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PROPOSITION DE SUJET DE THESE

Intitulé : Model reduction for nonlinear control of open flow aerodynamics

Référence : **MFE-DAAA-2025-17**
(à rappeler dans toute correspondance)

Début de la thèse : 01/10/2025

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Mots clés

Reduced Order Models, Computational Fluid Dynamics, flow control, nonlinear dynamics

Profil et compétences recherchées

Mechanical/Aerospace engineer (master recherche, grande école généraliste)

Présentation du projet doctoral, contexte et objectif

Suppressing flow instabilities is a significant challenge with industrial potential, including drag reduction and noise minimization. Standard feedback control requires a linear time-invariant (LTI) model, which is why linear strategies remain common due to their simplicity and robustness [1-3]. However, strongly nonlinear systems present challenges that linear techniques struggle to address [4]. More sophisticated nonlinear control strategies formally exist, but for high-dimensional dynamical systems, as in open-flow aerodynamics, the dimensionality of the governing equations becomes a bottleneck, and solving nonlinear Model Predictive Control (MPC) problems in an online fashion becomes quickly intractable. To make such nonlinear techniques applicable in real-life applications, low-dimensional approximations, i.e. Reduced Order Models (ROMs) of the governing equations are needed. In this perspective, the Spectral Submanifold (SSM) theory [5-9] has recently emerged as a powerful data-driven, yet physically-interpretable, model reduction tool, identifying key dynamics through techniques like Proper Orthogonal Decomposition (POD). The resulting SSM normal form produces a sparse low-dimensional surrogate model of the original high-dimensional system, while preserving essential dynamics, hence offering an ideal platform for efficient nonlinear control.

This PhD research precisely aims to apply and extend SSM theory to open flow aerodynamics control, enabling efficient real-time nonlinear control. For this purpose, open cavity flows (see Fig. 1(a)), which are prone to self-sustained instability and aero-acoustic feedback (Fig. 1(b)) leading to strong nonlinear interaction of multiple coherent structures [10], known as Rossiter modes, provide a challenging test case for SSM modeling. For applications like weapon bays, controlling these instabilities is crucial to prevent damage, fatigue failure and ensure safety during munition deployment.

Work Program :

- Year (1) : The candidate will start by familiarizing with the SSM theory and with the existing open-source packages for data-driven SSM, i.e. SSMTool/Learn [7]. Initial numerical experiments will be performed on an idealized incompressible two-dimensional cavity in laminar regime, possibly far above the instability onset of multiple unstable modes to enhance nonlinear interactions. Such a strongly nonlinear regime will offer a first benchmarking scenario to test the predictive power of the SSM reduction in self-sustained autonomous dynamics where nonlinear interactions of multiple coherent structures may induce a dynamical mode switching [10].

- Year (2) : Successively, the candidate will focus on the modelling of the input-output dynamics for nonlinear real-time control. Particularly, the candidate will test whether the reduced model learnt from exclusively the autonomous dynamics (in **year (1)**) generalize to forced response, thus offering a surrogate low-dimensional model for the design of the control strategy (Fig. 1(c,d)). Compressibility effects will also be introduced to explore the robustness of the reduced autonomous model to the additional physics introduced by acoustic disturbances, which are key features in input-output dynamics of realistic cavity flows. If the reduced model is found to perform poorly, additional theoretical modelling, based on existing literature [2,11] will be required to improve and extend the SSM modeling beyond its current range of applicability and, specifically, to derive meaningful low-dimensional normal forms for highly non-normal dynamics [11].

- Year (3) : Lastly, if satisfying results are obtained at this stage, the candidate will attempt the reduced modelling of a turbulent three-dimensional subsonic cavity (Fig. 1(a)), using as training datasets, available homemade experimental measurements or high-fidelity simulations performed with our in-house CFD tools. This last challenge, on top of naturally increasing the complexity of the underlying flow because of the three-dimensionality, will also require the modelling of stochastic forcing [9] to mimic the effect of turbulent incoherent fluctuations that could potentially play a role in intermittency phenomena and mode switching [10].

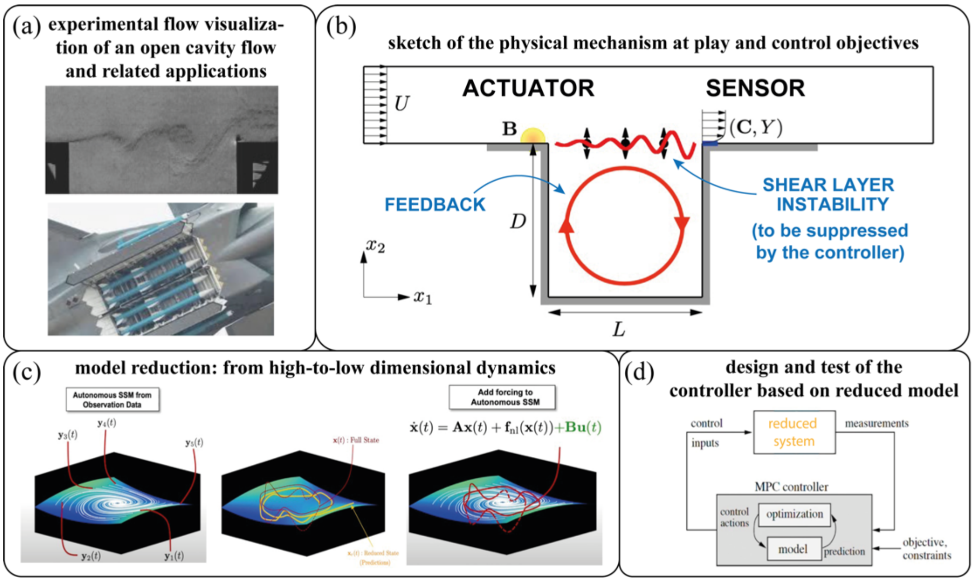

Figure 1: (a) Experimental snapshot [10] of a self-sustained oscillatory instability in a subsonic open cavity flow and connection with real-life scenarios, e.g. cavity flow past a weapon bay of a military aircraft. (b) Sketch of the physical mechanisms, i.e. shear-layer instability and destabilizing acoustic feedback, and control objectives in a typical cavity flow [4]. (c) Work-flow of the SSM-based model order reduction : the autonomous dynamics of the full system is projected onto a low-dimensional « manifold » or state-space ; once the reduced model is constructed, the latter is used to make predictions about the forced response to a control input **u**(t) [8]. (d) Sketch of nonlinear closed-loop control : the Model Predictive Controller (MPC) is designed using the reduced system, instead of the original high-dimensional one [8].

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