Ph.D. proposal 2022: PDE-Based active flow control of turbulent separated flows

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Context

This Ph.D. thesis is motivated by economic and societal challenges related to the Transportation industry [3] and it is at the intersection of control engineering, mathematics, and fluid mechanics. It falls within the CPER 2021-2027 RITMEA by the FR TTM CNRS, of which CRIStAL laboratory is part.

The need to reduce energy consumption, CO2 emissions, and energy losses in aerodynamics is a central issue in the transportation industry and has been part of substantial research efforts for many years. One of the causes of the aerodynamic losses is what is called « the drag force » in fluid mechanics, which is associated with the flow separation phenomenon and the high flow velocity and turbulence. It appears that aerodynamic losses are one of the primary sources of waste energy for vehicles at speeds above 50km/h. The current ecological estimates indicate that a 25 % reduction in these losses would decrease pollution by more than 10^7 tonnes of CO2 per year.

The turbulence is related to the drag and the phenomenon of flow separation; one reason is higher Reynolds number (the most important parameter in fluid dynamics, which relates to the velocity of the fluid and the viscosity). Indeed, the higher the flow's velocity, the higher the Reynolds number leading to a transition of a steady fluid profile to a turbulent profile. On the other hand, the separation is also related to the vehicle's shape. There are critical points, often called stagnation points (or separation points), where the flow separates from the surface. Consequently, this results in drag forces that cause energy losses, more vehicle efforts, more energy consumption, and more CO2 emissions.

The reduction of the drag force has been handled, on the one hand, by using the *Passive Control* methodologies that aim to modify the vehicle's geometry (body moving in a fluid, e.g., airplane, fast train, truck, etc.) by changing its shape. For example, small vortex generators placed on the vehicle's surface to change the boundary layer constitute a typical passive control strategy. However, passive control strategies require studying extremely expensive numerical solutions to optimally size and locate its generators. Optimization of (static) shape of vehicles remains the industrial solution for reducing aerodynamic losses linked to turbulence mechanisms such as boundary layer separation. Nevertheless, in general, passive control may not lead to an optimal solution, especially when the flow at which the vehicle is subject varies significantly.
On the other hand, ***Active Control*** deals with actuators towards changes in the flow dynamics. Indeed, active control strategies involving actuators interacting with the flow - and whose control parameters may vary dynamically in real-time to maintain the solution's optimality (and the minimization of aerodynamic losses) - constitute a desirable solution. Some advances in this regard utilize machine learning techniques [1]. Although strategies for active control turn out to be more robust with respect to passive control ones, most of them work in open-loop. One drawback of open-loop active flow control is that not all parameters, changes in the geometry, and fluid dynamics in real-time can be adequately handled, yielding the open-loop strategies not being as robust as desired. This is a clear motivation to use closed-loop active flow strategies (by means, e.g., of feedback). Hence, control theory would offer the proper framework in order to tackle these problems. The main difficulty in controlling turbulence comes from the fact that the behavior is strongly nonlinear. It is described by the Navier-Stokes equation, which is a model with distributed parameters, therefore in infinite dimension. Implementing control or estimation algorithms for such equations requires too much computing power. In order to design controllers, suitable control-oriented models are needed. Most of the existing ones are based on reducing the complex model (e.g., reducing the Navier -Stokes equation) to some easier to handle. However, most of the

model-based and closed-loop control approaches rely on finite-dimensional system modeling (see, e.g. [1,2]) at the expense of losing precision on the modeling and possibly on the control objective.

Scientific Objectives

The PhD thesis aims at reducing the drag forces of a body moving in a fluid. Based on partial differential equations and reduced-order models, novel and robust active flow control strategies will be designed to minimize drag. In particular, the targeted scientific objectives are:

1) *Modeling/identification and validation.* We shall consider different configurations and geometries, e.g., an airfoil with moving angle (see [2]), Ahmed Body (see [5]) - illustrating the back of a car or any body moving in a fluid. We will focus on the boundary layers, i.e., the behavior near the vehicle's surface, and propose suitable control-oriented models. Then, the goal is to reformulate the boundary control problem, which will lead to a realistic setting for implementation. We can use nonlinear hyperbolic PDEs and the viscous Burgers equation as the latter has been considered as a model of the fluid suitable for active control design.
2) *Minimization of the drag through a reduction of the recirculation zone.* We are interested, at first instance, in characterizing the separation flow profile and the unstable flow profiles in the recirculation zone (in open-loop). The recirculation zone becomes more significant as the fluid detaches from the surface; therefore, the drag force is more potent. The main objective is then to reduce as much as possible the recirculation zone. To that end, one strategy would be to move the stagnation point to optimal locations. The characterization of the separation profile will be carried out in a closed-loop, e;g. when applying a control feedback.
3) *Stabilization and fixed-time estimation.* The whole machinery of automatic control to study the behavior stability of the system and the corresponding flow profile and separation flow profiles can be applied. We are particularly interested in applying finite/fixed-time concepts for estimating the states (e.g., by using fixed-time observer) and for boosting the convergence of the desired separation profiles to obtain as much as possible precision in the separation point location.
4) *Establishing a simulator for control validation.* In order to validate both the mathematical model and control we require to establish an experimental setup. While experimental setups are not always available due to scheduling constraints, we expect to develop a suitable simulator on which we can implement and validate the active flow control strategies. The task would be simulating the Navier-Stokes equations using e.g., FREEfem++ and then obtaining data for 1) identification and validation of the model and 2) test of the proposed active flow control strategy. Other simulators like STARCCM+ and Openfoam software may be worth considering. Simulation is a much cheaper and faster alternative to real-world testing and will allow the implementation and validation of control strategies in a much easier manner. Besides, it will lead the foundations to implement the strategies in actual applicative setups. Of course, this would not be a high-fidelity simulation, but it would be enough to verify the control design concepts numerically.
5) *Feasibility issues and digital realization.* The questions of feasibility, consistent discretization and implementation of controllers into digital platforms will arise and be addressed. For example, based on the flow state at the boundary layer, sampling-data and event-triggered control strategies ([8]) will drive to determine when the control action (blower collocated at the boundaries) needs to be applied and its required frequency of actuation.

Work plan

The first part of the thesis will be devoted to a bibliographical review on the up-to-date works relating to the problem of active flow control: both from fluid mechanics point of view, including modeling, using infinite-dimensional systems (Navier-Stokes equations and several reduced-order models), and then from the control theory point of view. Advantages of active control against passive control, robustness to uncertainties, disturbances, the need for feedback, etc., will be motivated and highlighted.

The second part of the thesis will be devoted to the accomplishment of the objectives described above. New algorithms for active control of turbulent flows will be developed. Special focus will be devoted to numerical simulations of the control system.

An annual report will present an assessment of the progress and the perspectives for the next upcoming years. Finally, this work will be punctuated by the presentation at international conferences and writing articles in top-ranked journals.

The required skills: We are looking for a talented and motivated candidate who is passionate about research, with very good English skills and who has a strong background in applied mathematics and/or in control theory.

Practical informations on the application: Please send to A.Polyakov and N.Espitia a detailed CV including the list of master courses and projects you have worked on, academic record, a motivation letter and contact details of one or two references

Application deadline: 18th of March 2022.

Note: CRIStAL laboratory and Inria research center are subject to "zone à régime restrictif" (ZRR). Further documents may be asked to the applicant for a security assessment by the "France Securité Defense" (FSD).

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