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14. ABSTRACT The eighteenth biennial Summer Program of the Center for Turbulence Research (CTR) was held from July 17 to August 12, 2022. CTR hosted 71 participants from 15 countries, including 20 U.S. institutions. 40 CTR staff members, including graduate students, postdoctoral fellows and faculty, worked alongside the participants. 35 project teams were selected on the basis of the quality of their research proposals and their synergy with the current scientific interests of CTR. The role of CTR continues to be that of providing a forum for the fundamental study of multiphysics turbulent flows for engineering analysis. As a result of additional synergistic collaborations between participants, 41 projects were carried out during four-week program.					
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CTR Summer Program 2022

1. Introduction

The eighteenth biennial Summer Program of the Center for Turbulence Research (CTR) was held from July 17 to August 12, 2022. CTR hosted 71 participants from 15 countries, including 20 U.S. institutions. 40 CTR staff members, including graduate students, postdoctoral fellows and faculty, worked alongside the participants. 35 project teams were selected on the basis of the quality of their research proposals and their synergy with the current scientific interests of CTR. The role of CTR continues to be that of providing a forum for the fundamental study of multiphysics turbulent flows for engineering analysis. As a result of additional synergistic collaborations between participants, 41 projects were carried out during four-week program.

This proceedings volume contains 41 reports that are divided into six groups: Modeling Turbulence and Transition Using Data-Driven Approaches, Data-Driven Methods, Multiphase and Particle-Laden Flows, Combustion, Analysis of Turbulent Boundary Layers and High-Fidelity Simulations and Applications. Preceding each group of papers is a technical overview that summarizes the main accomplishments of each group.

While data analysis has always been at the foundation of the CTR Summer Programs, a major theme of this year's program was data-driven modeling. The group on Modeling Turbulence and Transition Using Data-Driven Approaches focused on developing predictive models for wall-bounded flows. These projects used supervised and reinforcement learning, proper orthogonal decomposition and the macroscopic forcing method. These models combined classical physics-based modeling principles with data-driven closure techniques.

The Data-Driven Methods group focused on developing novel techniques drawing on principles from optimization, resolvent analysis and deep learning. The group had two main research thrusts: (i) acceleration of numerical simulations with data-based closures, and (ii) developing reduced-order descriptions of turbulence for making predictions and deriving physical insight.

Research activities in the group on Multiphase and Particle-Laden Flows focused on the analysis and modeling of dispersed particle-laden turbulence and two-phase turbulent flows. In the area of particle-laden turbulence, this group studied numerical methods for coupling the momentum of the fluid and dispersed phases, the effect of subgrid-scale modeling on particle transport and innovative methods for computing particle statistics. In the area of two-phase flows, the focus was on the modeling of phase change in interfacial flows, microconfined turbulence in high-pressure transcritical conditions and current-driven instabilities in plasmas.

A primary focus of the Combustion group was investigating how the unique properties of hydrogen combustion require novel computational methods and models. Other activities included an investigation of iron-powder combustion and the high-fidelity simulations of high-temperature gas-turbine combustors and rotating detonation engines.

The Analysis of Turbulent Boundary Layers group conducted several investigations of canonical, rotating, deforming and high-speed boundary layers. In addition to analyzing turbulence structure

and dynamics, new analysis techniques were developed for accounting for compressibility and pressure-gradient effects.

Finally, development of methodology and validation of large-eddy simulation technique to complex flows was the focus of the High-Fidelity Simulations and Applications group. The applications included drag reduction, trailing edge noise, transition process in high-speed boundary layers and performance of a helicopter rotor in hover.

As in previous years, four weekly tutorials were given during the Summer Program. The topics discussed in the tutorials this year were “Machine learning for turbulence modeling” by Adrián Lozano-Durán (MIT), “Resolvent analysis of turbulent flows” by Beverley McKeon (Caltech), “The transition to hydrogen: simulations of future engines and safety scenarios” by Thierry Poinsot (CERFACS-CNRS), and “Interface-resolved simulations of multiphase turbulent flows: achievements and new challenges” by Luca Brandt (KTH).

The participants of the 2022 Summer Program presented their accomplishments on August 12. This final event was attended by several colleagues from industry, academia and government.

The 2022 Summer Program was sponsored by the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), the Department of Energy (DoE), and the Office of Naval Research (ONR). The joint commitment of four different federal agencies to support the program underscores the importance of understanding and modeling multiphysics turbulent flows for engineering analysis. The wide discretionary mandate they afforded to CTR for selection of the technical projects featured in these volumes is much appreciated.

The collection of reports comprising the Proceedings of the 2022 Summer Program is available online. <https://ctr.stanford.edu/publications/summer-program-proceedings/proceedings-2022-summer-program>

2. Research Activities on Modeling Turbulence and Transition Using Data-Driven Approaches

Turbulence modeling and its applications are foundational activities of the Center for Turbulence Research. The name is now preceded by the term “data-driven,” which refers to progress compelled by data rather than by only physical insight and intuition. This might give the impression that data-driven turbulence modeling has recently emerged as a new branch within the realm of fluids, although the exploitation of data to enhance our physical understanding and modeling capabilities has been at the core of turbulence research from its early years. This is especially true since the advent of numerical simulations in the 1980s and 1990s. Even the experiments in transitional pipes by Osborne Reynolds in the 1880s could be regarded as “data-driven.” Nonetheless, it is undeniable that current advances in machine learning and data science have incited new efforts to complement the existing turbulence modeling approaches in the fluids community. Moreover, technological considerations call for the exploration of machine learning venues to avoid paradigm lock in the field. The stakes are high—for example, the impact of

turbulence models enabling the reduction of transportation drag by 5% is estimated to be equivalent to that of doubling the U.S. wind energy production.

During the 2022 CTR Summer Program, five projects dedicated to turbulence modeling for engineering applications have contributed to the development of new, groundbreaking ideas in the field. The focus of the group revolves around the common theme of data-driven modeling, and 11 scientists from 8 institutions worked for a month at Stanford University. The participants, supported by eight hosts, tackled problems of fundamental and technological significance, ranging from novel large-eddy simulation (LES) modeling strategies for complex flows to high-speed laminar-to-turbulent transition and computationally efficient methods for operator recovery.

The activities during the Summer Program include a subset of projects on novel approaches for LES. Ling et al. developed a unified subgrid-scale (SGS) and wall model for LES by devising the flow as a collection of building blocks. The model, referred to as BFM, computes an eddy viscosity via artificial neural networks (ANNs) that accounts for zero-pressure-gradient wall-bounded turbulence, adverse pressure-gradient effects, separation and laminar flow. The ANNs were trained to guarantee consistency with the numerical discretization and are applicable to complex geometries. The authors showed that BFM outperforms traditional SGS/wall models in the NASA Common Research Model High-Lift, becoming the first demonstration of a successful ANN-based LES model in a realistic aircraft configuration. Hansen et al. used proper orthogonal decomposition (POD) to augment the law of the wall in the traditional equilibrium wall model. The first POD mode extracted from a canonical turbulent channel flow was included as an additional term in the equilibrium wall model with a constant determined through a second matching location. They showed that the augmented model provides improved predictions in turbulent channel flows under non-equilibrium conditions such as strong mean unsteadiness and adverse pressure-gradient effects. The authors also hypothesized that further data-driven corrections from modal analysis might further improve the predictions in a wide variety of flows. The third wall model application is offered by Zhou et al., who developed a model using multi-agent reinforcement learning (RL) that captures pressure-gradient effects. In the RL approach, agents distributed along the wall learn how to predict the wall stress guided by a judiciously chosen reward. The model was trained in a periodic hill at low Reynolds number and successfully deployed over periodic hills at higher Reynolds numbers. An important outcome of the work is that imposing the wall shear stress through an eddy-viscosity is superior to the traditional wall shear stress boundary condition in terms of predicting the mean flow in the separated region.

The second group of applications includes modeling of high-speed laminar-to-turbulent transition and efficient operator recovery. Marxen et al. studied perturbation amplification in a Mach-4.8 flat-plate boundary layer with two-dimensional discrete roughness. High-fidelity simulation data was collected to train a neural network capable of predicting the effect of roughness on disturbance amplification. In addition, further physical insight into the mechanism for perturbation growth was gained using an autoencoder. The latter showed that disturbance frequency and roughness location can be combined into a single parameter. Bryngelson et al. presented a computationally efficient methodology to accurately reconstruct eddy-diffusivity operators using only a few simulations. The method utilizes peeling and sparse factorization to reduce the number of simulations required to recover key physical features of the operator. The approach was leveraged to reconstruct the

RANS eddy-viscosity tensor in a turbulent channel flow and was shown to be 100 times more economical than recovering the operator by perturbing degrees of freedom individually.

A general consensus from our discussions is that truly revolutionary improvements in turbulence modeling will encompass advancements in multiple fronts: physics, numerics, grid generation, wall/SGS modeling and so on. There is obviously also a data science component to the problem, such as the need for efficient and reliable machine learning techniques and efficient data analysis tools. Much progress has been made, as shown by the results discussed above, although machine learning is still far from being a panacea to solve long-standing problems in turbulence modeling. As in the times of Osborne Reynolds, physical understanding remains the cornerstone of turbulence modeling. Machine learning offers a set of powerful tools to accelerate progress as long as we recognize that problems are not solved by tools but by the people using the tools.

3. Research Activities on Data-Driven Methods

Owing to the inherent scale separation encountered in high-Reynolds-number turbulent flows, resolving all scales of turbulent motion with direct numerical simulation remains computationally intractable for the predictive analysis of most engineering systems. The simulation of reacting turbulent flows, which is relevant for characterizing not only the performance of internal combustion engines but also the external aerodynamics of hypersonic flight vehicles, often requires even further resolution due to the additional length scales and timescales introduced by the chemistry. By combining physical intuition and domain expertise with techniques from optimization, resolvent analysis and deep learning, the six projects in the Data-Driven Methods group have pursued the development of reduced-order models in order to mitigate the computational cost associated with the simulation and control of complex turbulent flows. The projects fall into the following two categories: (i) accelerating the numerical solution of partial differential equations for multiscale systems with machine-learned closures, and (ii) model reduction of dynamic systems for physical insight, development of control techniques and prediction of extreme events in wall-bounded turbulence.

With application to reacting hypersonic boundary layers, Scherding et al. refined a data-driven algorithm for constructing a lightweight thermochemical modeling library. By accelerating the computation of molecular transport properties and chemical reaction rates, the surrogate model halved the overall computational cost associated with the simulation of a Mach-10 laminar boundary layer. Through the utilization of local similarity solutions as training data, significant improvements in the efficiency of the data-driven approach itself were also realized.

Developing a machine-learned closure model for the truncated harmonic-balanced Navier-Stokes equations, Rigas & Schmid applied deep learning to enable accurate numerical solution of time-periodic flows in the frequency domain with a limited number of harmonics. As such, a neural network was utilized to model the impact of unresolved high frequency harmonics on the resolved dynamics of the flow. In applying the data-driven closure model to numerical simulation of flow past a cylinder, close agreement with direct numerical simulation was achieved with an appreciable reduction in the computational cost.

Investigating the relative importance of parametric and regenerative mechanisms for sustaining turbulence, Farrell et al. considered a set of modified Navier-Stokes equations for which a parameter is introduced to scale the magnitude of the fluctuation/fluctuation nonlinearity. In the context of Couette flow, modulation of this scaling parameter revealed the presence of two distinct regimes in which turbulence is maintained by parametric and regenerative mechanisms, respectively, together with a third regime characterized by laminarization. Further insight into the interaction between fluctuations and a timevarying base flow was achieved via application of time dependent resolvent analysis.

In order to reduce the computational cost associated with resolvent analysis, Gomez et al. developed an adaptive method based on Bayesian optimization and Gaussian process regression to efficiently locate regions of maximum resolvent gain in spectral space. The algorithm demonstrated particular promise for reacting flows, for which the state vector is augmented by a large set of species' concentrations. The subsequent application of adaptive resolvent analysis to high-enthalpy hypersonic boundary layers revealed that chemical activity can significantly influence the resolvent mode shapes as well as the associated gains, with the largest differences observed in the relatively subsonic region of spectral space.

Finally, Doan et al. proposed a data-driven approach for the prediction of extreme events in turbulent flows. Comprised of a convolutional autoencoder for dimensionality reduction and an echo state network for time advancement in the latent space, the method was applied to turbulent channel flow. The composite neural network successfully predicted not only the statistical properties of the velocity field but also the temporal evolution of quasi-relaminarization events for the minimal flow unit. In order to provide additional insight into this machine-learning method, Magri & Doan presented a methodology based on differential geometry for interpreting the latent spaces of autoencoders, together with an associated proper latent decomposition for turbulent flows.

4. Research Activities on Multiphase and Particle-Laden Flows

In the past two decades, multiphase flows have emerged as an important topic of research within the Center for Turbulence Research (CTR). In this Summer Program, similar to the past six editions, projects in the field of multiphase flows were agglomerated as a separate group. The Multiphase and Particle-Laden Flow group was in fact the largest among all groups, consisting of 8 projects, 15 participants, and 14 hosts. The work in this group spanned a wide range of topics, including four projects on particle-laden flows, two projects on interfacial flows, one project on transcritical flows, and one project on direct kinetic modeling of plasmas. In spite of the size of the group and diversity of the projects, we make note of a remarkably cordial, interactive, productive, and collaborative environment, which is reflected in the quality of the work carried out, summarized in the following.

Apte developed a novel approach that corrects for the self-disturbance created by particles in a two-way coupled approach. The method uses an overset grid to solve a system of advection-diffusion-reaction (ADR) equations to compute the disturbance field. One of the main advantages of the proposed method compared to other methods in the literature is that it is easily applicable to a wide range of flows, including wall-bounded flows, and can be used with different interpolation

kernels and arbitrary grids. Using this ADR method in simulations of particle-laden decaying isotropic turbulence, Apte et al. performed a systematic study on the effect of the choice of interpolation kernels (grid-based Roma and Gaussian) and kernel widths. They showed that the kernel widths used for Euler-to-Lagrange and Lagrange-to-Euler interpolations should scale with the particle size and be independent of the grid resolution to maintain the same region of influence of the particle on the flow, irrespective of the grid resolution. This was found to yield optimal accuracy. They also found that use of a wider kernel in proportion to the particle size, for Euler-to-Lagrange interpolation, will sample the flow from a region less affected by the particle disturbance, leading to better predictions of the particle velocity even without using any correction model for self-disturbance. This has significant implications in point-particle simulations of particle-laden flows.

As part of a large team effort led by Professor Schneider, Matsuda et al. developed a wavelet transformation–based multiresolution tessellation technique to analyze scale dependent statistics of particle velocity divergence in turbulent flows. They verified the newly developed method by comparing it against the energy spectrum obtained from a Fourier-based approach using two test cases: (i) synthetic randomly distributed particles and (ii) inertial particles in isotropic turbulence from direct numerical simulations (DNSs). This fast and efficient tool, which doesn't require the projection of particle cloud data onto Eulerian grids, can be used to understand the multiscale dynamics of particle clustering in turbulent flows. Another work from this team was on the development of data-driven machine learning models for predicting preferential concentration of particles in isotropic turbulence (Oujia et al.). They trained autoencoder, U-Net, and generative adversarial networks (GANs) to predict the particle density fields using the flow field as the input, and vice versa, and validated the models using DNS data. They found that the GANs are accurate in predicting the statistical quantities of interest for particle distributions, which has implications for subgrid modeling of particle-laden turbulence. Finally, West et al. performed four way–coupled simulations of particle-laden turbulent channel flow for various mass loadings, and computed the divergence and curl of the particle velocity using Delaunay tessellation. They performed statistical analyses of these quantities at various locations away from the wall and found that the divergence and curl are strongest in the buffer layer, owing to the stronger fluctuations of fluid velocity. They also found that increasing mass loading results in damping of these quantities in the viscous sublayer.

Vartdal and Jain performed particle-resolved simulations to generate a database of the flow around monodispersed particles at various Mach and Reynolds numbers, particularly in the presence of volume fraction gradients. Using the database, closure models for volume-averaged multiphase flows were improved. They found that the drag law that was previously derived from homogeneous conditions gave accurate predictions in the presence of volume fraction gradients. Additionally, they proposed a modification to the previously developed algebraic model for pseudo-turbulent stresses by correctly accounting for the effect of volume fraction gradients using the information of the wake of the particles upstream. This work can be applied to modeling various particle-laden flows of engineering interest.

Santos et al. studied the effect of subgrid-scale (SGS) turbulence on the flight behavior, transport, and settling distribution of size-changing firebrand particles in atmospheric turbulent boundary layers. An approximate deconvolution-based SGS model was used to account for the effect of SGS

turbulence on particles, and a dynamic burning model was incorporated to account for the variation in size and mass of the smoldering flying firebrand particles. They found that the SGS turbulence makes particles travel larger distances along the streamwise direction and shorter distances along the spanwise direction, and results in reduction of overall dispersion of particles. This study has implications for the accurate prediction and modeling of wildland fires, since the transport of firebrand particles by wind is the primary mechanism responsible for the spread of these fires.

Scapin et al. developed a numerical method for simulating low-Mach compressible twophase flows involving phase change and wetting effects. The method uses a four-equation diffuse interface model, augmented by regularization terms for maintaining the interface thickness, relaxation terms for phase change, and Lagrange multipliers for imposing contact angles while preserving mass conservation. Multiple test cases, including tests involving boiling for varying levels of surface wettability, demonstrated the method's robustness and accuracy for practical simulations.

Goodrich et al. extended the dual-scale subgrid closure for large-eddy simulation (LES) of two-phase flows to handle phase change. By capturing the transport of the interface due to resolved and modeled subgrid velocities on a high-resolution overset mesh, filtered interface quantities are computed directly. This work studied the effect of subgrid velocities due to phase change and their interaction with surface tension forces. Comparing against DNS of an interface undergoing phase change in HIT, the authors demonstrated their LES model's accuracy in the infinite Weber number regime. Moreover, these simulations were analyzed to reveal the restorative role of surface tension forces on interface curvature statistics during phase change.

In a trailblazing effort, Bernades et al. (a,b) explored the possibility of turbulence in microfluidic devices, allowing for enhanced mixing and transfer rates that can be especially beneficial in energy applications. They introduced a novel kinetic-energy-preserving and pressure-equilibrium-preserving numerical scheme [Bernades et al. (a)] that enabled the computational observation of microconfined turbulence in high-pressure transcritical conditions [Bernades et al. (b)]. The numerical model developed in this work can be useful to the community in the broad context of modeling compressible flows with real-gas effects (e.g., transcritical and supercritical conditions). Most notably though, the DNS results in this project revealed that the statistics of microconfined turbulence in supercritical fluids deviates from standard turbulent flows (e.g., modified law of the wall), and that heat transfer rates are amplified by a factor of 20 compared to an equivalent subcritical configuration.

With the overarching goal of achieving a fundamental understanding of plasma turbulence, Chan et al. developed a direct kinetic solver to study current-driven plasma instabilities in one- and two-dimensional settings. Spectral analysis was used to reveal the interplay of longitudinal and transverse instabilities in the transition to plasma turbulence, in addition to the similarities and disparities of plasma turbulence compared to hydrodynamic turbulence. We expect the simulation tool and analysis approach developed in this project to aid in addressing many fundamental questions in the field of plasma turbulence.

5. Research Activities on Combustion

High-fidelity numerical simulation of turbulent combustion has become an important tool for guiding the design of energy and propulsion systems in aerospace, transportation and various other industrial sectors. Ever-increasing demands for clean and sustainable energy have recently been driving combustion research toward carbon-free technologies and efficient engine design—“to burn less but burn better,” as phrased by Thierry Poinsot.

The research topics addressed in the CTR Summer Program 2002 Combustion subgroup highlight this trend. Targeted application systems of the six projects cover lean hydrogen combustors, high-temperature gas-turbine engines, rotating detonation engines (RDEs) and iron-powder combustors. Modeling of these systems may require not only the extension of previous simulation tools to accommodate new regimes of flows, chemistry and/or geometries but also deep insights into underlying flow physics, which can be unique to the fuels and engines considered therein. To this end, each project primarily focused on physics-based modeling and analysis of flames and combustion that are relevant to the targeted systems.

Hydrogen is attracting considerable attention as a low-emission fuel. Flames of lean hydrogen/air mixtures tend to be thermodynamically unstable due to strong differential diffusion. The instability can lead to small-scale flame wrinkling, which may influence the fuel consumption rate and NO_x production. Previous simulation tools, which do not account for the effects of instability, may not provide accurate predictions of the efficiency and pollutant emission of application systems.

Three projects addressed hydrogen flames with an emphasis on the thermodynamically unstable instability. Berger et al. developed a subgrid-scale model for large-eddy simulation (LES) of premixed hydrogen flames, which accounts for the instability in the flamelet-progresses variable framework. Manifold optimization was performed to accurately parameterize the subgrid-scale probability density functions of transport variables. A-priori analysis of this model using three-dimensional (3D) direct numerical simulation (DNS) data of canonical slot-burner flames showed favorable results. Wen et al. performed 2D and 3D DNS of canonical, thermodynamically unstable premixed hydrogen flames to characterize the NO_x formation. Results show that 3D simulation is crucial to accurately predicting the NO_x production. A reaction path analysis was conducted to identify relevant reaction pathways. Moreover, the performance of a flamelet model in predicting the NO_x species was evaluated a-priori. The model accuracy was found to critically depend on the local flame curvature. Aniello et al. developed a dynamic thickened-flame (TF) model for LES of premixed hydrogen flames to account for the instability. The effects of subgrid-scale flame wrinkling and modifications of the consumption rate were parameterized to express the efficiency function, with the aid of DNS data provided by Berger et al.. The TF model was used to simulate flames in realistic swirl combustors. Results were compared with recent experiments.

RDEs are promising for propulsion and energy systems due to their high potential efficiencies and compact designs. The criteria of detonation-to-deflagration transition (DDT) in realistic RDEs are elusive. Elasrag et al. introduced a characteristic Damkholder number (Da) to distinguish detonation and deflagration regimes in hydrogen/air flames. The Da is defined in terms of the H radical that was identified as a suitable ignition indicator in chemical explosive mode analysis of 1D

canonical flames. This criteria was applied to various simulation data of detonation flames, including those of AFRL 6-inch RDE.

The operating temperature of gas-turbine engines is continuously increasing to improve combustion efficiency. Accurate predictions of the temperature distribution on the combustor wall are crucial for cooling design. Cui & Bose performed coupled wall-modeled LES and conjugate heat transfer analyses of the full-scale NASA Energy Efficient Engine combustor. The simulated temperature distribution on a perforated cooling liner in the combustor showed favorable agreements with previous measurements.

Finally, iron powders produced as industrial byproducts can be considered to be carbon-free renewable fuels. Combustion processes of gaseous turbulent flows laden with nano-sized iron particles have not been fully understood. Ravi et al. introduced an Eulerian-Lagrangian framework to resolve the fine-scale flow field near individual reacting particles by using a distribution kernel method. A grid-convergence study was performed by simulating the reaction of a single isolated particle. A canonical 2D simulation was performed to capture the formation of discrete flames in a stoichiometric, dilute particle/air mixture.

6. Research Activities on Analysis of Turbulent Boundary Layers

Turbulent boundary layers play a key role in a wide range of natural and engineered flows. The atmospheric boundary layer mediates many of the most crucial phenomena for understanding weather and climate patterns, including natural disasters such as wildfires and hurricanes. Aquatic wildlife such as sharks and dolphins have long been admired for their low drag and high swimming velocities. Transition to turbulence is costly for many aerodynamic and hydrodynamic vehicles, from civilian and military aircraft to large transport ships. Turbulent boundary layers are also ubiquitous in the energy sector, from gas turbine engines to large-scale wind farms. Even with such wide-ranging applicability, our current understanding of the fundamental physics of wall-bounded turbulence leaves much to be desired. Key topics include the identification and role of coherent structures and the development of efficient flow control and drag reduction technologies, as well as understanding how turbulent boundary layers respond to high-speed effects. These issues were the focus of six projects in the Analysis of Turbulent Boundary Layers group.

Coherent structures in atmospheric boundary layers were the topic of Momen et al., who studied the effect of rotation on hurricane boundary layers. They utilized a novel scheme to simulate the hurricane boundary layer in a subregion so as to avoid the need to include the entire storm in the simulation domain. This allowed for turbulence-resolving large-eddy simulations to be run over a range of parameter values. The team analyzed the effects of physical parameters such as distance from the center of the storm as well as numerical parameters such as subgrid model coefficients. Meanwhile, Elnahas et al. studied coherent structures in aerodynamic boundary layers. They identified and tracked structures through the late stages of transition to observe the similarities and differences between the transitional and fully turbulent regions. In this work, structures are identified as coherent regions of space belonging to the same quadrant via quadrant analysis. Quadrant analysis assigns each point in space into one of four quadrants based on the sign of streamwise and wall-normal velocity fluctuations, allowing for the identification of coherent ejections and sweeps. They identified that the geometrical properties of strong and attached sweeps

and ejections are the same between the fully developed stages of turbulence and the late stages of transition.

Yang et al. proposed a transformation for boundary layers with imposed streamwise pressure gradients. Inspired by variable property transformations used for high-speed boundary layers, this work nondimensionalizes the streamwise velocity and wall-normal coordinate using local velocity and length scales that vary with wall-normal distance. The transformation successfully collapses a wide range of velocity profiles into a single law of the wall profile.

On the topic of flow control and drag reduction, Shariar et al. developed a fully coupled computational framework for fluid/structure interaction to study the potential of passive flow control and drag reduction via the design of compliant surfaces. Taking inspiration from dolphin skin, an anisotropic subsurface structure is studied in their work. One key step in their work is the homogenization of the complex subsurface material structure to simplify the computational task. Due to the high cost of direct simulation with fluid/structure interaction, resolvent analysis is used to identify regions of interest in the overwhelmingly large parameter space for this problem.

At high Mach numbers, aerodynamic heating decreases the mass density and increases the viscosity within boundary layers. The net result is lower skin friction coefficients and Stanton numbers as the Mach number increases, but the wall temperature boundary condition also plays an important role. Kianfar et al. has extended the Angular Momentum Integral (AMI) equation to compressible flows to quantify how changes to the flow within turbulent boundary layers at high Mach number lead to the observed changes in skin friction and surface heat flux, providing a fundamental connection between high-speed turbulent boundary layer physics and engineering quantities of interest. When the freestream enthalpy is high enough, even more physical phenomena come into play. Di Renzo et al. elucidate the impact of the vibrational excitation of gas molecules on turbulent boundary layers. In this study, a canonical compression ramp geometry is chosen to characterize high-enthalpy effects on shock-boundary-layer interactions. In particular, it is shown that vibrational excitation can have significant effects on the heating and structural loads relevant to hypersonic vehicle design.

7. Research Activities on High-Fidelity Simulations and Applications

Advancing our understanding of engineering problems involving wall-bounded, turbulent shock-laden flows requires the development of high-fidelity computational tools, including robust numerical methods and predictive reduced-order models. Such problems often feature high Mach numbers, flow discontinuities and unsteadiness. Developing and evaluating predictive science tools for these complex flows were the primary focus of the High-Fidelity Simulations and Applications group.

In wall-bounded turbulence, drag reduction is a compelling challenge. Inspired by drag-reducing riblets, Zahtila et al. perform direct numerical simulations to quantify the drag-reduction potential of surfaces generated from a Miura-origami basis. The authors attempt to interpret their findings via analogy with drag reduction due to the dynamic oscillation of walls. Their work is a first step toward optimal, dynamic origami surface-based design in the drag-reduction context.

For compressible flows, the wall temperature boundary condition also affects drag. On this note, De Broeck et al. investigated the temporal stability problem for a compressible boundary layer over a cooled wall with impedance boundary conditions. Their findings provide an explanation for the stabilization effects of temperature-controlled impedance walls, with additional developments for applications involving porous surfaces.

For robust and accurate simulations and control of shock-laden flows, numerical methods need to be devised that correctly capture shocks and their sensitivity to change. Bodony & Fikl study the adjoint-based sensitivity of shock-driven flows to parametric changes in the governing equations or to internal forcing, with a specific focus on calculating the resolvent and input/output operators for shock-laden flows. Using the nonlinear inviscid Burgers' equation as a guide, they show that localized artificial diffusivity-based methods produce correct discrete adjoints, while stencil-switching schemes like MUSCL and WENO do not.

The large-eddy simulation (LES) paradigm is an attractive approach for studying turbulent flows with increasingly high Reynolds numbers, but the filter kernel-wall interaction has complicated the modeling effort. In this spirit, Ghosal et al. propose a new formulation of LES in which the filter width is fixed as the wall is approached. This formulation removes many mathematical inconsistencies in the LES equations, while potentially creating a new approach for constructing a reduced-order model to study near-wall physics. In this work, the unfiltered or primitive field is filtered using a fixedwidth filter to generate both an interior closure problem and a surface LES field that interacts with it through surface stresses and source terms.

With the existing combinations of minimum dissipation numerics and phenomenological subgrid-scale models, LES is also used as a predictive and analytic tool for complex engineering systems. Two projects in this group focus on applications of LES, specifically in the flow over an airfoil for noise detection and in rotor-blade applications for hover.

Lee et al. perform wall-resolved LES to analyze noise caused on a high angle of attack, NACA0012 airfoil geometry. Using wavelet thresholding, the authors decompose the pressure field to identify the dominant noise source at specific frequencies, such as the noise from low-frequency vortex shedding and from the high-frequency laminar separation bubble and trailing-edge noise. This work advances the value of wavelet-based decomposition as a tool to study mechanisms of airfoil noise generation.

Finally, Stratton et al. study the problem of a scaled helicopter rotor in hover, which is one of the most challenging applications in which LES has been used to date. Their systematic analysis quantifies the effects of laminar-turbulent transition over the blade and its impact on integrated forces. Despite the complex flow phenomena involving bladevortex interactions, the authors demonstrate the ability of LES to accurately predict forces over the blade with as few as 2–7 grid points within the boundary layer. A remarkable feature of this work was that the turnaround times for these simulations were under two days on 40 GPUs, which points to the readiness of LES for widespread use in industrial applications.

8. List of Publications Compiled in the Proceedings of the 2022 Summer Program - <https://ctr.stanford.edu/publications/summer-program-proceedings/proceedings-2022-summer-program>

I. Modeling Turbulence and Transition Using Data-Driven Approaches

Wall-modeled large-eddy simulation based on building-block flows.

Y. Ling, G. Arranz, E. Williams, K. Goc, K. Griffin and A. Lozano-Duran

POD-mode-augmented wall model and its applications to flows at nonequilibrium conditions.

C. Hansen, M. P. Whitmore, M. Abkar and X. I. A. Yang

Multi-agent reinforcement learning for wall modeling in LES of flow over periodic hills.

D. Zhou, M. P. Whitmore, K. P. Griffin and H. J. Bae

Investigation and prediction of roughness-induced high-speed boundarylayer transition using machine learning.

O. Marxen, A. T. Margaritis, P. J. Schmid, T. J. Flint and G. Iaccarino

Fast Macroscopic Forcing Method.

S. H. Bryngelson, F. Schafer, J. Liu and A. Mani

II. Data-Driven Methods

Data-driven reduction of lookup libraries for the simulation of non-equilibrium effects in hypersonic flows.

C. Scherding, T. Sayadi, C. Williams, M. Di Renzo, G. Rigas and P. J. Schmid

Data-driven closure of the harmonic-balanced Navier-Stokes equations in the frequency domain.

G. Rigas and P. J. Schmid

Investigating nonlinearity in wall turbulence: regenerative versus parametric mechanisms.

B. F. Farrell, E. Kim, H. J. Bae, M.-A. Nikolaidis and P. J. Ioannou

Adaptive resolvent analysis with application to high-enthalpy flows.

S. Gomez, C. Williams, M. Di Renzo, P. Schmid and B. McKeon

Convolutional autoencoded echo state network for the prediction of extreme events in turbulence.

N. A. K. Doan, A. Racca and L. Magri

On interpretability and proper latent decomposition of autoencoders.

L. Magri and N. A. K. Doan

III. Multiphase and Particle-Laden Flows

A zonal advection-diffusion-reaction model for self-disturbance correction in point-particle computations.

S. V. Apte

Effect of interpolation kernels and grid refinement on two waycoupled point-particle simulations.

S. V. Apte, N. Keane, S. S. Jain and M. A. Khanwale

Multiresolution analysis of inertial particle tessellations for clustering dynamics.

K. Matsuda, K. Schneider, T. Oujia, J. West, S. S. Jain and K. Maeda

Neural networks for synthesizing preferential concentration of particles in isotropic turbulence.

T. Oujia, S. S. Jain, K. Matsuda, K. Schneider, J. West and K. Maeda

Divergence and curl of the inertial particle velocity in a four-way coupled turbulent channel flow.

J. R. West, T. Oujia, K. Matsuda, K. Schneider, S. S. Jain and K. Maeda
Improving volume-averaged particle-laden flow models using resolved simulations of particle diffusers.

M. Vartdal and S. S. Jain

Lagrangian subgrid-scale modeling applied to evolving firebrand particle transport.

I. D. Santos, B. Mahato, B. Bornhoft, S. S. Jain and N. Yaghoobian

A mass-conserving pressure-based method for two-phase flows with phase change.

N. Scapin, A. Shahmardi, W. H. R. Chan, S. S. Jain, S. Mirjalili, M. Pelanti and L. Brandt

A dual-scale sub-grid closure for LES of phase interfaces with phase change.

A. Goodrich, D. Kedelty and M. Herrmann

Flow physics characterization of microconfined high-pressure transcritical fluids turbulence.

M. Bernades, F. Capuano, K. Maeda and L. Jofre

Investigation of a novel numerical scheme for high-pressure supercritical fluids turbulence.

M. Bernades, L. Jofre and F. Capuano

Spectral analysis of multidimensional current-driven plasma instabilities and turbulence in hollow cathode plumes.

W. H. R. Chan, K. Hara, J. M. Wang, S. S. Jain, S. Mirjalili and I. D. Boyd

IV. Combustion

Development of large-eddy simulation combustion models for thermodiffusive instabilities in turbulent hydrogen flames.

L. Berger, A. Attili, J. Wang, K. Maeda and H. Pitsch 247

Characteristics and NO_x formation mechanism of thermodiffusively unstable premixed hydrogen flames.

X. Wen, L. Berger, K. Maeda, J. Wang, A. Parente and H. Pitsch

Introducing thermodiffusive effects in large-eddy simulation of turbulent combustion for lean hydrogen-air flames.

A. Aniello, D. Laera, L. Berger, A. Attilik and T. Poinsot

A Local criterion for distinguishing detonation and deflagration for pressure gain combustion.

H. A. Elasrag, J. Hoke, B. Rankin and S. A. Schumaker

Investigation of the effect of conjugate heat transfer on the adiabatic effectiveness of an annular gas turbine engine combustor.

M. Cui and S. Bose

Modeling turbulence interaction with reacting iron particles.

S. Guhathakurta, S. S. Hemamalini, A. Ravi, J. A. van Oijen, B. Cuenot, J. Wang, K. Maeda, H. Wang and X. C. Mi

V. Analysis of Turbulent Boundary Layers

Characterizing mean and turbulent structures of hurricane winds via large-eddy simulations.

F. Sabet, Y. R. Yi, L. Thomas and M. Momen

Geometrical comparison of the Reynolds shear stress within boundary layer transition and fully developed turbulence.

A. Elnahas, A. Lozano-Duran and J. Wallace

A universal velocity transformation for boundary layers with pressure gradients.

X. I. A. Yang, P. E. S. Chen, W. Wu and K. P. Griffin

A framework for studying turbulent boundary layer interaction with anisotropic compliant surface.

A. Shahriar and K. Shoele

An angular momentum integral equation for high-speed boundary layers.

A. Kianfar, M. Di Renzo, C. Williams, A. Elnahas and P. L. Johnson

Stagnation enthalpy effects on turbulent compression corner flow at Mach 5.

M. Di Renzo, C. T. Williams, J. Urzay and S. Pirozzoli

VI. High-Fidelity Simulations and Applications

Influence of Miura-origami shapes on drag in turbulent flows.

T. Zahtila, L. Chan, A. Ooi, K. Liu, M. Benjamin and G. Iaccarino

Temporal stability analysis of high Mach number boundary layers over cooled impedance walls.

L. De Broeck, S. Görtz, T. Flint, C. Gonzalez, M. Oberlack and S. Lele

Adjoint-based sensitivity of shock-laden flows.

D. J. Bodony and A. Fikl

A new approach to large-eddy simulations of wall-bounded turbulence using a fixed-width filter.

S. Ghosal, R. Agrawal, A. Elnahas and P. Johnson

Airfoil trailing-edge noise source identification using large-eddy simulation and wavelet transform.

S. Lee, D. Kang, D. Brouzet and S. K. Lele

Rotor performance and turbulent wake simulations of a scaled helicopter

rotor in hover using wall-modeled large-eddy simulations.

Z.T. Stratton, S.T. Bose and J. Svorcan

9. Participants' Countries/Institutions

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Germany	RWTH Aachen Univerity Technische Universitat Munchen
Greece	National and Kapodistrian University of Athens
Italy	Sapienza University of Rome
Japan	Japan Agency for Marine-Earth Science and Tech
Netherlands	Delft University of Technology Eindhoven University of Technology
Norway	Norwegian Defence Research Establishment Norwegian University of Science and Technology
Saudi Arabia	KAUST
Spain	Universidad Politecnica de Catalunya

Sweden
United Kingdom

United States

Barcelona Tech
Royal Institute of Technology
Imperial College London
University of Edinburgh
University of Surrey
The Alan Turing Institute
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California Institute of Technology
Cascade Technologies, Inc.
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Florida State University
Georgia Institute of Technology
Harvard University
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Naval Air Warfare Center
Northwestern University
Oregon State University
Pennsylvania State University
Princeton University
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University of Maryland