UK Fluids Network

Special interest group on

Flow instability, modelling & control

1st SIG meeting, Southampton

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ABSTRACTS

Jack Brewster & Matthew Juniper (Cambridge)

Shape optimisation in stability problems

Abstract: A linear stability analysis about a solution of the steady incompressible Navier-Stokes equations is performed, generating a set of mode shapes and their corresponding growth rates and frequencies. The Hadamard form [1] for the growth rate of a given mode is then derived. As a model problem, this shape derivative is then used to find the aspect ratio of an ellipse required to suppress vortex shedding at Re = 90.

Combining this gradient information with a projection method enables the linear stability of the ow to be used as a constraint during the optimisation procedure. To demonstrate this, the shape derivative is used to keep a shape marginally stable whilst optimising for a different objective function - the viscous dissipation within the domain (Figure 1). Projecting the search direction into a space where the growth rate is corrected to zero with first order accuracy allows us to ensure the shape remains marginally stable at each iteration.

References

[1] J. P Zolesio and M. C Delfour Shapes and geometries: analysis, differential calculus and optimization SIAM, 2001

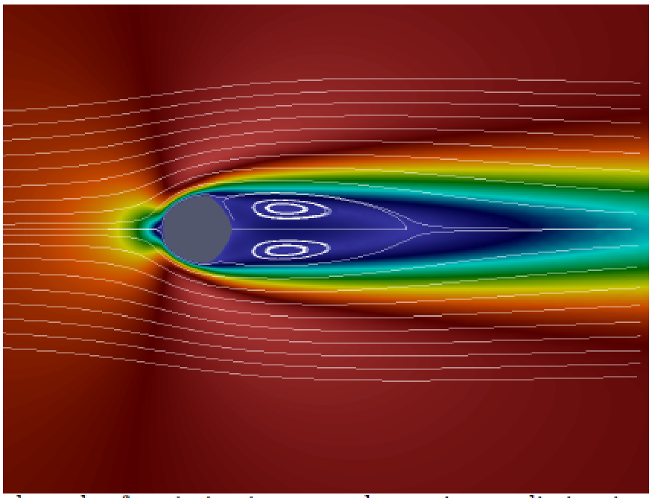

Figure 1: End result of optimisation procedure: viscous dissipation is minimised whilst area is kept constant and growth rate of the leading global mode is held at zero

Pietro Servini & Frank Smith (UCL)

The impact of roughness elements on flow separation

Abstract: Previous experimental and numerical work suggests that dynamic roughness elements (small bumps that oscillate up and down) have the potential to suppress the separation of a laminar boundary layer or increase the critical angle of attack at which it takes place. Our goal is to try to understand the physical mechanism behind this and to attempt to determine the roughness parameters that are most beneficial. In this talk, we'll look at flow over a hump in a condensed boundary layer, as in the scenario of Smith & Daniels (1981). The roughness elements will be placed in the region where the skin friction passes regularly through zero (the local separation point), which gives rise to an integro-differential equation for the boundary layer displacement function, corresponding to the leading order skin friction term.

The effect of static and dynamic roughness on both the local and global separation point will be presented, as well as the impact of roughness height, width, position and oscillation frequency.

Xuerui Mao (Nottingham)

Optimal route from free-stream disturbance to bypass transition.

Abstract: The nonlinear optimal inflow disturbance to flow over a flat plate with a slender leading edge is calculated. The square integration of the inflow disturbance is considered as the constraint on magnitude. When this magnitude is small enough, the optimal perturbation is steady and has a single wavenumber in the spanwise direction. At a large enough magnitude, the optimal disturbance is dominated by a steady Fourier mode and augmented by an unsteady one. During the development of this inflow perturbation, its steady component induces high and low speed velocity streaks in the boundary layer, and the unsteady part triggers the secondary instability of streaks. This optimisation study clarifies the shortest route from free-stream perturbations to bypass transition.

Xiao Dandan & George Papadakis (Imperial)

Nonlinear optimal control of bypass transition in a boundary layer flow

Abstract: We apply and assess a nonlinear optimal control strategy to suppress bypass transition in a zero-pressure-gradient boundary layer. To this end, a Lagrange variational formulation is employed that results in a set of adjoint equations. The optimal wall actuation (blowing and suction from a control slot) is found by solving iteratively the nonlinear Navier-Stokes and the adjoint equations in a forward/backward loop using DNS. The optimization is performed in a finite time horizon. Large values of optimization horizon result in instability of the adjoint equations. The control slot is located exactly in the region of transition. The results show that the control is able to significantly reduce the objective function, which is de fined as the spatial and temporal integral of the quadratic deviation from the Blasius profile plus a term that quantifies the control cost. The physical mechanism with which the actuation interacts with the flow field is investigated and analysed in relation to the objective function employed. The spanwise averaged velocity is distorted by the control action, resulting in a significant reduction of the skin friction coefficient. We performed simulations with and without zero-net mass flow constraint of the actuation velocity. Results are also compared with uniform blowing using the same time-average velocity obtained from the non-linear optimal algorithm.

Arvind S Iyer, Sergei Chernyshenko, and Peter E Vincent (Aeronautics, Imperial College London)

Identifying the Eigenmodes and Eigenvalues of Small Averaged Perturbations to Turbulent Channel Flow using PyFR

Abstract: Turbulent flows are important in many scientific and engineering applications, including design of aircraft, automobiles, and buildings. In these applications, average quantities are of primary importance, often more so than the instantaneous values. However, the true governing equations for averaged quantities are not known, a famous problem of turbulence. In practical applications, the most common, almost ubiquitous, approach is to use one of the several semi-empirical closures, the so-called turbulence models. k-ε, k-ω, shear-stress-transport, etc are some of the most commonly used models. The accuracy of a given closure is often estimated by comparing results from the model with Direct Numerical Simulation (DNS) or experimental data.

The evolution of small perturbations to turbulent flows is of fundamental importance. In the present work, we have used PyFR, a GPU accelerated, high-order accurate computational fluid dynamics solver, to study the evolution of small perturbations to the average stream-wise velocity profile of a pressure driven channel ow with a steady-state shear Reynolds number of 180. Specifically, we undertook two ensembles of simulations, one with an even perturbation (256 instances) and one with an odd perturbation (768 instances). Averages over each ensemble were then obtained and analyzed. We hypothesized that the decay of a given perturbation is initially dominated by a non-linear process, followed by a linear phase where the perturbation is composed of a sum of distinct eigenmodes with differing eigenvalues. Based on this hypothesis, we analysed temporal windows of averaged data to see if a pure eigenmode emerged before the perturbation became indistinguishable from the turbulent noise. We indeed found pure eigenmodes emerged in both ensembles, which we associated with the slowest decaying odd and even eigenmodes, and their corresponding eigenvalues.

Interestingly, the eigenvalue was found to be complex for the symmetric perturbation and real valued for the antisymmetric perturbation. We hope that the results can be used to distinguish between semi-empirical turbulence models and, eventually, to improve them. To our knowledge, this is the first time such a study has been undertaken.

John Craske (Imperial)

Adjoint chaos via cumulant truncation

Abstract: We describe a simple method for obtaining approximate sensitivity information from a chaotic system using a hierarchy of cumulant equations. The resulting forward and adjoint systems yield useful information about the gradient of flow functionals and typically do not suffer from the convergence issues that are associated with the tangent linear representation of chaotic systems. Our approach is premised on the desire to obtain robust sensitivity information in a systematic way from the direct numerical simulation of chaotic systems such as turbulence. Since the flow functionals in which one is typically interested are ensemble-averaged quantities, such as the average drag or the average temperature variance in a heated space, we focus on the system's statistical state dynamics rather than individual trajectories. Making use of observations from direct simulation, we look for an optimal truncation of the cumulants' tangent linear system that does not require the specification of model parameters.

This talk will motivate adjoint sensitivity analysis in the context of civil engineering flows, such as the confined convective flows that arise from the heating and cooling of buildings. In such situations one is typically concerned with the response of a small number of flow functionals to changes in the problem's boundary conditions, making the adjoint formulation of the problem an appropriate choice. In addition to their usefulness in gradient-based optimisation routines, local gradients of a solution are of intrinsic value, providing insight into the underlying physics and assisting the development of accurate models. We will describe the problem associated with the adjoint analysis of chaotic systems before reviewing several existing methods that can be employed to circumvent the problem. A brief summary of the theory associated with statistical state dynamics will be provided before we discuss the application of our proposed method to the Lorenz equations.

Davide Lasagna (Southampton)

Can invariant solutions be used to control turbulence?

Abstract: Recent progress in characterising low-Reynolds-number turbulent flows highlights the importance of the so-called invariant solutions of the Navier-Stokes equations. These solutions have a profound influence on the dynamics and often reproduce the statistics and the coherent structure observed in such flows remarkably well. This perspective carries the promise of describing turbulence in terms of the dynamics of a handful of solutions and has become a prominent basis for analysis. However, it is currently unclear if and how the same perspective can be used as fruitfully for design and control applications.

In this talk, I will present recent work at Southampton that aims to bridge this gap. I will describe a variational method for sensitivity analysis of a particular class of invariant solutions, i.e. periodic orbits. The key enabler, is that when formulated on periodic orbits, these variational methods are always well conditioned, regardless of the length and stability characteristics of the orbit. In a nutshell, periodic orbits act as a proxy for design: what is an algorithmically and computationally difficult problem, obtaining the sensitivity of time averages over long chaotic trajectories, becomes feasible and well behaved for periodic orbits.

I will demonstrate ideas and algorithms on a paradigmatic design problem, i.e. the design of a feedback controller to mitigate chaotic dynamics in possibly the simplest spatially extended system exhibiting chaos, the Kuramoto-Sivashinsky equation. Current progress, challenges and outlook will be discussed.

Jonathan Healey (Keele)

Using inflexion points to stabilize boundary layers

Abstract: The linear stability of many boundary layers is often approximated well by solutions of the Orr-Sommerfeld (OS) equation (and its generalizations to 3d boundary layers). From a mathematical point of view, this problem has been solved, and there seems to be little more to say about it: its asymptotic scalings were established a long time ago, and its numerical solution has been relatively straightforward for decades. But from a practical point of view, it is not always obvious what the effect of a given change to a velocity profile will be on its stability, until after OS solutions have been obtained. In this presentation it is suggested that this lack of understanding of the OS equation may have led us to overlook some useful strategies for stabilizing boundary layers. We give examples of small flow modifications that produce dramatic stabilization, even when they introduce inflexion points to profiles.

Arslan Ahmed & Ati Sharma (Southampton)

Low-order equilibrium solutions in plane Couette flow

Abstract: A new approach to understanding the dynamics of moderate-Reynolds number wall-bounded flows has emerged recently, based on the computation of exactly recurring or steady flows.

Such solutions are thought to represent coherent structures, and the connections in state-space between these solutions can explain the dynamics and self-sustaining nature of wall-bounded turbulent flows.

Since 1990, only 5 branches of equilibria have been found for plane Couette flow, because finding non-trivial solutions is computationally expensive.

In this talk, we will present a novel and computationally cheap `project-then-search' method, which has been used to find 5 new branches of equilibria in plane Couette flow.

Matteo de Giovanetti & Yongyun Hwang (Imperial)

Secondary instability of the outer-layer streak as the initiating mechanism of the large-scale motions in turbulent channel flow

Abstract: The instability and breakdown of amplified streaky motions in the outer layer (i.e. very-large-scale motions) are studied in turbulent channel flow. A LES-based numerical experiment is designed, at moderate Reynolds numbers ($Re_\tau \approx 2000$), in which a time-constant, streamwise-uniform forcing profile is applied to the flow, in order to generate the optimal flow response. The instability of the streak is shown to be of sinuous type, and mainly caused by regions of high spanwise shear, in a fashion similar to transitional flows. The streamwise velocity spectra show the appearance of more energetic structures at $\lambda h \approx 3 - 4h$ of the streamwise length (h is the half height of channel) particularly in the wall-normal and spanwise components. This is interpreted as proof that the large-scale motions are directly generated by the secondary instability of the streaks. Furthermore, application of dynamic mode decomposition reveals that the most energetic eigenmode is represented by the meandering streak, and that the phase speed of this structure scales with the outer velocity. Moreover, it is shown that the instability is initiated around the critical layer of the streaky flow. Finally, a Floquet stability analysis clarifies the effect of viscosity on the most unstable eigenmodes and on the critical layer itself.

Hui Xu, Andrea Cassinelli & Spencer J. Sherwin (Imperial)

Nektar++: Applications in boundary layer instability and turbomachinery flows

Abstract: The spectral/hp element framework Nektar++ is designed to support a variety of different high-performance solvers for partial differential equations. Among the range of its applications, two cases are presented.

First we consider the influence of a smooth three-dimensional (3D) indentation on the instability of an incompressible boundary layer by linear and nonlinear analyses. The numerical work was complemented by an experimental study at City University, to investigate indentations of approximately 11 and 22, δ_{99} width at depths of 45%, 52% and 60% of δ_{99} at $\Re_x = 780\,K$. Numerical corroboration against experimental data reveals good quantitative agreement. Comparing the structure of the 3D separation bubble to that created by a purely 2D indentation, there are a number of topological changes particularly in the case of the widest indentation and more rapid amplification and modification of the upstream TS waves along the symmetry plane of the 3D indentation is observed. The destabilising mechanism is found to be due to the confined separation bubble and is attributed to the inflectional instability of the separated shear layer. Finally, the results of the linear analysis are compared with direct numerical simulations. A comparison with the traditional criteria of using N-factors to assess instability of properly 3D disturbances reveals that a general indication of flow destabilisation and development of strongly nonlinear behaviour is indicated as $N = 6$ values are attained.

In the second application within the Nektar++ framework, we consider flow past low-pressure turbines (T106A) at $\Re = 50\,K - 100\,K$. Parametric studies are currently being performed, varying blade loading conditions, Reynolds number and discretization order. The dynamics of the boundary layer and separation bubble have been captured, as a more detailed assessment is made of the suitability of these LES/DNS high-fidelity methods for turbo-machinery modelling.

David Dennis (Liverpool)

Experimental evidence of symmetry-breaking supercritical transition in pipe flow of shear-thinning fluids

Abstract: Novel experimental results reveal that the asymmetric flow of a largely inelastic shear-thinning fluid through a cylindrical pipe, which was previously associated with the laminar-turbulent transition process, appears to have the characteristics of a non-hysteretic, supercritical instability of the laminar base state. Contrary to what was previously believed, classical transition is found to be responsible for returning symmetry to the flow. Lack of evidence of the instability in simulations (either linear or non-linear) suggests that an element of physics is lacking in the commonly used rheological model for inelastic shear-thinning fluids. We also demonstrate that a viscoelastic fluid, with approximately the same shear-thinning characteristics as the inelastic fluid, does not exhibit the asymmetry when freshly mixed. However, once the elasticity of this fluid is degraded (by prolonged shearing) the asymmetry reappears. We find an inverse relationship between viscoelasticity and the magnitude of the asymmetry, although the Reynolds number at which the instability is first observed stays approximately constant.This suggests that the shear-thinning nature of the fluid causes the instability and the viscoelastic nature works to dampen the asymmetry. These unexpected discoveries raise new questions regarding the stability of these practically important fluids and how they can be successfully modelled.

Rowan Brackston, Juan Marcos Garcia de la Cruz, Andy Wynn, Georgios Rigas & Jonathan Morrison (Imperial)

Drag reduction of a bluff body by feedback control

Abstract: Three-dimensional bluff body wakes are of key importance due to their relation to the pressure drag on automotive vehicles. In recent years a specific feature of these wakes, flow bistability, has been the subject of particular interest. This feature consists of a random flipping of the wake between two asymmetric configurations. In this study we apply the modelling approach recently suggested for axisymmetric bodies by Rigas et al. (2015, J. Fluid Mech. , vol. 778, R2) to the bistable mode of the rectilinear Ahmed body wake.

Marco Placidi, Evelien van-Bokhorst & Chris Atkin (City, University of London)

Effect of surface imperfections on the stability of 3D boundary layers.

Abstract: The talk will present an overview of recent experimental and numerical efforts overtaken at City University over the past 3 years. After a brief overview of the different projects, a particular relevance will be given to the effect of 2D and 3D surface imperfections on the instability and transition of 3d boundary layers. Both the mechanisms for primary and secondary instabilities were investigated and will be discussed.