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OUTPUT FEEDBACK CONTROL OF FLOW SEPARATION OVER AN AEROFOIL USING PLASMA ACTUATORS

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Abstract. We address the problem of controlling the unsteady flow separation over an aerofoil, using plasma actuators. Despite the complexity of the dynamics of interest, we show how the problem of controlling flow separation can be formulated as a simple set-point tracking problem, so that a simple control strategy may be used. A robust output feedback control is designed, on the basis of a low-order, linear, dynamical model approximating the incompressible Navier-Stokes equations, obtained from the snapshots of 2D laminar finite element simulations at $Re = 1,000$. Fast flow reattachment is achieved, along with both stabilisation and increase/reduction of the lift/drag, respectively. Accurate 2D finite element simulations of the full-order nonlinear equations illustrate the effectiveness of the proposed approach: good dynamic performances are obtained, as both the Reynolds number and the angle of attack are varied. The chosen output can be experimentally measured by appropriate sensors and, despite its simplicity, the proposed set-point tracking controller is sufficient to suppress the laminar separation bubble; moreover, its extension to 3D turbulent configurations is straightforward ([33; 7]), thus illustrating the effectiveness of the designed control algorithm in more practical conditions, which are far from the design envelope.

Key words. Feedback flow control, robust control, reduced-order modelling, Plasma actuators, nonlinear systems.

1. Introduction

Closed-loop flow control is aimed at altering a natural flow state into a more desirable state, which is chosen depending on control objectives. Crucial examples are: manipulation of flow separation and flow reattachment, drag reduction, noise suppression, stall prevention, increasing mixing and combustion efficiency. Within this context, feedback controllers are pivotal, as they can achieve a full and efficient regulation of the flow field in real-time, see [18]. In particular, the incorporation of control theory into many open problems in fluid mechanics presents a host of new opportunities, with a wide range of applications in disparate fields (*e.g.* gas turbines, aircraft, as well as ground and marine vehicles).

The control input is usually an electric signal, which has to be converted to a physical quantity by means of an actuator. A new and original technology using non-thermal surface plasmas has witnessed a significant growth in interest in recent years, see [10; 12; 15; 31; 39], as they: have no moving parts; exhibit an extremely fast time-response; are characterised by low mass and low input power [8]. These surface dielectric barrier discharge (DBD) actuators are used to accelerate the near-wall flow, thus modifying the velocity profile within the boundary layer. The ionised fluid results in a localised body force vector field, which acts on the overlying neutrally charged fluid. The plasma actuator AC voltage can be used as a control input so that the generated force directly affects the flow over the aerofoil. However, the coupled neutrally-charged fluid and plasma dynamics are not trivial to model: neither the analytical model, which results in a system of nonlinear Partial

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Differential Equations (PDEs), nor the high-dimensional discretised dynamics, are suitable for control design purposes. Furthermore, the dependence of the dynamical properties on both the unknown flow and geometry parameters is highly nonlinear. Therefore, it is very difficult to obtain an accurate control-oriented model. On the other hand, we show that the problem of controlling flow separation along the aerofoil can be formulated as a simple set-point tracking problem, so that a simple control strategy may be used. In particular, we aim to design a robust integral controller, on the basis of the recent results in [25], which however requires some stability conditions to be satisfied by the model. Then, the objective becomes to find a suitably accurate but "cheap" model, which allows for the design of such a simple controller.

In this regard, the introduction of a dedicated, reduced-order model (ROM), which is based on the explicit description of the flow dynamics, can convey a clearer understanding of the underlying physics of the problem, compared to system identification methods, see [9; 11]. One way of obtaining tractable ROMs is to project large-scale problems onto lower-dimensional subspaces, thus providing insight into the key spatial modes of fluid/structure systems, contrarily to black-box identification techniques, see [2]. The most popular model reduction technique in the control community is the balanced truncation, a classic method developed in [30] for stable, linear systems, which was extended in [41] to unstable, linear systems.

An approximated balanced truncation method, called balanced Proper Orthogonal Decomposition (POD), was extended in [34] to linear fluid systems and is based on a variant of the method proposed in [20], which forms approximate empirical Gramians. Moreover, the balanced POD was extended in [1] to unstable linear systems, when the dimension of the unstable subsystem is relatively small. The balanced POD projects the system onto the subspace spanned by the most observable and controllable modes and was shown to outperform the standard POD introduced in [22] for closed-loop flow control applications, see [4; 16]. Several authors have focused on the feedback control of balanced POD models, based on the Navier-Stokes equations, linearised about a single steady trajectory, see, for instance, [1; 4]. These linearisation-based approaches allows for the application of well-established linear model reduction methods. However, an accurate approximation of the nonlinear behaviour can only be obtained in a small neighbourhood of the considered trajectory, whose choice heavily affects the control performance. Moreover, the resulting model is unstable, in contrast with the typical stability properties of fluid systems. The key idea is then to take advantage of the effectiveness of this linear model reduction method, while avoiding the restrictions related to linearisation approaches.

A variant of the Arnoldi algorithm called Dynamic Mode Decomposition (DMD) was proposed in [36] to approximate part of the spectrum of the Koopman operator, see [19]. The latter is an infinite-dimensional linear operator describing the evolution of observables on the phase space, which has been used to analyse uncontrolled, nonlinear dynamical systems, see [28; 27; 29], evolving on an attractor. The article [35] showed that the DMD modes approximate some of the Koopman modes, which can be interpreted as the eigenmodes of a finite-dimensional linear map that approximates the true, nonlinear one. This method does not rely on linearisation of the dynamics: indeed, it captures the full information of the nonlinear system.