Ensemble variational-based open-loop control of cavity flows

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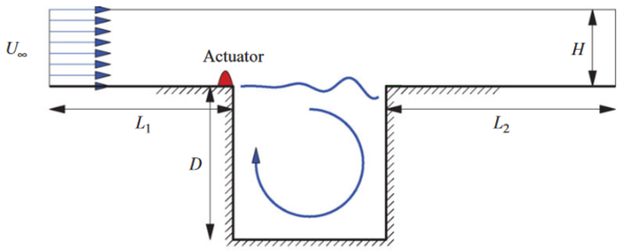
Flow control in fluid mechanics is an important concept in ensuring that fluid systems operate efficiently and reliably. It involves guiding the flow to achieve specific goals, such as reducing energy losses or improving stability. Often, flow control is viewed as an optimization problem aimed at achieving objectives such as preventing the growth of flow disturbances or maintaining desired flow behavior.

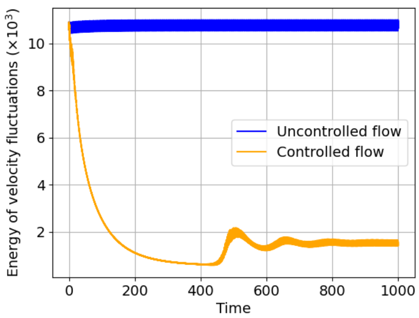
In this study, we aim to address the optimization of an open-loop control strategy using ensemble-based variational techniques (EnVar) [1] [2], offering an alternative to the adjoint-based optimization method. In fact, while adjoint methods require intensive gradient computations, such as Jacobian calculations, the EnVar method, which originated in the data assimilation community, is non-intrusive and therefore easier to formulate and implement. The search for an optimal control strategy takes place within a subspace defined by an ensemble of realizations, corresponding to various simulations with different control parameters. The iterative procedure aims to determine the optimum through a linear combination of controls in the ensemble of realizations.

Our goal is to apply this methodology to perform the control of a two-dimensional cavity flow [3] [4] (Figure 1a), which exhibits multiple instabilities at high Reynolds numbers. To this end, we first introduce a parameterized (in frequency and amplitude) localized forcing term in the momentum equations, which mimics blowing/suction close to the cavity walls. Subsequently, a forcing term that varies in both time and space is also considered, greatly increasing the dimension of the control vector. The considered control vectors are optimized in order to minimize a cost function that is defined as the norm of the velocity fluctuations relative to the base flow, i.e. a fixed-point solution of the Navier-Stokes equations, considering the full (i.e. nonlinear) unsteady Navier-Stokes equations as equality constraints.

The control vectors that result from the optimization framework successfully lead to a significant reduction in the kinetic energy of the fluctuations, as illustrated through Figure 1b. In addition, we compare the EnVar optimization method with the adjoint method to highlight the advantages of the newly implemented approach, and we explore different aspects of the optimization process – such as the generation of the ensemble members – with a future focus on applying the EnVar methodology to identify open-loop control strategies for complex and unstable applications, such as rotor-stator cavities.



(a) Cavity configuration[4]



(b) Kinetic energy of velocity fluctuations

Figure 1: Open-loop control of a cavity flow at $Re = 6250$: (a) flow setup and (b) evolution of the kinetic energy in time in the uncontrolled case and when applying an EnVar-based optimized parameterized forcing.

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