that need to be understood for the construction and implementation of accurate brownout models include: 1) What is the appropriateness of existing saltation models, and how should they (or can they) be modified to account for non-equilibrium flux, particle collisions, etc.? 2) How do scour events by the vortex structures create substantive changes in bed topography? 3) How can high-loading effects be accounted for in the modeling of particle suspensions? Given the intense nature of rotorcraft wakes, scouring and direct suspension is expected, likely producing a sufficiently high loading within the boundary layer to make two-way coupling (particle/fluid) and possible four-way coupling (particle-particle collisions) significant. To make progress in the prediction of particle suspension and sedimentation within coupled particle-laden flows relevant to the problem of rotorcraft brownout, detailed characterization of the micro-scale mechanics is needed within a prototypical flow that captures the essence of the rotorcraft/ground wake interactions. Answers to the above questions will require detailed dynamic characterization of the local particle concentration and velocity statistics relative to the large-scale turbulent vortical structures that are inherent characteristics of brownout flow fields. Such measures can be used to obtain local particle flux in response to turbulent fluid stresses, while further details on the coupling can be derived from measures of the particle to fluid velocity cross-correlations. The challenges involved in obtaining this type of information are numerous: 1) Well-controlled particle characteristics are needed in order to generate repeatability in the experiments, as the suspension characteristics are know to be sensitive to shape, surface roughness, triboelectric charging, and moisture levels; 2) Making reliable high-resolution simultaneous two-phase measurements is not a trivial task, as care must be taken to ensure proper phase discrimination, accurate determination of the effective detection volume and adapt to high concentration and glare near the mobile bed boundary.



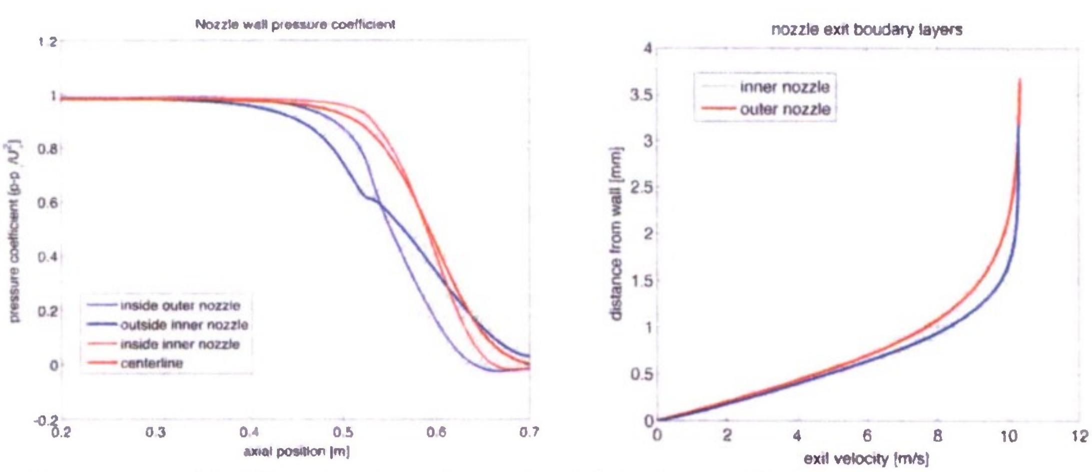
Technical Approach: To achieve the above goals, several highly detailed experiments are planned in a controlled-environment dust chamber in the presences of a prototypical flow that captures the essential features of the rotorcraft wake in ground effect. The prototypical flow will consist of a forced co-annular jet impinging on a mobile sediment bed. This configuration will allow for the generation of coherent vortex rings embedded within a stagnation point flow. Unlike in a single nozzle flow, the co-annular configuration will allow an embedded vortex to be spontaneously generated through pneumatic forcing of the inner jet. Depending on the forcing signal, single or multiple vortex structures of arbitrary strength could be generated and allowed to interact with the stagnating wall flow, providing for the same essential features of radial vortex stretching and vortex/wall interaction. The particles used for the studies will primarily consist of well-sorted borosilicate glass spheres (standard sieve sizes to within ±15% of the mean diameter). Under several select tests, two size classes may be used to study the effects of adhesion and saltation impact on the particle suspension process. The adhesive properties of the material will be modified through several means: 1) Control of humidity level within the test chamber; 2) Surface treatment of the glass spheres (hydrophilic or hydrophobic coatings); 3) Charge neutralization to prevent long-term changes in bed mobilization thresholds due to triboelectric charging. Quantitative measurements of the particle suspension and corresponding fluid velocity will be conducted through a combination of high-speed imaging and fluorescent two-phase particle imaging velocimetry. The high-speed imaging will be conducted under both general continuous illumination and laser sheet conditions to observe the instantaneous evolution of single events. In addition, the repeatable generation of a single vortex structure using the applied forcing will allow for the effective reconstruction of single event at different phases of the cycle, using slower conventional illumination. The two-phase PIV imaging will be conducted using a dual camera fluorescent technique. In this method, micron-sized fluorescent droplets will be imaged through a long-wavelength filter to measure the motion of the gas phase, while direct scatter from the dispersed phase will provide information about the sediment particles. Simultaneous imaging in this manner is flexible enough to provide a clear image of both phases with minimal cross-talk between the two phases.

Progress in Last Quarter:



Schematic of dust chamber test facility and softwall cleanroom with details of the co-axial jet.

This quarter's efforts have been devoted to designing the test facility required for the dust suspension experiments. Specifically, a custom co-axial nozzle and jet plenum is nearing completion of design and specification phase. Toward this end, the contour of the axisymmetric dual nozzle has been determined using a set of matched cubics to provide favorable pressure gradients throughout its length. This provides for attached flow throughout, and an exit boundary layer level thickness of approximately 1.5 to 1.8 mm at the nozzle exit. The design contour was checked through the use of the commercial CFD software, Fluent, to confirm the wall pressure gradients and evolution of the wall boundary layer was within the anticipated range.



Wall pressure coefficients and exit boundary layer profiles calculated for proposed nozzle design.

The co-annular nozzle will be connected to a co-axial housing, which consists of a turbulence management section, inlet plenum and forcing system. The turbulence management consists of two screens and a honeycomb section downstream of the inlet plenum. At the apex of the housing, a 1.5 kW subwoofer will be connected to central plenum chamber to provide the oscillatory forcing needed to generate the coherent vortex ring embedded within the stagnation flow. These components have all been sized, but the exact fabrication details are still in progress. Appropriate materials and quotations for the fabrication of the nozzle are also in progress.

Anticipated Progress in Next Quarter: During the next quarter, we plan to finish the design of the test facility and have initiated the construction phase. This will include sending the nozzles out for fabrication, acquiring the appropriate hardware for the main jet housing, and machining in-house those components that can be fabricated on campus. The construction details of the main assembly, the jet support and traverse structure, the tank mounting hardware, and the tank closure lid will be designed. In addition, quotations and purchase requests will be issued for the air conditioning system and portable cleanroom that will be used to contain the dust and fluorescent tracer particles within the test enclosure. Work will also begin on setting up the sub-bed illumination profile system, which will be used to quantify the scour and deposit of sediment before and after individual transient vortex events. This system will consist of a diffuse illumination source placed under the tank constructed from an array of multiple fluorescent lights operated on different phase banks to remove the effect of 60-Hz flicker common to single-phased banks. Initial trials will be conducted to tests its efficacy, once the lightbox is constructed.

Papers Published: No papers have been published as of yet.

Technical Interactions: No significant interaction to report as of yet.

Task 2.4 – Large-Eddy Simulation of the Interaction Between Wake Vortices and the Ground

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Investigator(s):	**Ugo Piomelli**
Institution/Department:	**University of Maryland and now at Queen's University, Dept. of Mechanical and Materials Engineering**
Graduate Student(s):	**None**
Contact email(s):	**ugo@me.queensu.ca**

Background and Technical Challenges: Brownout models rely on several ingredients. Among them are a rotor wake model, which predicts the motion of the blade tip vortices, and a particulate uplift model, which quantifies how small particles are lifted and entrained by the vortices as they spread out radially close to the ground. Typically, the rotor wake model is based on potential flow theory, and the motion of the vortices near the ground is predicted by assuming that vorticity is conserved. Detailed flow visualizations, however, show that the rotor wake forms an expanding turbulent wall jet near the ground. The tip vortices interact with this wall jet by entraining near-wall fluid. Flow visualization also shows that turbulence is a significant player in the dynamics of the vortices near the ground, and that the viscous and turbulent effects (neglected in potential wake models) can significantly affect their motion and decay rates. Underestimation of the decay rate of a vortex or neglect of stretching effects, for instance, will alter the entrainment of particles, and lead to different regions of particle lift-up. Turbulent diffusion, however, may increase the mixing of particles, and may result in significant changes in the shape of the developing dust cloud compared to predictions made by using inviscid assumptions.

Technical Approach: Calculations will be performed of increasingly realistic configurations, using several modeling strategies. These calculations will: 1) Validate the LES model by comparison with the laboratory experiments; 2) Serve as baseline for validation of lower-order models applied to situations at higher, more realistic Reynolds numbers. 3) Allow a detailed study of the interaction of the vortices with the wall, which will benefit our understanding and help the development of simpler mathematical models for the viscous interaction that could, for example, be included in global models of the brownout problem.

Progress in Last Quarter: One Post-Doctoral Fellow at Queen's University, Dr. Iftekhar Naqavi, has been learning to use the finite-volume code that will be used for large-eddy and direct simulations of the flow. He is presently running standard test cases to become familiar with the numerical methods and input/output. In parallel, Prof. Piomelli (in collaboration with Prof. K.D. Squires from the Arizona State University), has begun the implementation of particle-tracking routines into a Cartesian code. The Cartesian code cannot be used to simulate the interaction between the rotor wake and the ground, which has axial symmetry, and requires the use of the curvilinear code. However, since the Cartesian code is about 10 times faster than the curvilinear one, it will be used for initial investigations and to develop liftup models.

Anticipated Progress in Next Quarter: During the next quarter we will begin to explore the wake-rotor configuration (initially without sand particles. We will, in particular, develop ways to implement boundary conditions that match the mean flow measured in the experiments. We will also implement and test the particle-tracking routines in the Cartesian code.

Papers Published: None

Technical Interactions: Professor Piomelli is interacting closely with Professor Squires from the Arizona State University for the implementation of the particle-tracking model, as well as with colleagues at the University of Maryland.

Task 2.5 – Two-Phase Large Eddy Simulation Using the Mesoscopic Eulerian Formalism

Investigator(s):	**Kyle Squires**
Institution/Department:	**Arizona State University, Mechanical and Aerospace Engineering Department**
Graduate Student(s):	**Fernando Morales**
Contact email(s):	**squires@asu.edu**

Background and Technical Challenges: The brownout problem encompasses multiple scales, from the largest, comparable to the dimensions of the rotorcraft, to the smallest, comparable to the sediment particle size. This extended range leads to complex effects that influence the processes of entrainment, deposition, and resuspension of the dispersed sediment. Once suspended, sediment particle interactions occur with the coherent wake vortices characterizing the rotor flow, and with the finer scale turbulence generated near the ground as it interacts with the sediment bed. Factors that influence transport characteristics of the resulting two-phase flow, include particle-turbulence interactions, particle-particle interactions, particle interactions with the bed (e.g., entrainment, suspension, deposition), and momentum coupling that modifies the carrier flow. In general, the primary technical challenges can be sub-divided into those residing at the microscale (i.e., essentially the scale of a single particle) and the mesoscale (i.e., essentially the scale comprised of a large ensemble of particles with dimensions, for example, comparable to the boundary layer thickness of the two-phase flow). Specific technical challenges include simulation or measurement of the detailed processes of particle lift-off from a sediment bed, the role of turbulence influencing dispersed-phase transport, particle-particle interactions, and the influence of particle momentum exchange on properties of the carrier phase turbulent flow.

Technical Approach: The main effort revolves around simulations used to shed light on the near-surface dynamics of particle transport near a sediment bed and to advance practical simulation strategies that will be needed for the multi-scale simulation approaches. Currently, an Euler–Lagrange approach is being employed in which the incompressible Navier–Stokes equations are solved for the gas-phase carrier flow, and a particle equation of motion is solved for each particle in the ensemble. The simulations permit a detailed examination of mechanisms leading to turbulent entrainment of particles and will guide model development on the appropriate wall boundary conditions that are necessary for specifying the particle flux into the flow.

Progress in Last Quarter: A graduate student, Mr. Fernando Morales, was hired in the first quarter of the project. Mr. Morales is using Navier-Stokes solver that forms the backbone of the Euler-Lagrange method used in this work by running test cases used to assess both the fluid phase and the particle phase. In addition, we have also conducted a preliminary assessment of particle resuspension models available in the literature with an eye towards incorporation of such models into our simulations.

Anticipated Progress in Next Quarter: During the next quarter, Mr. Morales will complete the code assessment and then perform Euler-Lagrange simulations in order to begin generating the database that is needed to assess the mesoscopic Eulerian formalism at later stages of the work. A component of the Euler-Lagrange simulations that will also be initiated in the next reporting period will be implementation of near-surface models (deposition and resuspension), a necessary component for subsequent interfacing model predictions with experimental measurements.

Papers Published: None

Technical Interactions: Professor Squires is interacting closely with Professor Ugo Piomelli from Queen's University concerning implementation and assessment issues of particle tracking models.

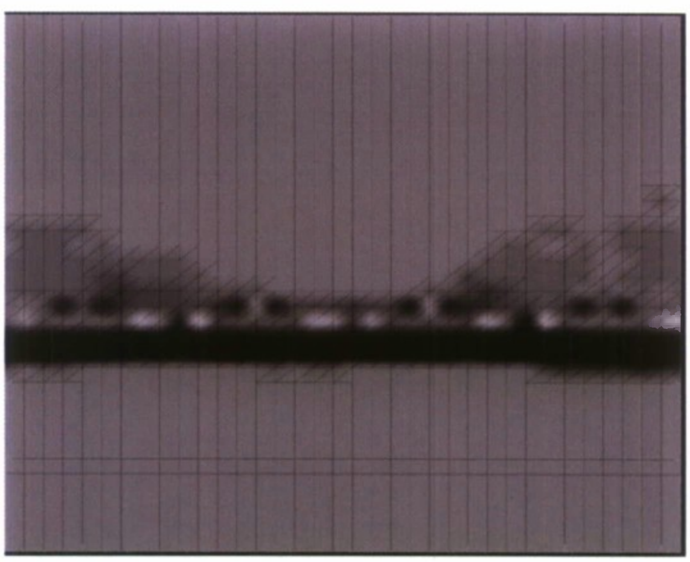
Task 3.1 – Optical Characterization of Brownout Clouds

Investigator(s):	**Roberto Celi, J. Gordon Leishman**
Institution/Department:	**University of Maryland, Department of Aerospace Engineering**
Graduate Student(s):	**TBD**
Contact email(s):	celi@umd.edu, leishman@umd.edu

Background and Technical Challenges: The concept of brownout "mitigation" implies the ability to characterize a sediment dust cloud as being "better" or "worse" than another. Such characterization presents several challenges. First, it must reflect that a brownout cloud is a three-dimensional two-phase flow structure with fluid and optical properties that can substantially change in space and time. Second, a characterization must properly address the type of problem of concern because the potential negative consequences of brownout clouds can be as diverse as rotor blade abrasion, engine performance losses and wear due to dust ingestion, and handling qualities (HQs) deterioration from the loss of external visual cues. Finally, to be practically meaningful, any characterization needs to be quantitative, and amenable to both theoretical prediction and experimental validation, both in the laboratory and in the field. Because the topic of the present MURI addresses primarily piloting problems, as a reflection of recent operational experience in desert conditions, the appropriate characterization of brownout clouds is one that is based on their optical properties, and that can be directly related to pilot workload and HQs in brownout conditions.

Technical Approach: The main objective of the proposed task is to formulate, and validate experimentally, quantitative metrics for the characterization and evaluation of brownout clouds, based on the optical properties of the cloud, and directly related to the difficulty of piloting in brownout conditions. The proposed metrics to characterize brownout clouds will be built around the use of the Modulation Transfer Function (MTF). The MTF is the magnitude portion of the Optical Transfer Function (OTF), which in turn, is a measure of the reduction in contrast and change of phase of sinusoidal patterns, as light (or any other electromagnetic radiation) traverses an optical instrument or, in this case, a sediment dust cloud.

Progress in Last Quarter: During the last quarter, work has begun on the development of the metrics for the characterization of a sediment cloud based on its optical properties. In preparation for the use of the MTF, preliminary work is being carried out using a simpler measure of optical attenuation based on the space and time distribution of the sediment particles. This requires the determination of the spatial distribution of the sediment particles *as seen by the pilot*, i.e., as projected onto an idealized sphere centered at the pilot's point of view (head or eye motions do not move this idealized sphere). The position of each particle, expressed in Cartesian coordinates with respect to a ground fixed coordinate system, is first converted to a pilot-fixed coordinate system, with axes parallel to those of the aircraft body-fixed coordinate system, still in Cartesian form. Then, the Cartesian coordinates are converted to spherical coordinates, and a 2-dimensional binning is performed, where the bins subtend spherical angles corresponding to equally spaced azimuth and elevation grids.



A preliminary example of the results of the binning procedure is shown in the figure above. The horizontal axis is the azimuth angle θ, ranging from -180° to +180°, i.e., from a position aligned with the tail, moving clockwise (as seen from above) to the nose of the aircraft and then back to the tail. The vertical axis is the elevation ϕ, ranging from -90° (straight down, parallel to the aircraft *z*-body axis) to +90° (straight up). The bins have sizes of 10° in azimuth and 5° in elevation. The graphics program interpolates in azimuth and elevation, therefore the plot does not have a "blocky" appearance. The plot reflects the spatial density of 75k sediment particles at a given instant in time.

Anticipated Progress in Next Quarter: During the next quarter, the binning procedure will be further refined to include calculations of the spatial distribution of optical attenuation, besides the simple particle counts shown in the figure above. Furthermore, we plan to acquire, install, and learn how to use MODTRAN.

Papers Published: None

Technical Interactions: The results shown in the figure refer to a particle distribution generated using the STAR algorithms as part of Task 3.2.

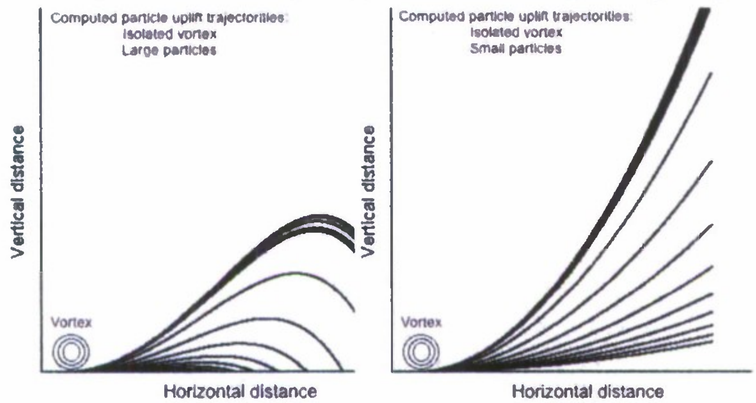
Task 3.2 – Development of Numerically Efficient Airborne Sediment Tracking Algorithms

Investigator(s):	**J. Gordon Leishman**
Institution/Department:	**University of Maryland, Department of Aerospace Engineering**
Graduate Student(s):	**Monica Syal**
Contact email(s):	leishman@umd.edu

Background and Technical Challenges*:* Tracking large numbers of particles in a typical brownout simulation is a significant computational task. Perhaps as many as several millions of particles need to be tracked over many rotor revolutions for the complete brownout pattern to evolve, and, therefore, to allow reasonable attempts to describe the sediment cloud using quantifiable optical characterization metrics such as the MTF (see Task 3.1). The goal in this task is to develop such numerical particle tracking methods so that they can be directly coupled (eventually in parallel) with free-vortex wake simulations of the rotor flow field. The overall objective is to rapidly simulate the development of brownout clouds around complete rotorcraft configurations, including those with multiple rotors.

Technical Approach: The proposed work is to develop computationally expeditious, airborne sediment tracking algorithms–called STAR (Sediment Tracking Algorithms for Rotorcraft). The 3-dimensional equations of motion of a sediment particle are expressed as a coupled set of ordinary differential equations (ODEs). These equations involve inertial terms (gravity, centrifugal, Coriolis) and viscous drag and lift (Stokes' flow). Direct numerical integration of these equations is computationally expensive, but approximations can be invoked. In particular, the particle response (trajectory) to a step change in the velocity field is known exactly, and this can be used in the development of fast, but very accurate methods to describe the motion of the sediment particles. The particle trajectory response to a series of small steps of limiting small magnitude can be written as a convolution integral that can be solved by sets of one-step in time recurrence equations. These types of equations are extremely quick to solve compared to the direct solution of ODEs.

Progress in Last Quarter: Work has started on exemplar problems, including the uplift of particle from a planar surface by single vortices. Using a simple uplift model based on the attainment of a threshold velocity, the trajectories of small and large particles has been studied. In the first instance, the idea is to compare the results to "exact" solutions to help quantify the magnitude and phase errors of the resulting particle trajectories. This will all eventually be handled within the ABATE framework (Task 3.4).



Anticipated Progress in Next Quarter: Various techniques, including particle-clustering methods, will start to be examined to minimize the number of particles to be tracked, and so to minimize computational costs for large brownout simulations. Key information on the sediment cluster, such as its velocities and momentum, is retained followed by a declustering based on local velocity gradients.

Papers Published: None so far.

Technical Interactions: None at this point.

Task 3.3 – Understanding Brownout and Developing Mitigation and Control Strategies

Investigator(s):	**Roberto Celi, J. Gordon Leishman, J. Baeder, and I. Chopra**
Institution/Department:	**University of Maryland, Department of Aerospace Engineering**
Graduate Student(s):	**TBD**
Contact email(s):	celi@umd.edu, leishman@umd.edu, baeder@umd.edu, chopra@umd.edu

Background and Technical Challenges: The development of a sediment cloud is a complex phenomenon affected by many design parameters. Its mitigation and control is a correspondingly complex problem: 1) "Mitigation" must be defined through a quantitative metric, related to mission effectiveness, that can describe why a given cloud is "better" than another. 2) The design methodology must capture the physics of all potential mitigation solutions. 3) Mitigation is likely to require the synergistic use of multiple solutions, and, therefore, the methodology must be capable of integrating these solutions and highlighting the couplings. 4) Numerical optimization is an ideal tool for this purpose, but it is difficult to apply because of the large computational requirements of brownout modeling, and the complexities of the design space (e.g., nonconvexity, time dependency, disjointness). Finally, brownout mitigation cannot be the sole design objective, and additional requirements (performance, vibrations, handling qualities, etc.) need to be considered.

Technical Approach: Brownout mitigation will be formulated as a numerical optimization problem. The precise definition of the objective function $F(\boldsymbol{X})$ to be optimized may evolve in the course of the research, but the starting point will be the equation $F(\boldsymbol{X}) = k_{\mathrm{MTF}}\, k_{\mathrm{D}}\, k_{\mathrm{Q}},$ where $\boldsymbol{X}$ is the vector of design variables. The parameters k_{MTF}, k_{D}, and $k_{\mathrm{Q}},$ are a measure of, respectively, the size of the areas where the visual cues available to the pilot are sufficient for navigation and stabilization, the times during which the visual cues are available (persistence), and the "quality" of the cues, weighing more heavily areas of good visibility that allow the pilot to close attitude and position loops.

Progress in Last Quarter: During the last quarter we have set up the procedure to evaluate the parameter k_{MTF}, based on the binning technique described in Task 2.5, and obtained some sample values. The procedure is based on the number of particles as a function of azimuth and elevation with respect to a system of spherical coordinates centered at the pilot.

Anticipated Progress in Next Quarter: During the next quarter, we will set up the procedure to calculate the other two parameters that make up the objective function. Then we will begin a simple parametric study by changing one or two parameters, one at the time, and studying the effect on combined size, persistence, and quality of the areas of good visibility available to the pilot.

Papers Published: None

Technical Interactions: The results are based on particle distributions generated using STAR algorithms as part of Task 3.2.

Task 3.4 – ABATE Simulation Framework and Validation

Investigator(s): **Dr. James Baeder, Dr. Shreyas Ananthan**
Institution/Department: **University of Maryland, Dept. of Aerospace Engineering**
Graduate Student(s): **Debojyothi Ghosh**
Contact email(s): ***baeder@umd.edu,***

Background and Technical Challenges: Rotorcraft brownout problem is a multi-physics phenomenon that requires the capability to reliably predict the lift and vortex wake generation at the rotor blades in ground effect, the interaction of the wake with the fuselage, and the multi-phase flow field near the ground involving the rotor wake vortices and the particles entrained into the flow field. A first-principles based continuum dynamics treatment of the brownout problem is impractical. A modular approach using domain decomposition principles, for e.g., domain decomposition at the fluid-structure interface, is a more practical option. Such an approach allows the individual solvers to use the most efficient, domain-specific solution technique to solve the governing equations. This approach also allows greater flexibility in the development, testing and validation of the individual solvers providing greater confidence in the final coupled simulation framework. However, the design of a robust, scalable modular framework must overcome the following challenges. The design must be scalable, robust and numerically accurate. In addition to the numerical accuracy of the participating solvers, care must be taken to ensure that the coupling processes preserve the overall desired order of accuracy and do not introduce additional errors during information transfer across domain boundaries. The modular framework must have a well-defined API, which the participating solvers can plug into to exchange data with other solvers without having extensive knowledge of the implementation details of the participating solvers. Such capability is extremely valuable in the development and testing of newer solvers by coupling it with previously validated solvers. Since the simulation of the brownout problem involves high-fidelity CFD solvers, the capability to support execution in a parallel environment in a transparent manner is of utmost importance. The framework must be capable of managing the execution of participating solvers across multiple processors, and ensure seamless information transfer not only between different solvers, but also across different processors without considering intervention from participating solvers or the end user.

Technical Approach: The heart of the simulation framework is a Python-based coupling library (coupler). Python is a freely available, dynamic object-oriented, general purpose programming language which an active development community and a rich variety of scientific libraries (such as NumPy and SciPy). Code written in Python can readily interface with solvers written in Fortran 77/90, C or C++ using wrapper libraries such as F2Py and SWIG. Python's interactive environment is a very useful tool for debugging or incremental development of complex scientific/mathematical models. Python's comprehensive support for object-oriented programming is very useful to model and manipulate participating solvers as objects with a well-defined behavior. This allows the designer to create a very abstract interface, which can be implemented by the solvers. From an end-user perspective this is advantageous because he/she can develop solution methodologies for new problems without worrying about the internal implementation details of all the solvers. The coupling library defines a standardized API for the participating solvers; the participating solvers *register* themselves with the coupler and post data requests to the coupler and respond to data requests from the coupler. The coupler's task during the computation is to manage the overall computational logic, collect data requests from participating solvers (requestor), determine which registered solver (provider) is capable of providing that data, posting request to the provider, obtain the data and relay it to the requestor after performing appropriate transformations if necessary. Thus the participating solvers just need to implement the API to interact with coupler and need not worry about interfacing with each and every other solver. This has the advantage of allowing for independent solver development without worrying about the implementation details of other solvers. This level of modularity improves the efficiency, development and debugging capabilities of the entire framework. Another advantage is that proven, validated, existing solvers can be incorporated into the coupling framework with minimal modifications. The entire simulation is controlled by a Python script, which initializes the coupler and the participating solvers and can be tailored for different flight conditions and rotor geometries. Such a design also allows the design of pre- and post-processing tools independently of the solver and can be used to analyze and visualize data

Progress in Last Quarter: The current research has focused on the following aspects: 1. Identifying the different components that will be necessary for modeling the brownout problem, and the data structures that will be shared between the participating solvers, 2. Development and refinement of the coupler API to allow for seamless data transfer in the brownout simulation, 3. Studying participating solvers (Tasks 1.2) to identify the modification that will be necessary to allow operation in a coupled parallel framework. In addition to the aforementioned tasks, an in-house incompressible Navier-Stokes solver is being developed at Univ. of MD to serve as a stand-in replacement for the solver being developed under Task 1.3. The objective of this exercise is to familiarize the student with the implementation details of an incompressible N-S solver and incremental development of the coupler library independently of Task 1.3.

Anticipated Progress in Next Quarter: With the coupling of the CSD and near-blade CFD solvers complete, the next step is to incorporate the wake vortex tracking models into the simulation framework. Most traditional Lagrangian vortex based methods are not capable of executing in a parallel environment. Some effort must be spent in improving the efficiency of these solvers and make them capable of executing in a parallel environment. The exact algorithm for coupling this vortex tracking models with the particle lifting and convection models must be determined. The final design must be capable of scaling to a large number of processors.

Papers Published: None yet.

Technical Interactions: Normal technical interactions with members of the MURI group.