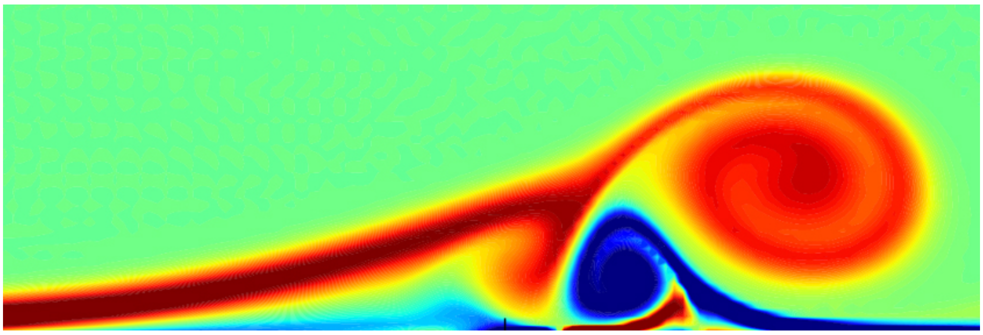
3rd UKFN SIG Meeting

Flow instability, modelling and control



Book of Abstracts

19 April 2024

Welcome and general information

Dear colleagues,

The SIG on Flow Instability, Modeling, and Control serves as a forum for UK experts, researchers, and practitioners to share their latest findings on flow instability, control, reduced order modelling, data-assimilation, dynamical systems, machine learning etc. To this end, we are pleased to organise the 3rd SIG event.

Location. The event will be held at **Imperial College London, in room 300 of the City and Guilds Building (CAGB)** with refreshments provided in the ground floor foyer of the building.

Speakers, flash talks & posters. We have allocated 15 min for each oral presentation (12 minutes for presentation, 2 min Q/A, 1 min change over). Poster presenters will have the opportunity to present their work in 3-minute flash talks. Posters will be displayed in the ground floor foyer of the building. The poster boards have dimensions 1m $\times$ 1m; these are the maximum dimensions of the printed posters.

Attendance. The event will be held in-person and registration is **free of charge**, but attendees will have to cover their travel, accommodation (if needed) and food expenses. For lunch, you are welcome to use any of the several nearby venues on campus and around the college. There are 17 outlets on South-Kensington campus that provide lunch/drinks (more details: www.imperial.ac.uk/food-and-drink/catering-outlets/) and plenty of options nearby at Gloucester road and around the South Kensington tube station.

We hope that you will enjoy the event!

The Organising Committee

George Papadakis
Davide Lasagna
Georgios Rigas
Elena Marensi

Programme

09:00 – 09:25 Arrival

09:25 – 09:30 Welcome

09:30 – 10:30 Invited talk – Chair George Papadakis
Valerio Lucarini – *Advancing our knowledge on the climate crisis by combining response theory and Koopmanism*

10:30 – 12:00
Session 1: Dynamical Systems and Machine Learning – Chair Ashley P Willis

Ira Shokar – *Extending Deep Learning Emulation Across Parameter Regimes to Assess Stochastically Driven Spontaneous Transition Events*

Xiaodong Li – *Frequency-domain nonlinear reduced-order modelling for turbulent flow*

Jacob Page – *Koopman deadzones*

Defne Ege Ozan – *Data-driven inference of adjoint sensitivities without adjoint solvers*

Liang Fang – *A Regularised Shadowing Method for Sensitivity Analysis of Chaotic Flows*

Chi Hin Chan – *State-space pathways towards spiral defect chaos*

12:00 – 12:15 Flash talks

12:15 – 13:45 Lunch

13:45 – 15:00
Session 2: Stability and transition – Chair Juan Guzman-Inigo

Pierre Ricco – *Nonlinear evolution of vortical disturbances entrained in the entrance region of a circular pipe*

Juhno Park – *Instability of stratified and thermally diffusive Taylor-Couette flow*

Abishek Kumar – *Suppressing instabilities in mixed convective flow using an actuation based on receptivity*

Pushpender Sharma – *Modal response of a shock-induced separation bubble under random forcing*

Shijun Chu – *The minimal seed for transition to convective turbulence in heated pipe flow*

15:00 – 15:30 Coffee break and Posters

15:30 – 16:30
Session 3: Data assimilation and Data-Driven methods – Chair Sean Symon

Matthew Juniper – *Adjoint-accelerated Bayesian Inference for data assimilation*

Matthew Yoko – *Inferring thermoacoustic properties of turbulent flames from pressure data*

Craig Thompson – *The state observer method applied to high intensity turbulence around a stalled airfoil*

Yunjiu Yang – *QSQH synthetic turbulence model*

16:30 – 18:00 Drinks reception

Invited talk

Prof. Valerio Lucarini, (v.lucarini@leicester.ac.uk) Professor of Applied Mathematics in the School of Computing and Mathematical Sciences, University of Leicester

Title: Advancing our knowledge on the climate crisis by combining response theory and Koopmanism.

Abstract: For systems near thermodynamic equilibrium, the classical fluctuation-dissipation theorem provides a powerful framework for relating forced and and free variability. By collecting sufficient statistics on the unperturbed system, we can predict its (linear) response to forcings. Things become considerably more challenging when studying general nonequilibrium systems, which are in fact ubiquitous in a multitude of applications. I will first discuss how using a more general form of response theory it is possible to perform climate change projections using climate models of different level of complexity, ranging from conceptual to fully-blown Earth System Models. I will then show how combining such theoretical framework with Koopmanism one can find a) a decomposition of the response operator as a sum of interpretable terms, each associated with a mode of variability of the system and b) develop a general theory of critical transitions in complex system and identify the critical mode associated with the loss of stability of a reference state. This perspective is extremely promising as it combines theoretical clarity with clear connections with much studied and developed data-driven methods.

References

V. Lucarini and M. Chekroun, Theoretical tools for understanding the climate crisis from Hasselmann's programme and beyond. Nat. Rev. Phys. (2023) doi: 10.1038/s42254-023-00650-8

M. Santos Gutiérrez and V. Lucarini, On some aspects of the response to stochastic and deterministic forcings, J. Phys. A: Math. Theor. 55 425002 (2022)

M. Ghil and V. Lucarini, The Physics of Climate Variability and Climate Change, Rev. Mod. Phys. 92, 035002 (2020)

Flash talks (posters)

Uttam Cadambi Padmanaban, Sean Symon and Bharathram Ganapathisubramani (University of Southampton)

Data assimilation of turbulent flows

3D data assimilation using experimental data can reduce the cost of studying turbulent separated flows by minimizing the number of experimental campaigns and reducing the computational cost of performing high fidelity simulations. We use the variational data assimilation with the discrete adjoint method implemented in DAFoam to investigate the possibility of combining experimental data with RANS simulations. A NACA0018 airfoil at 10 degree angle of attack and a Reynolds number of 10,000 is assimilated using full-field experimental data and Spalart-Allmaras (SA) RANS turbulence model by optimizing a momentum forcing. The reconstruction of the mean velocity field is remarkably accurate. This is then followed up by a 3D data assimilation of a surface mounted cube at Reynolds number 40,000 using time-averaged LES data as reference data and employing a correction to the production term of the turbulence transport equation of the SA model. A single spanwise-wall-normal plane of data that is placed a unit length downstream of the cube is able to correct the mean velocity in the entire domain. The learnings from these studies will be used to perform data assimilation for a more complicated 3D cases with experimental data.

Ekrem Ekici and Matthew P. Juniper (University of Cambridge)

Adjoint-based Shape Optimization for Thermoacoustic Stability of Combustors Using Free Form Deformation

We use the thermoacoustic Helmholtz equation to model thermoacoustic oscillations as an eigenvalue problem. We solve this with a Finite Element method. We parameterize the geometry of an annular combustor geometry using Free Form Deformation (FFD). We then use the FFD geometry, define the system parameters and impose the acoustic boundary conditions to calculate the eigenvalue and eigenvector of the problem using a Helmholtz solver. We then use adjoint methods to calculate the shape derivatives of the unstable eigenvalue with respect to the FFD control points. According to these gradients, we propose modifications to the control points that reduce the growth rate. We demonstrate the application of this approach on an industrial gas turbine combustor and lower the growth rate of the axial thermoacoustic mode. The findings show how this method could be used to reduce combustion instability in industrial annular combustors through geometric modifications.

Sidhartha Sahu and George Papadakis (Imperial College London)

Dynamical System analysis of irregular flow around two square cylinders

We investigate the dynamics of the irregular flow over two side-by-side square cylinders at Reynolds Number of 200, and gap ratio of 1. For this set of parameters, the flow is chaotic. We linearise the Navier-Stokes equations around the unsteady chaotic trajectory of the system and study the tangent space. We identify the characteristic Lyapunov exponents (LEs) of the flow using a Gram-Schmidt-based periodic orthonormalization algorithm. Furthermore, we also obtain the Covariant Lyapunov Vectors (CLVs) of the flow using the dynamical algorithm proposed by Ginelli The CLVs correspond to the eigenvectors of a typical linear stability analysis; the latter however is performed on a steady base flow, but in our analysis we have a time-varying base flow. For unsteady flows, analysis of a time-varying tangent space is physically more meaningful than performing linear stability analysis on a time-average base flow. We find that CLVs corresponding to the larger LEs consist of small-scale structures that have a footprint close to the cylinders. On the other hand, CLVs corresponding to the smaller LEs appear further away in the wake and consist of larger structures. To further study its features , we apply Proper Orthogonal Decomposition (POD) to the time varying CLVs. Additionally, we explore the system hyperbolicity by analyzing the angles between CLVs, which partition the tangent space into unstable, neutral, and stable subspaces. Hyperbolicity is an important property and is crucial for understanding system responses to parameter changes, it is also a key assumption of the shadowing lemma.

Elise Özalp and Luca Magri[*+] ([*]Imperial College London, [+]The Alan Turing Institute and Politecnico di Torino)

Learning the latent dynamics of turbulent Kolmogorov flow

The dynamics of turbulent flows are chaotic and characterized by multi-scale interactions. This makes the design of accurate reduced-order models for forecasting of turbulent systems challenging. We propose a fully data-driven method to predict the turbulent flow based on a reduced-order model. First, we compute a low-dimensional latent space with a convolutional autoencoder (CAE), approximating the manifold where the turbulent dynamics occur. Second, the temporal dynamics are predicted with two types of recurrent neural networks, a long short-term memory network (LSTM) and echo state network (ESN). This work employs two hybrid architectures, the CAE-LSTM and the CAE-ESN, for the latent space prediction of the turbulent Kolmogorov flow at Re=40, which exhibits turbulent behaviour and extreme events of dissipation. The vorticity snapshots are compressed with the CAE to a latent dimension of 96 (4% of the original size), then propagated with the ESN and LSTM. We show that both architectures accurately predict the next vorticity snapshot, even during extreme events. When feeding the prediction back as an input to the network, the networks autonomously predict the vorticity development over 4.5 eddy turnover times. The results suggest that forecasting short time windows can be effectively achieved by solely integrating the temporal evolution of the low-dimensional latent dynamics of extreme turbulence.

Session 1
Dynamical Systems and Machine Learning
(Chair Ashley P Willis)

Ira Shokar, Rich Kerswell and Peter Haynes (University of Cambridge)
Extending Deep Learning Emulation Across Parameter Regimes to Assess Stochastically Driven Spontaneous Transition Events

Given the difficulties encountered by neural networks when extrapolating beyond their training distribution and the computational complexities associated with simultaneous multi-task learning, we leverage fine-tuning to enable a transformer-based network to generalise across a range of parameters when emulating stochastic dynamical systems at a reduced training cost. We demonstrate the network's ability to generalise across diverse parameter regimes, including those not encountered during training, providing a resource-efficient approach for capturing stochastic models of physical systems. We validate the statistical properties of the proposed approach, ensuring alignment with the underlying physics across various integration periods. Notably, the deep learning approach method provides emulations five orders of magnitude faster than traditional numerical methods, facilitating the cost-effective generation of large ensembles. This acceleration enables the quantification of probabilities associated with spontaneous transition events, such as nucleation and coalescence of jets, and rapid changes in the rate of latitudinal translation, even in regimes not observed during training.

Xiaodong Li and Davide Lasagna (University of Southampton)
Frequency-domain nonlinear reduced-order modelling for turbulent flow

Gradient computation of turbulent flow quantities is of high importance in optimization and flow control. However, reliable and efficient methods to obtain these gradients are lacking due to the chaotic nature of turbulence. In previous work, we proposed to use Unstable Periodic Orbits (UPO) to bound the exponential growth of adjoint solutions. Although finding UPOs is feasible in low-dimensional dynamic systems or low-Re turbulent flows, the computing cost becomes expensive for high-Re turbulent flows. Rather than finding UPOs in full-state space, we propose here to utilize a reduced-order model (ROM) to circumvent such impediment while the benefit of periodicity constraints is maintained by considering the ROM in the frequency domain. To this end, the spatio-temporal basis functions of the low-order space are extracted using Spectral Proper Orthogonal Decomposition (SPOD). The Navier-Stokes equations are converted into a low-order nonlinear algebraic system via Galerkin projection. Due to the truncation of SPOD modes, the amplitude coefficients projected from flow data violate momentum conservation. Therefore, the ROM's amplitude coefficients are tuned with gradient-based optimization to conserve the momentum. The proposed approach is validated in a 2D lid-driven cavity at $Re = 20,000$. Numerical results show that the frequency-domain ROM captures dominant dynamical flow features and predicts well statistical quantities.

Jacob Page* and Rich Kerswell+ (*University of Edinburgh, +University of Cambridge)
Koopman deadzones

A Koopman decomposition of the state variables in a dynamical system appears to offer new opportunities for prediction and control owing to its simple, linear representation of nonlinear dynamics. However, analytical construction of Koopman expansions in a simple one-dimensional nonlinear system has shown that these representations can have a finite radius of convergence (Page & Kerswell, J. Fluid Mech. 879, 2019), breaking down at a crossover point along a connecting orbit between fixed points. In this talk we will show that the situation can be much 'worse' in more complex systems, and that there may be extended regions of state space where no Koopman decomposition exists at all. We refer to this phenomenon as a deadzone. We will explore the existence of deadzones in some simple canonical problems with additional fixed points and/or complex singularities, both analytically and with the assistance of dynamic mode decomposition.

Defne Ege Ozan* and Luca Magri*+ (*Imperial College London, +The Alan Turing Institute and Politecnico di Torino)
Data-driven inference of adjoint sensitivities without adjoint solvers

Adjoint methods offer a computationally cheap and accurate way to calculate the sensitivity of a quantity of interest with respect to all the system's parameters. However, adjoint methods require the implementation of an adjoint solver, which can be cumbersome. Furthermore, the accuracy of the adjoint solver relies on the physical model of the underlying system, which can be high-dimensional and nonlinear. Recently, Echo State Networks (ESNs) have been shown to successfully learn nonlinear dynamics from data. In this work, we learn the parametrized nonlinear dynamics to infer the adjoint sensitivity from data via a parameter-aware ESN. We derive the adjoint of the ESN and investigate two applications, (i) gradient-based optimization and (ii) climate, i.e., long-time average, sensitivity of chaotic flows. First, we consider a time-delayed nonlinear model of a thermoacoustic system, which captures instabilities that occur in propulsion and power generation. We employ the sensitivity provided by the adjoint of the trained ESN within a parameter optimization framework to minimise the acoustic energy. Second, we consider the Lorenz 63 system, which models atmospheric convection. Because adjoint sensitivities in chaotic regimes diverge for long integration times, we analyse the application of ensemble adjoint method to the ESN. This work opens possibilities for data-driven sensitivity analysis without adjoint solvers.

Liang Fang and George Papadakis (Imperial College London)
A Regularised Shadowing Method for Sensitivity Analysis of Chaotic Flows

There is increasing demand for optimisation using scale-resolving methods, such as direct numerical simulations and large-eddy simulations. However, standard sensitivity methods, like the adjoint method, fail for chaotic turbulent flows due to the so-called "butterfly effect". A very promising method for calculating the sensitivity of time-average quantities of chaotic systems to system parameters is the Least-Squares Shadowing (LSS) method. However, for systems that are not uniformly hyperbolic, the resulting system matrix arising from LSS has a very large condition number, which affects the accuracy of the computed sensitivities. In this presentation, we will introduce a regularised non-intrusive LSS method. By applying regularisation, we can reduce the condition number and ensure the system is well-conditioned. The optimal regularisation parameter is obtained by finding the maximum curvature of the L-curve. This innovation improves the accuracy of the method and extends its applicability to a broader range of turbulent chaotic flows. We apply the proposed method to the Lorenz 96 system and the Kolmogorov flow. The results demonstrate its effectiveness and stability. Additionally, we investigate the correlation between the angles of the Covariant Lyapunov Vectors (CLVs) and the regularisation of the linear system. The results indicate that the regularisation is activated at the time instants when CLVs tend to align.

Chi Hin Chan*, Mohammad Z. Hossain*+, Spencer J. Sherwin* and Yongyun Hwang* (*Imperial College London, +University of Western Ontario)

State-space pathways towards spiral defect chaos

The intrinsic bistable system between a chaotic state (spiral defect chaos - SDC), and stationary states (ideal straight rolls - ISRs) of Rayleigh-Bénard convection in a large extended domain ($\Gamma \geq 40$, where Γ is the aspect ratio of the domain) is well established. In this study, we aim to isolate the localised features of SDC via a minimal domain and identify the state-space pathways leading to SDC. By reducing the computational domain systematically, we have identified various stable states referred to as elementary states. Remarkably, these elementary states are statistically and visually similar to SDC. Next, we performed numerical experiments along the unstable manifolds of ISRs outside of the boundaries of the Busse balloon to identify the state-space structure. Near the Busse balloon, a network of heteroclinic orbits connecting unstable ISRs and stable ISRs was identified. On the other hand, integrating along some unstable manifolds of ISRs far from the Busse balloon led to a transient chaotic state before settling into an elementary state. An additional numerical experiment along the same unstable manifold in an extended domain led to a prolonged chaotic state. This suggests that the unstable ISRs sit on the state-space boundary between stable ISRs and SDC, providing a state-space pathway to SDC in an extended domain.

Session 2
Stability and Transition
Chair Juan Guzman-Inigo

Pierre Ricco and Kaixin Zhu (University of Sheffield)

Nonlinear evolution of vortical disturbances entrained in the entrance region of a circular pipe

The nonlinear evolution of free-stream vortical disturbances entrained in the entrance region of a circular pipe is investigated using asymptotic and numerical methods. Attention is focused on the long-wavelength disturbances which induce streamwise elongated streaks. A pair of vortical modes with opposite azimuthal wavenumbers is used to model the free-stream disturbances and their amplitude is assumed to be intense enough for nonlinear interactions to occur. The formation and evolution of the streaks are described by the nonlinear unsteady boundary-region equations written here in cylindrical coordinates for the first time. Supplemented by appropriate initial and boundary conditions, this initial-boundary-value problem is solved numerically by a marching procedure in the streamwise direction. Numerical results show the stabilizing effect of nonlinearity on the intense algebraic growth of the streaky structures. For a high free-stream turbulence level, all the disturbances attenuate sufficiently downstream with the exception of a pulsating mode. A parametric study is carried out to evince the effect of Reynolds number, streamwise and azimuthal wavelengths, and radial characteristic scale on the nonlinear evolution. Satisfactory agreement between our numerical results and the limited experimental data is obtained.

Junho Park (Coventry University)

Instability of stratified and thermally diffusive Taylor-Couette flow

Thermal diffusion in fluid flow is characterised by the Prandtl number Pr, which is the ratio between kinematic viscosity and thermal diffusivity. Depending on the context, the Prandtl number changes such as Pr of the order of 1 for the air, Pr of the order of 0.01 for liquid metals, or Pr of the order of 10^{-6} in the interior of stars. The Prandtl number dependence has been studied for various flow phenomena such as convection or stratified turbulence. Our study aims to examine stratified Taylor-Couette (TC) flow when the Prandtl number is sufficiently low as $Pr < 1$ (e.g. when the thermal diffusion is dominant). We first demonstrate from linear stability analysis that the strong thermal diffusion suppresses the effect of stratification, which stabilizes the centrifugal instability of TC flow. From direct numerical simulations and bi-global stability analysis, we investigate the non-linear evolution of the instability in the low-Pr regime. Our study reveals that secondary instability as well as the laminar-turbulent transition are delayed by strong thermal diffusion.

Abhishek Kumar and Alban Pothérat (Coventry University)

Suppressing instabilities in mixed convective flow using an actuation based on receptivity

Using the receptivity map of an unstable mode, we developed an actuation technique to stabilise oscillations in a mixed convective flow within a near-hemispherical cavity, akin to metallurgical casting processes where hot liquid metal is poured into a sump with cold walls, solidifying at the bottom. Previous analyses indicated that these unstable modes are three-dimensional (Kumar and Pothérat, J. Fluid Mech. 885, A40 (2020)). We proposed a suppression mechanism based on receptivity analysis. Solving the non-dimensional version of the direct and adjoint equations governing buoyancy-driven flows under the Boussinesq approximation with NEKTAR++ (Moxey , Comput. Phys. Commun. 249, 107110 (2020)), we found the inlet's mid-section highly receptive. Further, direct numerical simulations demonstrated that adjoint modes, acting as external time-dependent force, effectively suppress instability, crucially depending upon the adjoint modes' amplitude and phase, for a finite duration. This validates receptivity-informed actuation for stabilising convective oscillations and suggests a straightforward, potentially long-term control strategy (Kumar and Pothérat, arXiv:2312.15121 (2023)).

Pushpender Sharma and Neil Sandham (University of Southampton)
Modal response of a shock-induced separation bubble under random forcing

Understanding the unsteady behaviour of shock-wave boundary-layer interactions (SWBLI) is critical for shock-dominated high-speed internal/external aerodynamic flows. Direct numerical simulation (DNS) is a useful tool to identify various scales present in a flow. A simple configuration of shock impinging on a boundary layer developing on a flat plate is considered in three dimensions (3D) at Mach 2. The mean flow for this configuration is then exposed to random forcing at every point by uniformly distributed white noise. The objective is to identify the global modes that are activated when the flow is randomly perturbed instead of using deterministic forcing and to identify any divergence in the results predicted by the linear stability theory (LST). The initial perturbation amplitude of $\pm 1\%$ in density is selected based on a two-dimensional (2D) study for different perturbation amplitudes such that the system's response remains linear. Wall pressure data is collected over a very long time to perform a spectral analysis in frequency and wavenumber space. It is noted that the low-frequency response about the leading separation location is 2D, and the 3D modes present post the reattachment location are as predicted by LST. We also intend to do a similar study for stronger interactions.

Shijun Chu, Ashley P. Willis and Elena Marensi (University of Sheffield)
The minimal seed for transition to convective turbulence in heated pipe flow

It is well known that buoyancy suppresses, and can even laminarise turbulence in upward heated pipe flow. Heat transfer seriously deteriorates in this case. Through a new DNS model, it is found that, the minimal seed becomes thinner and closer to the wall, with an increase of buoyancy number C. Most importantly, we show that the critical initial energy required to trigger shear-driven turbulence keeps increasing, implying that attempts to artificially trigger it may not be an efficient means to improve heat transfer at larger C. The new minimal seed, found at C=6, is localised in streamwise direction and is active in the centre of pipe. To find this branch of optimal, we took advantage of a window of linear stability. While the nonlinear optimal causes transition to convective turbulence directly at this and larger C, transition via the linear instability passes via a travelling wave or periodic orbit solutions. Detailed analysis of the periodic solution reveals three stages: growth of the unstable eigenfunction, the formation of streaks, and the decay of streaks due to suppression of the instability. Flow visualization at C up to 10 also shows similar features, suggesting that convective turbulence is sustained by these three typical processes.

Session 3
Data Assimilation and Data-Driven Methods
Chair Sean Symon

Matthew Juniper, Alexandros Kontogiannis, Matthew Yoko and Lloyd Fung (University of Cambridge)

Adjoint-accelerated Bayesian Inference for data assimilation

Bayesian Inference provides a probabilistic framework that is well suited to Machine Learning of model parameters from data. We specify any number of candidate models, their parameters, and their prior probability distributions. When data arrives, we calculate (i) the most likely parameter values, (ii) their posterior probability distributions, (iii) the marginal likelihood of each model. This combines how well each model fits the data with how much each parameter space collapses when the data arrive. This penalizes (i) models that do not fit the data and (ii) models that fit the data but whose parameters require excessively delicate tuning to do so. Bayesian inference is usually prohibitively expensive, but its cost is greatly reduced if all distributions are taken to be Gaussian. This is often reasonable and can always be checked a posteriori. This allows the optimal parameter values to be found cheaply with gradient-based optimization and their posterior uncertainties and marginal likelihoods to be calculated instantly with Laplace's method. This requires calculation of the gradients of each model's outputs with respect to its parameters, which is achieved cheaply with adjoint methods at first and (optionally) second order. I will outline Bayesian inference, Laplace's method, the acceleration due to adjoint methods, and Bayesian experimental design. I will demonstrate this with assimilation of 3D Flow-MRI data, model selection in thermoacoustics, and Bayesian identification of nonlinear dynamics.

Matthew Yoko and Matthew P. Juniper (University of Cambridge)

Inferring thermoacoustic properties of turbulent flames from pressure data

We use approximate Bayesian inference, accelerated by adjoint methods, to construct a quantitatively accurate model of the thermoacoustic behaviour of a turbulent conical flame in a duct. We first perform a series of automated experiments to generate a data set. The data consists of time series pressure measurements from which we extract the (i) growth rate and (ii) natural frequency of oscillations. We assimilate the data into a thermoacoustic network model to infer the unknown model parameters. We begin this process by rigorously characterising the acoustics of the cold rig. We then introduce a series of different flames and infer their flame transfer functions with quantified uncertainty bounds. The flame transfer function is obtained with the flames in-situ, so it accounts for any confinement or heat loss effects. The inference process uses only pressure measurements, so the technique is suitable for complex combustors where optical access is not available. We validate the method by comparing the inferred fluctuating heat release rate against direct measurements. We find that the inferred quantities compare well with the direct measurements, but the uncertainty bounds can be large if the experimental error is large.

Craig Thompson, Sean Symon and Bharathram Ganapathisubramani (University of Southampton)

The state observer method applied to high intensity turbulence around a stalled airfoil

CFD using a RANS approach is a time-efficient method to simulate aerodynamic problems; however, from previous investigations, RANS simulations have difficulty predicting the transition, separation, and reattachment locations on the suction side of stalled airfoils. A state observer-based data assimilation approach is used to improve an incompressible RANS simulation of a NACA0012 airfoil under stall conditions with high-intensity turbulence levels. Experimental PIV measurements of a wing in high-intensity turbulence (Tu=19%) are used to drive the CFD prediction of the flow. The investigation demonstrates how an additional spatially varying forcing term within the RANS equation can be optimized to generate a more accurate prediction of the flow field. The physical understanding and significance of this forcing term are explored. Both one and two-equation turbulence models are applied to the state observer method, presenting advantages and disadvantages in terms of flexibility and accuracy in the resulting assimilation.

Yunjiu Yang and Sergei Chernyshenko (Imperial College London)
QSQH synthetic turbulence model

The QSQH theory refines the widely-used classical universality hypothesis by assuming that near-wall turbulence remains in equilibrium with the large-scale component of the wall friction instead of the mean friction, where the universality: the statistical independence of near-wall turbulence in relation to Re, is achieved by scaling it with the large-scale component of the wall friction. We present a synthetic turbulence model and a publicly available computational tool for easy application of the QSQH theory. The tool includes a database of the universal velocity field generated by rescaling with large-scale wall friction the turbulent channel flow at $Re = 5200$, which was downloaded from the Johns Hopkins Turbulence Database. The tool takes the wall friction of a real turbulent flow as input and uses the universal velocity field to generate a synthetic velocity field that closely resembles the statistics of the real flow and satisfies the QSQH theory. Statistics calculated from the synthetic field will be given, including a demonstration that contributions of the large-scale motions and pressure gradient to the change in Reynolds stress with Re are additive in plane channel flow. Hands-on demonstration of the tool will be given.