Modeling and Analysis of Fluid-Thermal-Structural Interactions in Hypersonic Flow

Jack McNamara
The Ohio State University

Over the last decade, motivated by a desire for air-breathing hypersonic systems, a growing body of research has emerged seeking to understand complex multi-physics interactions associated with compliant systems operating in the extreme hypersonic environment. This talk will review the modeling needs, challenges, progress to date, and remaining gaps for carrying out coupled fluid-thermal-structural analysis for different classes of hypersonic systems; i.e., reusable systems or weapons on terminal trajectories.

Towards Aerothermoelastic Tailoring of Waveriders

Narayanan Komerath
Georgia Institute of Technology

A capability is being developed to address the aerodynamics of airbreathing hypersonic vehicles. The thermo elastic response of a typical surface panel on the windward side of a generic waverider is considered starting from an analytical framework with real-gas effects modeled. A series of test cases progresses from textbook problems to cases dealing with waverider geometries. The postulate is that low-order aerodynamic formulations, when combined with accurate flow properties, can yield accurate predictions of aerothermoelastic deflections in equilibrium, and perhaps good predictions of unsteady response. The hyperbolic nature of the describing equations, and the particular regime of hypersonic flight, offer encouragement. A progression of aerodynamics models is used to develop predictions.

The Discontinuous Galerkin Method as a Mainstream Approach for Computational Fluid Dynamics

Andrew Shelton
Leidos

This research focuses on performing compressible unsteady computational fluid dynamics (CFD) with higher fidelity at lower cost using the discontinuous Galerkin (DG) method for high order spatial discretization. The discontinuous Galerkin (DG) method is the natural extension of finite volume to high order, and as such, enjoys high accuracy per degree of freedom while retaining geometric versatility. The method assumes a function expansion for the distribution of the flow variables within each individual element and solves for the modes of the expansion by minimizing the residual in the Galerkin approach. The flow variables are generally discontinuous across the element boundaries, requiring the application of a Riemann-like flux to maintain inter-element communication. The element solution reconstruction is self-contained such that the stencil is invariantly compact with increasing order of accuracy. This presentation will provide an overview of the DG method and demonstrate its application to problems such as shock interactions and vortex instabilities. A particular points of emphasis is a strategy to alleviate the Gibbs phenomenon (suffered by all high order methods) employing resolution-based damping.

Reactive Burn Model Parameterization Incorporating Ignition and Sustained Pulse Data Sets

Robert Drogan
Air Force Research Lab

Pressure based reactive models have been used successfully by the community for many years to investigate topics on problems involving high-velocity impacts, penetrations, and explosive ignition and detonations. Calibration of models for different materials is an important part of the modeling process and typically is performed using sustained pulse data from Pop-plot experiments. These data provided the run-to-detonation behavior for explosives due to a supported shock condition. However, simulations using Pop-plot derived coefficients are not generally able to match experimental data from thin-pulse-driven explosive ignition tests. This work focuses on the development of reactive models based on the combination of thin pulse and sustained pulse data sets. The additional complexity incorporated through a wide spectrum of experimental loading regimes allows for complex computational predictions. The Sandia National Laboratory hydrocode CTH is used to develop parameters for various reactive burn models, including Lee-Tarver's Ignition & Growth (I&G) model, Sandia?s History Variable Reactive Burn (HVRB) model, and the Arrhenius Burn model.

Approaches for Aggregating Information From Conflicting Sources

Tathagata Mukherjee
Florida State University

In this talk we will present approaches for aggregating information from conflicting sources. This problem has been given different names like the Veracity Problem, the Truth Finding Problem and the Information Fusion Problem and deals with aggregating information from n sources $S_1, S_2, \ldots, S_n$ which present potentially conflicting information about an object of interest O. This is also very similar to the sensor data fusion problem and the approaches discussed here have the potential of being applied to sensor data fusion as well. In this talk we will present three different approaches, the first one based on a PageRank type algorithm, the second one based on a Bayesian probabilistic network and the last one based on a geometric approach for detecting outliers.

Belief Propagation Algorithm for Near-optimal Graph Matching in Formation Reconfiguration Problems

Xin Li
University of Florida

Systems of networked autonomous vehicles often need to be reconfigured from one physical formation into another physical formation, depending on the tasks to which the vehicles are assigned. If the vehicles are identical, then an important problems is how to assign or map the vehicles in the initial formation to the set of desired positions (also called roles) in the final formation. The problem is complicated by the fact that the optimization criteria may not be additive in nature and that the optimization algorithm should be implementable in a distributed fashion. In this work, we propose the use of belief propagation (BP) to find suboptimal, but distributed solutions to these problems. BP is an iterative, local, message-passing algorithm for statistical inference on graphs. To apply BP to the formation-matching problem, we place the initial and final positions as vertices in a bipartite graph. Then the distances among the positions are mapped to probabilities, where the choice of the probability density function and its parameters affect the approximated optimization criterion. Because the bipartite graph is very loopy, we force decisions periodically in the BP algorithm. After the assignment of the destination to each identical vehicle, in order to navigate each vehicle to their decided position, we use prefix label algorithm to control the formation while maintaining the connectivity of the network.

Distances Between Multidimensional Distributions for Image Classification

Aleksandr Mafusalov
University of Florida

Image classification is an important problem for various applications. We consider metric-based classification algorithms. In order to use these algorithms we have to choose metric between images. Image can be represented as a matrix of brightness values of pixels. One heavily used class of metrics is pixel-to-pixel comparison based metrics. The alternative is cross-pixel comparison based metrics. We treat image as a two-dimensional probability measure with density proportional to pixel brightness. We propose several metric families in multidimensional probability measure space. We use kNN (k nearest neighbors) as a baseline classification method. We compare classification accuracy of metric-based algorithms for chosen metrics.

Support Vector Machines with Risk Constraints

Victoria Zdanovskaya
University of Florida

We consider a particular class of data-mining algorithms for classification called Support Vector Machines (SVMs). SVMs are used in a wide range of applications such as fraud detection, medical diagnostics, handwriting recognition, credit scoring, etc. In this research we introduce risk constraints to standard SVM formulations for the purpose of controlling their risk management characteristics.

Experimental Characterization and modeling of plastic deformation in Titanium

Oana Cazacu
University of Florida

A strong difference between the plastic response in tension versus compression is observed at the polycrystal level, if either twinning or non-Schmid type slip are contributors to plastic deformation at the single crystal level. Despite recent progress in modeling the effects of this asymmetry in yielding, its influence on damage evolution remains a challenge. In this paper, the combined effects of texture and asymmetric single-crystal plastic deformation mechanisms on the response of voided polycrystals are assessed for the first time. Using analytical homogenization, it is shown that for untextured metals deforming solely by slip, there should be a very specific dependence on the signs of the third-invariant and mean stress that induces a more accelerated void growth than predicted by current models. If the single crystal plastic deformation mechanism is twinning both numerical results using a full-field dilatational viscoplastic Fast Fourier (FFT)- based approach and a recent analytical yield criterion reveal unusual features of the dilatational response, namely a lack of symmetry of the yield surface with respect to both the hydrostatic and deviatoric axes.

Sensing and Imaging of Impact Damage in Composites

Olesya Zhupanska
University of Iowa

New three-dimensional strain-rate potential for porous metals with faceted yield surface

Benoit Revil-Baudard
University of Florida

Calculation of thermal properties of silicon carbide from the first principles using density functional perturbation theory of phonons

Anna Kuznetsova
Air Force Research Lab

The design of high-performance airframes for the next generation of maneuverable hypersonic vehicles operating at extreme environments requires multifunctional materials that are able to simultaneously resist high thermal, mechanical and oxidation loads. Immense thermal gradients and associated mechanical stresses that are developed at the leading edge of hypersonic vehicles require materials with not only high thermal conductivity but also with high thermal conductivity anisotropy. This anisotropy would allow efficient reduction of thermal gradients along the surface of the vehicle, while minimizing heating of the interior of the vehicle. Silicon carbide (SiC) is among the best candidates for such applications due to its ability to operate at high temperatures and superior properties, such as, low density, low thermal expansion, high strength, high thermal conductivity, high elastic modulus and superior chemical inertness. SiC has high thermal conductivity, which is substantially anisotropic and depends on its crystal structure. Thermal properties of SiC have not been sufficiently studied and the detailed investigation would facilitate development of a new material based on SiC with superior thermal transport properties. In the talk we will illustrate application of density functional perturbation theory of phonons to investigation of thermal properties of materials. We will also discuss a well-known example of phonon dispersion calculation for silicon.

Modeling of the effective thermo-mechanical properties of Aluminum/Zirconia composite over a wide temperature range

Philip Deierling
University of Iowa

In this work, micromechanical modeling is employed to determine the effective elastic and thermal properties as well as the temperature-dependent stress-stain relationships of an Aluminum/Zirconia functionally graded material (FGM). The analysis is performed at varying volume fractions and a wide temperature range. The modeling includes 3D finite element analysis (FEA) based numerical homogenization using a representative volume element (RVE) and comparison to variational bounds on the elastic and thermal properties.

The RVE in this work consists of a unit cube with randomly distributed monosized spherical inclusions. The inclusions represent the phase material with a lower volume fraction while the matrix represents the phase material with a higher volume fraction (i.e. Zirconia inclusions if the Aluminum volume fraction is greater or Aluminum inclusions if the Zirconia volume fraction is greater). Periodic boundary conditions are implemented into the FEA along with temperature-dependent mechanical and thermal properties for linear elastic Zirconia and elastic-plastic Aluminum.

Effective elastic moduli, thermal conductivity, specific heat and thermal expansion have be estimated using FEA and compared against the tightest variational bounds (i.e. Hashin-Shtrikman bounds on the elastic properties and thermal conductivity, Shapery and Rosen-Hashin bounds on the coefficient of thermal expansion, and Rosen-Hashin bounds on the specific heat). FEA results indicate that the obtained material constants are within bounds. Furthermore, it has been revealed through evaluation of the bounds that the elastic moduli, specific heat and coefficient of thermal expansion are well approximated by the upper bounds. However, the thermal conductivity bounds are wide and specific FEA microstructure is required to determine the overall thermal conductivity of the Aluminum/Zirconia composite.

The results of the aforementioned analysis are incorporated into the thermo-mechanical analysis of an Aluminum/Zirconia FGM plate subjected to a steep temperature gradient. Preliminary results illustrating the effect of spatial grading on the structural and thermal response will be discussed.

A stochastic PDE-constrained optimization approach to vibration control of a composite plate subjected to mechanical and electromagnetic loads.

Dmitry Chernikov
University of Iowa

It is known from previous studies that mechanical vibrations of a thin plate can be effectively damped by applying electromagnetic field to it. However, application of excessive electric current may lead to overheating and damage of the plate, thus it is crucial to find the proper profile of the electromagnetic field to apply. In addition, the mechanical load is assumed to be stochastic with known discrete distribution. In this work we address the problem to find the optimal profile of the electromagnetic field under stochastic mechanical load, which is formulated as a stochastic PDE-constrained optimization problem. The governing system of PDEs is solved numerically and the optimization is done with the aid of a two-stage stochastic programming. The gradient of the objective function is found by using automatic differentiation. Numerical results are presented.

Decentralized Riemannian Particle Filtering & Multiagent Navigation Without GPS

Martin Eilders
Air Force Research Laboratory

Integrated Control and Estimation

Adam Rutkowski
Air Force Research Lab

This work studies the problem of guiding a vehicle from a known initial location to a known goal location as accurately as possible, without direct observation of the goal location (such as a bearing measurement, or line-of-sight to the goal), and without direct position measurements, such as those provided by GPS. The vehicle travels in a planar environment and has an onboard inertial measurement unit and an onboard visual system to measure bearing angles to features in the environment. Taking a zigzagging path toward the goal provides better position estimation than a straight path. For a given energy budget, there is a certain path width, or amplitude, that results in the best estimation performance, and this optimal path width depends on the sensor noise parameters. A batch estimator is derived to analyze the effect of the entire time history of the vehicle trajectory on final position estimation performance. The formulation results in a linear system of equations. The path width that minimizes the condition number of the system matrix also minimizes the final position estimation error when the feature bearing measurement noise is relatively large compared to the inertial measurement noise.

Bioinspired Magnetic Reception and Multimodal Sensing

Brian Taylor
Air Force Research Lab

Several animals use the Earth's magnetic field in concert with other sensor modes to accomplish navigational tasks ranging from local homing to continental migration. However, despite years of research, animal magnetoreception remains poorly understood. Simultaneously, the Earth's magnetic field offers a potential signal for engineered systems to perform GPS-degraded or GPS-less navigation. This work uses a biologically inspired behavioral strategy with limited a priori environmental knowledge to locate a magnetic target, and respond to other sensory cues when they are present. The underlying data processing is performed within a biologically relevant framework that can be adapted to use methods that range from engineering-based to biomimetic. Work to date shows that by tracking two magnetic coordinates independently of each other, a simulated agent can move from a starting location to a goal. In addition, the agent's behavior can be context dependent so that it can respond to other sensory cues when they are available.

High Speed Fluid Structural Interactions and Reduced-order Modeling

Ryan Klock
Air Force Research Lab

Model reduction techniques are applied to a hypersonic strike vehicle on terminal trajectories to capture the aerodynamic, thermodynamic, and structural dynamic system evolution and couplings. The General Purpose Optimal Control Software (GPOPS-II) was used to determine a set of terminal trajectories which maximized impact velocity or range and minimized target error. Shock, Prandtl-Meyer expansion, and piston theory were combined to create an approximate flow solution over the vehicle outer mold line which was then compared to Fully Unstructured Navier-Stokes 3-Dimensional (FUN3D) computational fluid dynamics solutions. Proper orthogonal decomposition of the thermal state of the vehicle was conducted leading to 15 thermal degrees of freedom rather than approximately 28,000 contained by the original Abaqus finite element model, while sacrificing negligible system energy. Free vibration mode shapes are derived by the Lanczos algorithm and used to generalize the structural dynamics equations of motion reducing the number of structural degrees of freedom to 3 from the original 130,000. Finally, the combination of these reduced models is discussed in the context of future work toward a full vehicle simulation for control law development and evaluation.

Aerothermodynamic Modeling of Munitions on Terminal Hypersonic Trajectories: Grid Generation

Emily Dreyer
Embry-Riddle Aeronautical Universityå

A capability is being developed to address the aerodynamics of airbreathing hypersonic vehicles. The thermo elastic response of a typical surface panel on the windward side of a generic waverider is considered starting from an analytical framework with real-gas effects modeled. A series of test cases progresses from textbook problems to cases dealing with waverider geometries. The postulate is that low-order aerodynamic formulations, when combined with accurate flow properties, can yield accurate predictions of aerothermoelastic deflections in equilibrium, and perhaps good predictions of unsteady response. The hyperbolic nature of the describing equations, and the particular regime of hypersonic flight, offer encouragement. A progression of aerodynamics models is used to develop predictions.

Aerothermodynamic Modeling of Munitions on Terminal Hypersonic Trajectories

Jake Larkin
The Ohio State University

The research conducted over the summer was primarily focused on the CFD simulation of high-speed munitions on terminal, hypersonic trajectories. The development of high-speed weapons strongly relies on a multi-fidelity and multi-physics simulation framework that can model realistic munitions in a computationally efficient manner. To determine if the proposed approach could sufficiently handle large accelerations (12-20 g?s) at extreme operating conditions, a much simpler 2D model of the full-diamond control surface was put through maneuvers in similar flight conditions and compared to results previously found for the same geometry. This model required an in-depth grid convergence study, maneuver design and careful CFD analysis using FUN3D. This experience was applied to the full-scale vehicle to begin developing the high-speed simulation framework. The first step was to model aerothermodynamic loads (i.e. surface pressure, heat flux) using steady state CFD solutions of a sample hypersonic vehicle. This was done by generating a grid of the vehicle that was properly converged in order to capture different flow features accurately and then applying appropriate boundary conditions to simulate a variety of operating environments in the CFD solver. In addition, the full-scale vehicle was used to simulate different flight maneuvers of interest.

Aeroelastic Simulation of Flexible High Speed Vehicles

Dianne Zettl
USRA

My summer research with USRA-AFRL aims to identify and exploit the relevant physics associated with the fluid-structural interaction (FSI) effects critical for highly maneuverable (high AoA, 20-40 G loads) supersonic (Mach 3) air-to-air missiles. My partner on this project, Ryan Kitson of University of Michigan, focuses on the structural analysis while I focus on trajectories and fluid analysis. My research thus far has involved the study of 2D rigid body kinematics and non-uniform circular motion to define the trajectory of a flat plate traveling at uniform free stream experiencing a constant centripetal acceleration. In this analysis, both the radius of curvature and angle of attack are accelerating with time. The resulting induced velocities on the plate normal to the free stream will define a pitch-plunge motion to be simulated using computational fluid dynamics (CFD) and passed along for structural analysis. This summer marks the starting point of my graduate research for my Masters thesis, which I will continue at Ohio State University.

Aeroelastic Simulation of Flexible High Speed Vehicles

Ryan Kitson
University of Michigan

The fluid-structure interaction of a vehicle in supersonic flight is considered using reduced order modelling techniques. In particular the flexible vehicle is modeled similar to the AIM-9 sidewinder currently in use with the exception of no control surfaces towards the leading edge. In this work reducing the span and overall box size of the vehicle is explored with the use of direct attitude control systems similar to those seen previously on the Standard Missile-3. In addition the impact of flexibility on system maneuverability and agility will be explored in future work. Initial structural modelling and order reduction using the normal mode method is discussed. Aerodynamic forces are included using traditional shock-expansion theory with piston theory for unsteady corrections. Some preliminary time simulations of the vehicle in free flight and maneuver are included.

On solution approaches to a class of mixed-integer non-linear stochastic programming problems

Alexander Vinel
University of Iowa

A class of mixed-integer non-linear programming problems which arise in certain recent approaches to risk-averse decision making under uncertainty is considered. We aim at applying some of the techniques that have been shown to be successful for other types of mixed-integer programming problems. Among other approaches, we show how a family of linear disjunctive cuts can be derived for our problem class and develop an efficient branch-and-bound method based on outer polyhedral approximations. First results of a numerical case study that is being conducted will be presented.

A Multistage and Multiscale Stochastic Programming Approach to Electricity Infrastructure Investment

Zhouchun Huang
University of Central Florida

To study the infrastructure needs of an electricity grid, we propose a stochastic programming model that integrates long-term investment planning and short-term unit commitment models, both of which are multistage decision problems in nature but have different time scales. The infrastructure expansions are planned several years ahead and the time scales for unit commitment decisions are in hours.

Nonlinear Mixed Integer Programming Approaches for Generalized Geometric Programming

Yiduo Zhan
University of Central Florida

Generalized geometric programming (GGP) is a type of mathematical optimization problem with nonlinear objective and constraints. Some of the GGP problems have negative terms, and thus cannot be transformed to convex problems. Therefore, this leads to a global optimization problem that is difficult to solve. This talk will introduce a solution algorithm for non-convex GGP. This method involves employing method of generalized benders decomposition to separate the convex and non-convex part of the problem. The convex part will be solved efficiently by a convex solver. For the non-convex part, which is the main problem after decomposition, we developed an algorithm that utilized the logarithmic variable transformation and converted the non-convex terms to mixed integer linear programming (MILP) problems using piecewise-linear approximations. It is solved by an integer solver and therefore acquire the overall optimal of GGP.