Computational Aerosciences Laboratory
2017 Highlights

2017 was a productive year in many ways for CASL. In this newsletter, we recap some of the highlights.

UMich/NASA Symposium on 'Advances in Turbulence Modeling'

In July 2017, we organized this three-day symposium in Ann Arbor. The response to invitations was outstanding as was the caliber of the participants. In all, we brought together nearly 90 experts from academia, government and industry, with good international participation. Topics revolved around the state of the art in turbulence modeling, emerging ideas, and to wrestle with questions surrounding its future. Emphasis was placed on turbulence modeling in a predictive context in complex problems, rather than on turbulence theory or descriptive modeling. A notable aspect of the meeting was that we had ample time for intense (and often passionate and controversial) discussions. The website[1] has all the presentations and this NASA Technical Memorandum titled 'Status, Emerging Ideas and Future Directions of Turbulence Modeling Research in Aeronautics'[2] summarizes many of the questions, discussions, and conclusions from the symposium, and suggests immediate next steps for the community.

New Projects in 2017

Airforce Center of Excellence on 'Multi-fidelity Modeling of Rocket Combustor Dynamics'

We kicked off our 6-year AFOSR/AFRL center, which is focused on advancing the state-of-the-art in Reduced Order Models (ROMs) and enabling efficient prediction of instabilities in liquid rocket combustors. CASL is leading the project, in collaboration with Profs. Willcox (MIT), Anderson (Purdue) and Peherstorfer (Wisconsin). The key expected outcomes are the following:

1. Methods for ROMs of variable/adaptive fidelity derived from an organized hierarchy of higher fidelity simulations.
2. Framework for integration of ROMs into a multi-fidelity model that can predict the stability characteristics of a full-scale LRE containing multiple injector elements.
3. Given a nominal engine configuration, end use is a methodology that designers can use to:
   - Efficiently characterize combustion dynamics in $O(days)$ on $O(100)$ processors.
   - Explore effect of parametric changes on quantities of interest (QoIs), which include limit cycle amplitude, growth rate, and stability margin.
4. Innovations to the science of reduced modeling of complex systems
5. Engagement with AFRL researchers and exchange of knowledge, tools and data.

We received a lot of press. Here is an article [3] and an NPR soundbite [4].

[1] http://turbgate.engin.umich.edu/symposium/

[2] https://ntrs.nasa.gov/search.jsp?R=20170011477

[3] http://www.spacedaily.com/reports/Designing_new_rocket_engines_that_dont_blow_up_999.html

[4] https://cpa.ds.npr.org/michigan/audio/2017/04/20170405_SS_Better_Rocket_Engine.mp3

Data-driven and Multi-scale modeling of Battery Materials: This 4-year project, funded by Toyota Research Institute (and in collaboration with Profs. Garikipati and Gavini) seeks to advance a more complete and quantitative understanding of the physics of battery materials. It will enable battery design for performance, thermal management, prevention of mechanical degradation, and closed-loop control, guided by computational modeling. Machine learning programs will link the simulation codes at the various scales using large data sets from lower scale calculations to inform the models at each scale.

Turbulence Modeling Across Disparate Length Scales for Naval Computational Fluid Dynamics Applications: We started a 2+ year NAVY SBIR Phase II project (with Continuum Dynamics, Inc.) to develop efficient numerical techniques for vortex-dominated flows, with the goal of application in Rotorcraft and ship-wake problems. Specifically, we are targeting techniques to solve fluid flow equations in vorticity-velocity form. This technique presents many inherent advantages over solving the conventional Navier–Stokes equations. Toward this end, we are developing sharp gradient-capturing numerical schemes and implicit LES techniques such that coherent structures can be efficiently resolved.

Advancing Predictive Strategies for Wall-Bounded Turbulence by Fundamental Studies and Data-driven Modeling: This is a 4-year ONR project in collaboration with Prof. Durbin (Iowa State). We are looking to improve our physical understanding (via DNS and LES) and modeling of non-equilibrium wall-bounded turbulent flows of interest (such as high Reynolds number flows over rough walls) to the Navy. Both physics-based and data-enabled models are being explored.

A Diagnostic Modeling Methodology for Dual Retrospective Cost Adaptive Control of Combustion: This is a 5-year NSF project (with Profs. Bernstein and Gamba) to develop, demonstrate, and validate a novel diagnostic modeling methodology that that is based on limited sensor data to uncover the essential dynamics and control complex systems. The application is experimental control of instability a swirl combustor, which is being built by Prof. Gamba's group.

Aeromechanics of Unmanned Air Vehicles in Realistic Atmospheric Conditions: We are part of an NSF-funded industry/academia/government consortium on UAVs. The CASL contribution is to develop efficient and accurate models of atmospheric conditions and aeromechanical models of UAVs. The goal is to utilize these models for individual and collective mission planning.

Awards

Behdad Davoudi was awarded the Francois Xavier-Bagnoud fellowship. This is the most prestigious fellowship offered by the Aerospace Engineering department at UM and goes to a "student with an outstanding academic record, commitment to the study of flight vehicles, and the potential of broad impact of his/her work." With this award, which will cover the duration of his PhD, Behdad will pursue his dissertation on the analysis and design of distributed propulsion systems.

New Members

We added several new members to the lab:

1. Daniel Foti (Post-doctoral Fellow since March), PhD in Mechanical Engineering from Minnesota: Danny's PhD was in wind farm turbulence and uncertainty quantification. Danny is now focusing on numerical method development and implicit LES.

2. Yaser Afshar (Post-doctoral Fellow since June), PhD in Computer Science from TU-Dresden: Yaser has extensive experience in high-performance computing, scientific computing, image

segmentation, dissipative particle dynamics, particle methods (he is a key developer of the PPM library), etc.

3. Cheng Huang (Assistant Research Scientist since June), PhD in Aerospace Engineering from Purdue): Cheng is an expert in high-fidelity simulations, with a focus on combustion dynamics and will be helping out on several projects including the center of excellence and the adaptive control project.

4. Christopher Wentland (PhD student since September), BS in Mechanical Engineering from Rice. Chris will be a key contributor to the Air Force center and is initially focusing on reduced order models.

5. Adam Comer (Research Fellow since November), PhD in Engineering from Cambridge: Adam specializes in combustion simulations (RANS and LES), with a focus on practical applications such as aircraft engines.

On the move

1. Asitav Mishra (Post-doctoral fellow): Asitav is moving on to the National Institute of Aerospace and Univ of Maryland as a Research scientist after spending the last year at CASL. All the best, Asitav.

2. Sven Giorno (Masters student): Sven will be taking up a job at MDP, France, continuing his work on reduced order models! Bonne chance, Monsieur Giorno.

3. Walter Crosby (PhD student): Walter will be going back to industry, taking up a job with Barber Nichols, Inc. working on rocket turbopumps. (don't) Blow it up, Walt.

4. Anand Pratap Singh (PhD student): Anand successfully defended his thesis. Despite a good few options, Anand chose to continue on as a post-doctoral fellow for at least a year. Welcome back, Anand.

5. Eric Parish (PhD student): Just finished his pre-defense. He is on the job-market and his stock is as hot as bitcoin was. Way to go, Eric.

6. Shaowu Pan, David Xu and Vishal Srivastava became PhD candidates.

7. Karthik Duraisamy was promoted to Associate Professor.

Notable publications

We had a very productive year in terms of publications. Here are some of the notable ones:

1. *Gouasmi, A. "A Priori Estimation of Memory Effects in Reduced Order Modeling of Nonlinear Systems Using the Mori-Zwanzig formalism," Proc. Royal Soc.* A very elegant paper and a "must-read" if you are getting into Mori-Zwanzig (MZ), which is a closure technique inspired from a statistical mechanic view-point. The memory kernel in MZ, which formally exact, is intractable in general. A method to estimate the memory kernel is proposed using a neat "reverse-Liouville" idea. This is equivalent to assuming that the semi-group of the orthogonal dynamics is a composition operator and greatly simplifies the estimation of the kernel.

2. *Parish, E. "A Dynamic Sub-grid Scale Model for Large Eddy Simulations based on the Mori-Zwanzig formalism," JCP.* A new MZ-based closure model is developed for LES of turbulent flows. The model is constructed by exploiting similarities between two levels of coarse-graining via the Germano identity of fluid mechanics and by assuming that memory effects have a finite temporal support. The appeal of the proposed model, is that it is parameter-free and has a structural form imposed by the mathematics of the coarse-graining process (rather than the phenomenological assumptions made by the modeler, such as in classical subgrid scale models).

3. *Singh, A. "Machine Learning-augmented Predictive Modeling of Turbulent Separated Flows over Airfoils," AIAAJ.* This paper has attracted significant levels of attention from the community, especially from the industry. Inverse modeling is used to infer the spatial distribution of model discrepancies and machine learning is used to reconstruct discrepancy information from a large number of inverse problems into corrective model forms. The methodology is applied to turbulent flows over airfoils involving flow separation. These model forms are derived from very limited lift data but are shown to predict surface pressures extremely well, even in shapes and flow conditions that were not part of training. Portability of this approach is demonstrated by confirming that predictive improvements are preserved when the augmentation is embedded in a commercial solver.

4. *Aranake, A., "Aerodynamic Optimization of Shrouded Wind Turbines," Wind Energy.* A hybrid-fidelity model is developed for shrouded wind turbines, combining a RANS solver, an actuator disk model, and an inverse blade design technique. This hybrid model is incorporated into an optimization framework that seeks to design the geometry of the shroud and rotor to extract maximum power under thrust constraints. The optimal solution is also evaluated using a high fidelity solver. The predicted optimal designs yield power augmentations well in excess of the Betz limit, even if the normalization of the power coefficient is performed with respect to the maximum shroud area.

5. *Duraisamy, K., "Data-enabled, Physics-constrained Predictive Modeling of Complex Systems," SIAM News.* A more informal article on the use of data in modeling complex physical problems. The main idea is that data cannot be an alternative for physical modeling, but when combined withand informed bya detailed knowledge of the physical problem and problem-specific constraints, data-enabled modeling is likely to yield successful solutions.

Major Conferences

1. The year began with a bang at *AIAA Scitech* conference in Dallas. We presented five papers on a variety of topics including data-driven turbulence modeling, helicopter noise reduction, robust design and overset adjoints.

2. The next big venue was the *SIAM Computational Science and Engineering* conference in Atlanta, where we again had five presentations on topics spanning statistical mechanics, uncertainty quantification, turbulence modeling and adaptive control.

3. At the *AIAA Aviation* conference in Denver, we presented three papers on reduced order modeling (invited), data-driven modeling and multiple-fidelity modeling of aerodynamic interactions.

4. At the *APS Fluid Dynamics* meeting in Denver, we had five presentations on data-driven discovery of equations, numerical schemes for vorticity transport equations, closure schemes for discontinuous galerkin methods, combustor physics and data-driven turbulence modeling.

5. At the *US National Conference in Computational Mechanics* in Montreal, we presented our work in model-form uncertainty quantification and Mori-Zwanzig methods.

6. At the *AIAA/SAE/ASEE Joint Propulsion Conference* in Atlanta, Cheng and David presented their papers on reduced order models.

Workshops

It wasn't by design (or perhaps it was), but we ended up participating in workshops in some very cool locations

1. Karthik participated in a workshop held at the Banff Research Station (Canada) on *Data-Driven Methods for Reduced-Order Modeling and Stochastic Partial Differential Equations* and spoke about the use of Mori-Zwanzig for the closure of Reduced Order Models.

2. Sven gave a presentation on data-driven discovery of closure models in Rome (Italy) in a workshop on *Data-Driven Methods for Multi-Scale Physics and Complex Systems*

3. Karthik gave a presentation the the USACM workshop on *Uncertainty Quantification and Data-Driven Modeling* in Austin (Texas).

4. Eric gave a presentation on Mori-Zwanzig in the *Variational Multiscale Methods* workshop in Seville (Spain).

5. Karthik was hosted by *DLR* Braunschweig (Germany) for a crash course on data-driven turbulence modeling and exchange of ideas.

MICDE Symposium on 'New Era of Data-Enabled Computational Science'

With the Michigan Institute of Computational Discovery and Engineering (MICDE), we organized a day-long symposium featuring an all-star list of speakers on a range of topics spanning important advances in computational science and the emerging role of data-enabled methods. The website [5] has more information.

CASL team in 2017

Research Scientists: Cheng Huang, Adam Comer.
Post Doctoral Fellows: Asitav Mishra, Daniel Foti, Yaser Afshar.
PhD Students: Anand Pratap Singh, Helen Zhang, Eric Parish, Nicholas Arnold-Medabalimi, Ayoub Gouasmi, David Xu, Behdad Davoudi, Shaowu Pan, Vishal Srivastava, Walter Crosby, Christopher Wentland.
Masters Students: Sven Giorno.
Lead: Karthik Duraisamy.

[5] http://micde.umich.edu/symposium17/