Active feedback control of the flow past a thick flat-plate

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Résumé

L'étude concerne le contrôle en boucle fermée par retour de sortie du sillage laminaire et instationnaire d'une plaque épaisse, pour un nombre de Reynolds de 200. Cette configuration est en effet très proche de celle recontrée au bord de fuite épais d'aile, où différents types d'actionneurs peuvent être efficacement introduits afin d'ameliorer les performances aérodynamiques. C'est aussi une configuration de la littérature qui permet de nombreuses validations. Le forçage de l'écoulement proposé ici est réalisé en utilisant un système de soufflage/aspiration au bord de fuite de la plaque. Des capteurs de vitesse sont disposés dans le sillage pour fermer la boucle de contrôle. Pour diminuer la dimension du problème issu de simulations numériques directes (DNS), un modèle réduit non linéaire obtenu par décomposition en modes propres orthogonaux (POD) est obtenu par projection de Galerkin en prenant en compte un mode de forçage.

Différentes stratégies de contrôle sont réalisées sur le modèle réduit linéarisé et à partir de la reconstruction de l'état (LQG en particulier). Une loi de commande par retour de sortie s'avère plus simple à implémenter dans la simulation directe en prenant en compte les mesures dans le sillage car aucun produit de convolution est nécessaire. La performance et la robustesse de cette méthodologue de contrôle seront testés par les simulations numériques directes.

Keywords: POD, ROM, feedback control, thick-flat plate

1 Introduction

The flow region developing at the trailing edge of airfoils and wings has great influence on their aerodynamic performance, thus representing a good candidate for the introduction of flow control devices. The need for such devices becomes even more important when blunt trailing-edge geometries are considered. In this case, indeed, the unsteady flow separation with the onset of vortex-shedding results in detrimental effects, such as induced structural vibrations and noise production, which can be mitigated or even suppressed by means of a suitable control mechanism.

A prototypical configuration often addressed in the investigation of these phenomena is represented by the flow past a truncated thick flat-plate. At $Re_H = 200$, where Re_H is the Reynolds number based on the plate thickness H and the free-stream velocity, Henneman and Oertel [6] carried out a local stability analysis of the flow, reporting the existence of a region of absolute instability located just downstream of the trailing-edge. Later, the secondary instability of the wake past a flat plate with an elliptic leading-edge has been extensively investigated by Ryan et al. [14] using direct numerical simulations and Floquet analyses. The authors have found that three-dimensional instabilities occur for $Re_H = 400 - 475$, depending on the body aspect-ratio AR, with a dominant spanwise wavelength of $\approx 2.2H$ for $AR > 7.5$. These numerical predictions have been substantially confirmed in a series of experiments carried out by Naghib Lahouti et al. [11], although intermittent large-scale three-dimensional structures were found at Reynolds numbers as low as $Re_H \approx 250$. A Direct Numerical Simulation (DNS) study of the turbulent flow past a rectangular trailing-edge has been performed by Yao et al. [16] for $Re_H = 1000$ and an incoming boundary layer displacement thickness of $\delta^* \approx H$. Unsteady two and three-dimensional RANS computations of the same flow have also been performed by Yao et al. [17] using the $k - \epsilon$ model and different low-Reynolds near-wall treatments. However, several quantitative discrepancies with DNS data are observed, especially in the near-wake region, whose complex physics still represents a challenge for RANS modeling.

Most of the control studies of the unsteady wake past a thick flat-plate have focused on the 3D spanwise forcing of the nominally two-dimensional flow [3], resulting in the disorganization of the large-scale spanwise vortical structures rolling up at the trailing-edge of the body. Both passive, [12], and active open-loop techniques, [10], have been proposed, being characterized by a spanwise length-scale of $\approx 2.5H$, close to the natural three-dimensional instability wavelength. Spanwise-uniform time-periodic forcing has been tested by G. Nati [5] using plasma actuators located at the trailing-edge of the body. In this case the large vortical structures are broken up in smaller ones, thus inhibiting the natural shedding process. Closed-loop control techniques have been considered as well, with the main advantage of self-adapt to different flow conditions and incoming disturbances. As an example, successful applications are described in the experimental studies by Pastoor et al. [13] and Stalnov et al. [15], using adaptive nonlinear and simple proportion feedback controls, respectively. Nevertheless, in most cases the control design is tailored to the specific flow configuration and forcing technique adopted, lacking of a general and robust methodology.

A general model-based framework to tackle the flow control problem is based on linear dynamical system and optimal control theories, [8]. When dealing with model-based flow control, one of the main difficulties is represented by the high-dimension of the discretized flow systems. Therefore the derivation of accurate and robust Reduced Order Models (ROMs) defines an essential step in the control design. Different model reduction techniques have been introduced in application to the linearized flow equations around a given base/mean flow state, such as the modal and the balanced truncation techniques [1, 4]. Another popular class of methods exploits the Proper Orthogonal Decomposition (POD) and the Galerkin projection of the governing Navier-Stokes equations [9], with the system linearization being performed after the model reduction step.

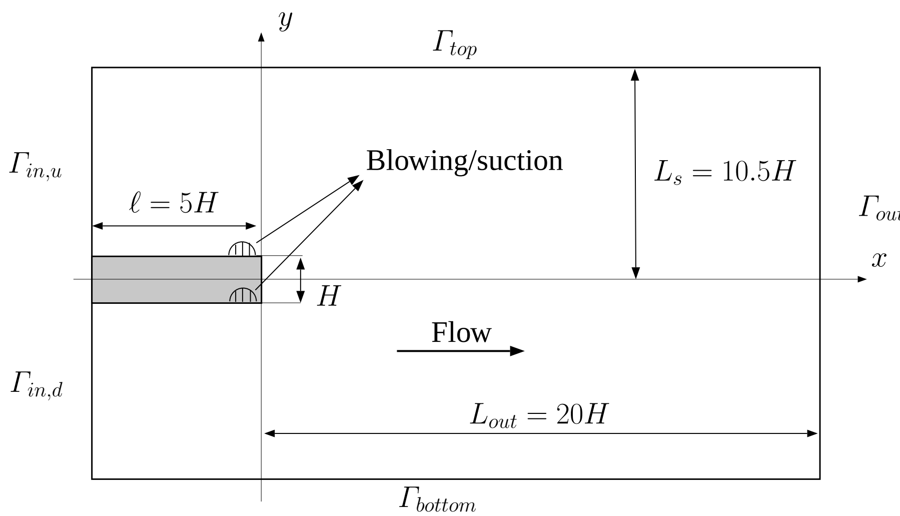

Figure 1: Sketch of the flow configuration and of the adopted computational domain.

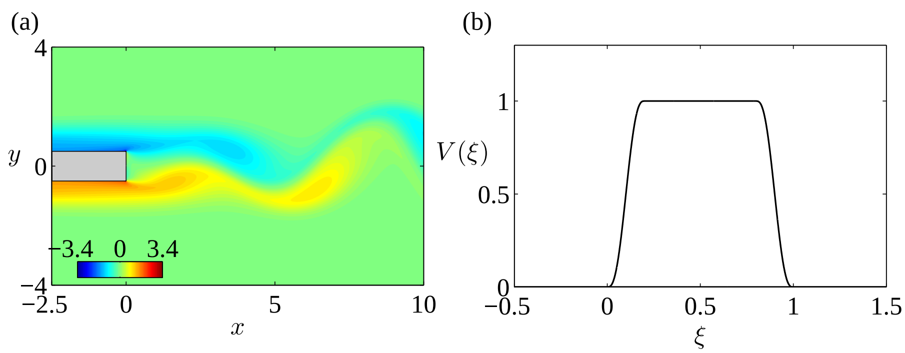

Figure 2: Flow past a thick flat-plate: (a) Instantaneous vorticity field of the uncontrolled flow. (b) Reference blowing/suction velocity profile.

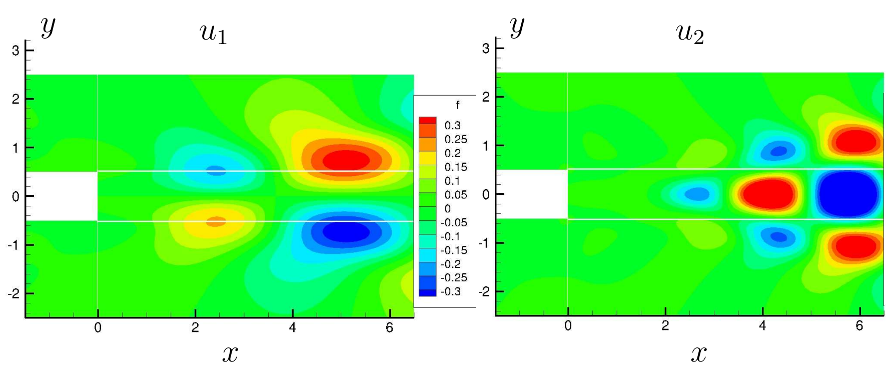

Figure 3: First and third POD modes of the uncontrolled flow past a thick flat-plate: x-velocity component.

2 Present works

The approach described by [9] is considered in the present work and applied to the control of the two-dimensional incompressible flow past a thick flat-plate trailing-edge at $Re_H = 200$. The flow configuration and the adopted computational domain are illustrated in figure 1. Two symmetric Blasius velocity profiles are enforced at the inlet boundary $\Gamma_{in,u} \cup \Gamma_{in,d}$ with a conventional thickness of $\delta = 1.1H$, which approximately corresponds to the value of $AR \approx 15$ considered in [6]. Direct numerical simulations of both the natural and the controlled flow are performed using the open-source software OpenFOAM (*www.openfoam.com*). In our numerical setup, the incompressible Navier-Stokes equations are discretized using standard finite volume central schemes on a structured Cartesian grid. The iso-vorticity lines of the flow are plotted in figure 2(a). In order to control the considered flow, unsteady blowing/suction slots are introduced on the upper and lower side walls, close to the blunt trailing edge, for $x \in [-0.5, -0.1]$, by imposing a boundary condition of the form $v(x,t) = V(x)c(t)$, where $V(x)$ is a reference velocity profile and $c(t)$ is the given control amplitude. More precisely, at each time instant, the same boundary condition is enforced on both wall sides, thus resulting in a zero net-mass blowing/suction actuation. The reference blowing/suction profile is represented in 2(b) and assumes the expression

$$V(\xi) = \mathcal{H}_m(\xi/w - 1) + \mathcal{H}_m((\xi - 1)/w + 1), \quad \xi \in [0,1], \tag{1}$$

where ξ is a nondimensional abscissa along the slot width. The function $\mathcal{H}_m(s)$ corresponds to a *mollified* step function defined as:

$$\mathcal{H}_m(s) = \begin{cases} 0 & \text{if} \quad s \leq -1, \\ 0.5 + s(0.9375 - s^2(0.625 - 0.1875s^2)) & \text{if} \quad s \in (-1,1), \\ 1 & \text{if} \quad s \geq 1, \end{cases} \tag{2}$$

where the parameter w is set equal to $w = 0.1$. At the same time, in order to close the feedback loop, velocity sensors are located in the wake.

The same procedure described by Nagarajan et al. [9] is adopted here to derive the linearized POD ROM for control design. In particular a Tikhonov regularization is employed for the calibration of the derived ROM and the *actuation mode technique* proposed by [7] is used to embed the control in the POD basis. The streamwise velocity fields corresponding to the first and the third POD modes are displayed for instance in figure 3, displaying characteristic antisymmetric and symmetric patterns, respectively. From a forced DNS with the function $c(t)$ known as a specific chirp function [2], an actuation mode ψ orthogonal to the POD basis is determined and a nonlinear dynamical system with actuation is designed. From this set of Ordinary Differential Equations (ODEs), two different control methods are considered that are the Linear Quadratic Gaussian (LQG) control and a *direct output-feedback* law. This latter avoids the convolution product between the flow measurements and the compensator transfer function, as, for instance, in the LQG approach. In particular, a linear constant feedback rule of the flow measurements $m_j(t)$ is obtained as $c(t) = K_j m_j(t) + \beta$. This law can be more easily introduced within a numerical simulation of the controlled flow and moreover in a flow control experiment. The two computed low-dimensional controllers will be applied to the considered flow, investigating and comparing their performance for the attenuation of the vortex-shedding. Variations of both control and flow parameters will be considered in order to assess the robustness of this general approach.

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