Space-adaptive simulation of transition and turbulence in shear flows

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1 Supervision

The present PhD thesis was supervised by Prof. Philipp Schlatter (PS) and Dr. Saleh Rezaeiravesh (SR) who acted as the main and co-supervisor, respectively. PS is a professor at the FLOW Centre, Engineering Mechanics, KTH Royal Institute of Technology, Stockholm, Sweden and also chairs the Institute of Fluid Mechanics (LSTM) at the Friedrich-Alexander-Universität (FAU), Erlangen, Germany. SR is a Lecturer at the Department of Fluids and Environment at the University of Manchester, Manchester, UK.

2 General summary

Transitional and turbulent flows are widespread, from the swirling patterns of clouds around an island to the blood flow in our circulatory system. Accurately studying the flow physics through experiments and numerical simulations is challenging yet essential for making accurate predictions and subsequently taking appropriate actions, such as design optimisation, flow control, or medical interventions.

Imagine yourself as a particle soaring a few thousands of metres above sea level. Suddenly, you encounter an isolated volcano and swiftly enter the island wake, starting a swirling motion, as depicted in Figure 1(a). As you leave the island, you come across a flock of geese migrating to warmer lands. On their wings, the flow spatially develops, and the motion transitions from smooth and orderly to chaotic. This brief journey illustrates the various spatial scales encountered: from the island vortex patterns (L spanning kilometres), through the V-shaped formation of a flock of birds (l of a few metres), to the boundary layer flow on a wing (δ spanning millimetres). The variety of intricate flow structures is evident even in more canonical geometries, such as the turbulent pipe flow illustrated in Figure 1(b). Simulating these flows requires a computational model capable of capturing motions across a wide range of spatial scales while maintaining an affordable computational cost. Therefore, this thesis focuses on implementing a space-adaptive numerical framework, essential for investigating new physical phenomena.

We analyse the flow around bluff bodies where vortex patterns develop similarly to the island wake in Figure 1(a). Examples are the stepped cylinder, see Figure 2(c), a model for the foundation of offshore wind turbines and the Flettner rotor. This latter is an engine-driven rotating cylinder utilising the Magnus effect to generate aerodynamic thrust. Understanding the turbulent flow around the rotor is crucial for reducing fuel consumption and offering a sustainable solution for marine shipping, see Figure 2(a, b). In wall-bounded shear flows, we study transitional and turbulent pipe flows, including the 180°-bend pipe flow. This configuration resembles the aortic arch and understanding the instability mechanism is crucial for pathologies like aneurysms.

3 Scientific summary

This thesis focuses on implementing a space-adaptive numerical framework to accurately simulate transitional and turbulent shear flows and uncover novel physical mechanisms. To perform direct numerical simulations (DNS) of shear flows in complex geometries, we develop a space-adaptive numerical framework that automatically enhances the resolution where the grid is not sufficiently fine to capture small scales. The adaptive mesh refinement (AMR) technique is implemented in the open-source software Nek5000, a spectral-element code combining the geometrical flexibility of finite-element methods and the exponential error convergence of spectral methods.

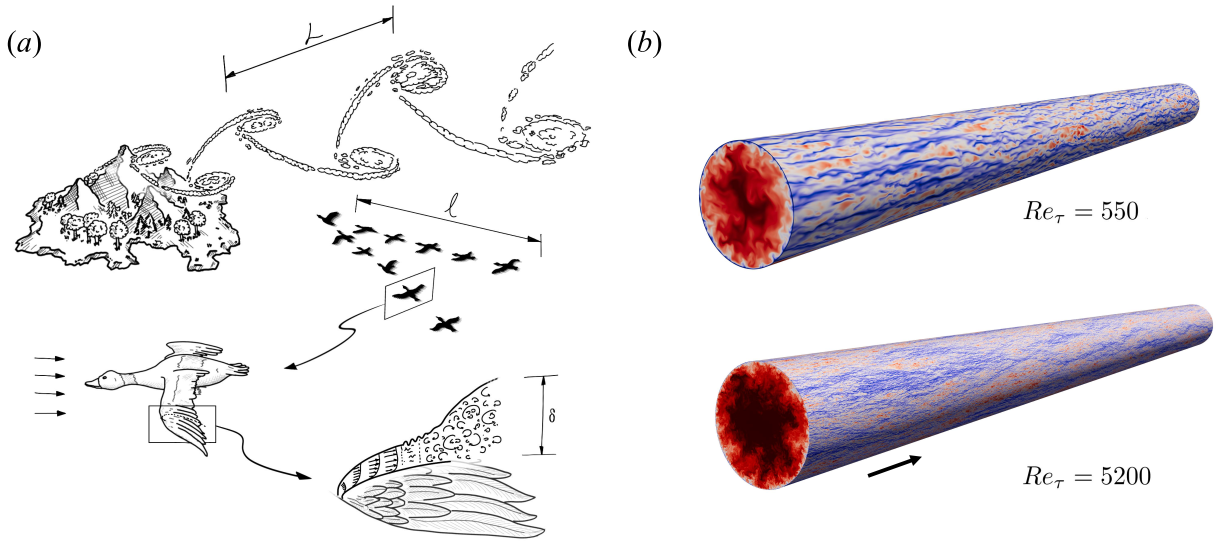

Figure 1: (a) Illustration of the motion of the fluid particle journey through three distinct natural flows: the island vortex shedding, the V-shaped flock formation and the wing boundary layer, credit to P. Suárez. (b) Instantaneous streamwise velocity contours of low- and high-speed velocity streaks, in *blue* and *red*, respectively.

The first crucial ingredient of the AMR algorithm is the error measurement. Thus, we compare the spectral error indicator (SEI), an estimation of truncation and quadrature errors in the solution field, with the adjoint error estimator (AEE), a goal-oriented error measure. The SEI is preferred when more homogeneous refinement is required, while the AEE targets specific quantities of interest (**Paper 1 & 3**). However, the AEE fails in turbulent flows, *i.e.* in chaotic dynamical systems, due to the exponential sensitivity to perturbations of the linear adjoint operator. Therefore, we introduce a novel causality-based error indicator based on Shannon transfer entropy (TE), assessing the drawbacks and costs associated with the TE (**Paper 2**). TE is a causality metric from Information Theory, which is fully data-driven, handles non-linearities and distinguishes between cause and source events, unlike correlation. In the thesis, for the first time, we also explore the possibility of using TE to extract causally coherent structures in turbulent flows. As the Reynolds number increases, we prefer using the Karhunen-Loève decomposition (KL), a bi-orthogonal stochastic process expansion, to describe coherent motions. In high-Reynolds number pipe flows (**Paper 4 & 5**), we combine the KL decomposition with a Voronoi analysis to introduce a new classification of wall-attached and detached eddies solely based on their energy contribution. The Voronoi-based approach can be used to create novel reduced-order models (ROM) and improve synthetic eddy inflow generation techniques which are crucial to reduce the transient time to develop turbulence and, consequently, the required computational cost.

Expanding our focus to more complex geometries, we move from straight to curved pipes, see Figure 2(d). The origin of the swirl-switching (SW) phenomenon, an alternating rotation of the Dean vortices around the equatorial plane, is investigated through data-driven and statistical analysis (**Paper 8**). The SW is critical for fatigue effects and the structural stability of pipelines, making it crucial to identify its potential causes. We consider different bending angles (90° and 180° degrees) and inflow conditions (laminar and turbulent). Our analysis rules out the influence of upstream turbulence, including large- and very-large-scale motions, as potential causes of swirl switching and suggests a Ruelle-Takens-Newhouse route to turbulence with a symmetry-breaking bifurcation, presumably caused by shear instability. Proper orthogonal decomposition (POD) is used to extract the most energetic modes responsible for the SW, see Figure 2(d). Furthermore, we investigate the onset of transition in the 180°-bend pipe using an AMR approach for the first time (**Paper 7**). Specifically, we design three different meshes for the different solutions: non-linear, linear direct, and adjoint. The AMR application in the global stability analysis is fundamental for reducing the numerical errors which can trigger the transition to turbulence (**Paper 6**).

In the context of free shear flows, firstly, we study the flow around a stepped cylinder, composed of two cylinders with different diameters joined at one end, see Figure 2(c). This configuration serves as a model for offshore wind turbine towers and aircraft landing gears. We investigate the origin of the three distinct vortex-shedding patterns in the wake and explain the downwash mechanism (**Paper 9, 10 & 11**). Both aspects are important as the three wake cells generate structural loads with different frequencies on the cylinder. Secondly, we conduct the first-ever direct numerical simulation of the flow around a Flettner rotor,

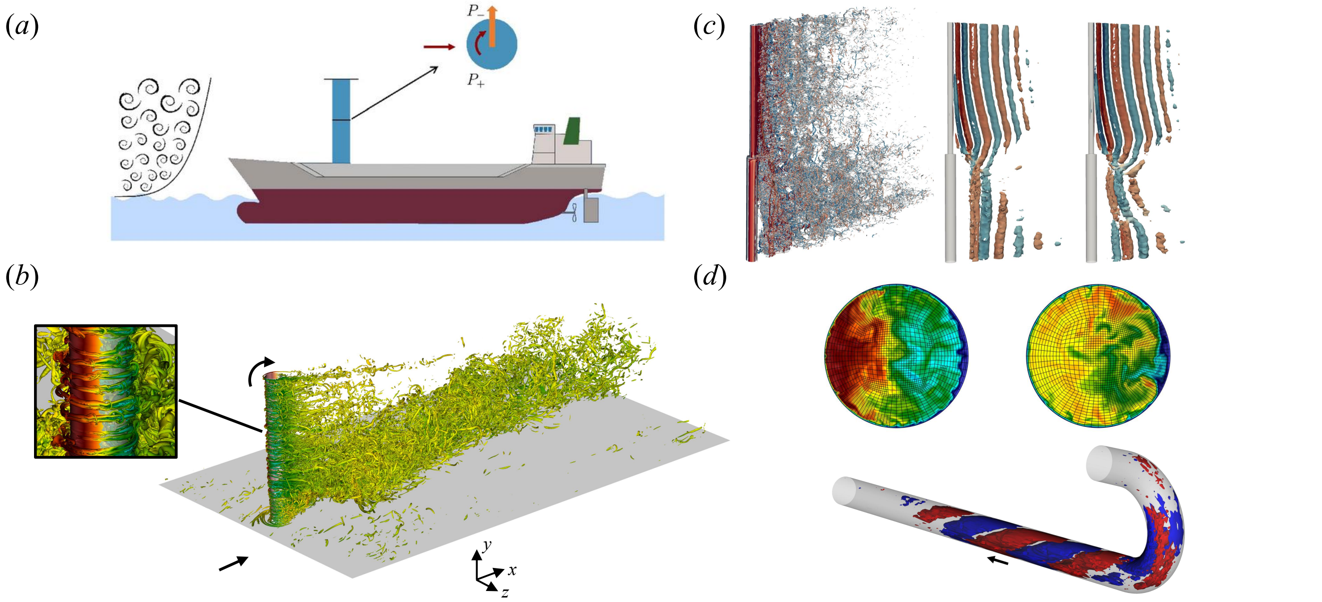

Figure 2: (a) Illustration of a ship with a Flettner rotor. (b) Instantaneous vortical structures coloured with the streamwise velocity. (c) Flow around a stepped cylinder: instantaneous vortical structures coloured by vertical vorticity from the original DNS and the ROM. At different times, two and three different wake cells are extracted via POD and visible. (d) Examples of the non-conforming mesh and isosurfaces of the positive and negative streamwise velocity of the most energetic anti-symmetric POD mode of the 180°-bend pipe with laminar inflow.

an engine-driven cylinder that extends vertically on the ship deck in the turbulent atmospheric boundary layer, see Figure 2(a, b). We discuss the local vortex shedding suppression, the development of large-scale vortical motion at the base of the cylinder and the variation of the aerodynamic loads as a function of the wall distance (**Paper 12**). These simulations were performed using the modern numerical framework Neko, which was selected as a finalist for the prestigious ACM Gordon Bell Prize in 2023. This framework represents a bridge to the future, and present, of computational fluid dynamics (CFD), where accelerators, like Graphics processing units (GPU), enable unprecedented DNS.

In conclusion, this thesis implements a space-adaptive numerical framework within high-order spectral element methods. The framework is used to explore transitional and turbulent mechanisms in both wall-bounded and free shear flows. The discussion presents novel physical insights, employing statistical and data-driven analysis based on causality metrics and the identification of coherent structures.

4 Selected publications and research output

The research conducted during the PhD program has yielded **19 papers**, 16 already published. In this compilation thesis, **12 papers** are included, 10 papers have already been published, while 2 are currently under review. The five selected publications are:

- D. Massaro, S. Rezaeiravesh , P. Schlatter, *On the potential of transfer entropy in turbulent dynamical systems*, Nature Scientific Reports, 13, 22344, 2023. **(Paper 2)**
- D. Massaro, J. Yao, S. Rezaeiravesh, F. Hussain, P. Schlatter, *Energy-based characterisation of large-scale coherent structures in turbulent pipe flows*, Journal of Fluid Mechanics, 996, A45, 2024. **(Paper 5)**
- D. Massaro, V. Lupi, A. Peplinski, P. Schlatter, *Global stability of 180°-bend pipe flow with mesh adaptivity*, Physical Review Fluids, 8, 113903, 2023. **(Paper 7)**
- D. Massaro, A. Peplinski, P. Schlatter, *The flow around a stepped cylinder with turbulent wake and stable shear layer*, Journal of Fluid Mechanics, 977, A3, 2023. **(Paper 10)**
- D. Massaro, M. Karp, N. Jansson, S. Markidis, P. Schlatter, *The Flettner rotor: a rotating cylinder in the atmospheric boundary layer*, Nature Scientific Reports, 14, 3004, 2024. **(Paper 12)**