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Optimal control of a transitional jet using a continuous adjoint method

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ABSTRACT

The use of active flow control with unsteady means gains increasing interest in engineering designs. The main bottleneck of the methodology is the strong dependence on trial and error to find the right set of control parameters. In this context, adjoint-based control using high-fidelity simulations is a promising method to explore optimal values in large parameter spaces. However, the applicability of the methodology to complex engineering geometries remains extremely limited. In this work, we employ adjoint-based optimal control using unsteady high-fidelity simulations in a generic unstructured grid framework. To this end, an optimal flow control study is conducted in OpenFOAM® using the continuous adjoint method and DNS simulations. To demonstrate the methodology, we study control of an incompressible axisymmetric jet at $\mathrm{Re}_D = 2000$, with focus on improving its mixing properties. The gradient of the cost functional is calculated with a newly developed unsteady-adjoint solver based on a classical incremental projection scheme. Particular attention is paid into the presentation of mathematical and algorithmic details. Moreover, we address three main issues that remained relatively undiscussed in common practise: the choice of adjoint boundary conditions on computational boundaries, the failure of the adjoint methodology for long optimization horizons in turbulent flows and the treatment of the additional transposed convective term in the adjoint equations. Practical solutions are employed for these issues. Two optimization cases with different initial conditions are designed. To this end, we considered maximization of enstrophy in the near field, for which increments of 10.5% and 5.6% are obtained.

1. Introduction

With the experimental visualization of orderly structures in high Reynolds number turbulent flows by pioneering works of Crow and Champagne [1], and Brown and Roshko [2], scientists and engineers dissolved the belief that turbulence is a totally random phenomenon. This new understanding immediately revolutionized flow control strategies. Simple control designs, targeting the mean properties of flows, have been replaced with more sophisticated unsteady methods aiming to manipulate quasi–periodic large–scale coherent motions. This new era in flow control, termed also modern flow control [3], has a huge potential to improve somewhat saturated engineering designs using steady active controls or passive geometrical modifications. The main challenge in modern flow control is the lack of predictive methods. Overall progress mainly depends on empirical parametric explorations in large dimensions, as the dynamics of deterministic coherent events and their interaction with random background turbulence is still not very well understood.

Flow optimization methods are efficient tools to explore large parameter spaces in active control of turbulent flows. A typical flow optimization, or optimal flow control study, aims to minimize a cost functional quantifying the flow control objective by using an optimization algorithm and a mathematical flow model. In early efforts, optimal control was successfully applied to boundary layers using simplified flow models such as boundary-layer equations or parabolized stability equations (See, e.g., Refs. [4,5]). With the increasing availability of computing resources, flow optimization methods using the nonlinear Navier–Stokes equations are establishing themselves as an alternative method in optimal flow control. To date, flow optimization studies using the nonlinear Navier–Stokes equations were carried out almost exclusively with gradient-based methods, as these methods have better convergence properties compared to other classes of optimization algorithms, e.g. evolutionary and stochastic methods. These methods are based on finding descent directions in the optimization landscape and updating the controls using these descent directions. These directions are constructed from the gradient of the cost functional. Therefore, this gradient has to be calculated at every optimization iteration. To that end, the adjoint method is commonly used, as it provides the whole gradient vector by solving the adjoint Navier–Stokes equations, and is insensitive to the dimension of the control parameter space.

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When the adjoint method is applied to unsteady flows using the nonlinear Navier–Stokes equations, it requires the storage of velocity fields at each time step. Early efforts using the adjoint method in combination with DNS or LES suffered due to this excessive storage requirement, and focused on simple canonical flows such as periodic channel flow [6], and spatially developing [7], or convective mixing layers [8]. More recently, optimal control using the adjoint method was applied to reduce jet-noise emisssions using the compressible Navier–Stokes equations, e.g., Marinc and Foysi [9], Schulze et al. [10] and Kim et al. [11]. All these studies investigated turbulent flows in idealized geometries using special high-order discretization methods.

The application of the adjoint methodology on unsteady flows demands further development and testing before it can be employed in engineering problems with complicated geometries. The support for these complex geometries can be achieved only by a transition to generic unstructured CFD frameworks. In recent years, this transition is enabled for steady-flow optimization studies, and optimization with the adjoint method is rapidly emerging to become an industry standard [12–16]. In these studies, passive control designs have been improved using shape or topology optimization methods that require only a modest description of the flow, e.g. by Reynolds-Averaged Navier–Stokes Equations (RANS). More recently, Carnarius et al. [17] conducted an unsteady adjoint-based control study on unstructured grids by using unsteady RANS in combination with continuous and discrete adjoint method to delay the flow separation on an airfoil by steady blowing or suctioning. However, to date not much experience exists on the use of transient adjoint methods with DNS simulations in generic unstructured CFD frameworks.

In the current work, we perform an adjoint-based optimization study using unsteady high-fidelity turbulent flow simulations in a generic unstructured grid framework. To this end, we have selected the general purpose open-source CFD library OpenFOAM® v2.3.x as the development environment. An incompressible axisymmetric jet at $\mathrm{Re}_D = 2000$ is selected as the application case, and we conduct an optimization study using the continuous adjoint method and DNS simulations to improve the mixing properties of the jet. A steepest-descent algorithm with backtracking line-search is the method of choice for DNS-based optimization. To apply this methodology in OpenFOAM®, the only extension required is the implementation of the unsteady adjoint Navier–Stokes equations. As these equations have a very similar structure to their primal counterparts, maximum code re-usability is possible. The continuous adjoint approach is selected because of this convenience in the implementation. It is often the method of choice in optimal flow control studies with high-fidelity turbulent flow simulations, e.g. [6–8,11,18]. Particular attention is paid to the continuous formulation of the problem and its subsequent discretization. Moreover, we elaborated three main issues in the adjoint-based control of unsteady turbulent flows: the choice of adjoint boundary conditions on computational boundaries, the failure of the adjoint methodology for long optimization horizons in turbulent flows and the treatment of the additional transposed convective term in adjoint equations.

In turbulent jets, increasing the mixing rate between the injected fluid and stagnant ambient fluid is one of the major interests with, e.g., possible applications towards cleaner combustion with less carbon emissions, or more efficient pollutant and waste-water discharge. It can be effectively improved using active flow control with unsteady actuators where the aim is to manipulate dynamic vortical features of the turbulent jet [19]. If unsteady actuators are driven in a regime close to the jet preferred mode, large-scale structures are significantly promoted and the jet spreading is increased [20,21]. This yields dramatic changes in global mixing characteristics such as the entrainment rate, the decay rate of centerline velocity and passive scalar [22]. However, enhanced coherence in the flow increases the strength and stability of large scale structures and therefore delays their breakdown into smaller scales [23]. Such a delay yields an inefficient molecular mixing. Therefore, in a mixing augmentation problem, all relevant scales of turbulent motion should be properly addressed by controls. This requires a complicated multi-frequency actuation, as large-scale events occur with characteristic low frequencies, and fine-scale motions are typically observed in high-frequency regimes. Optimal control using high-fidelity turbulent simulations can be very interesting to explore multi-frequency actuation. To our knowledge, the only effort to date in optimal control of jet mixing has been made by Hilgers and Boersma [24]. They maximized the spreading of the jet using stochastic optimization algorithms and DNS simulations. They used in total four control parameters that were amplitude and frequency for helical and axial excitations. Such a low-dimensional optimization problem with a cost function that is mainly sensitive to large-scale motions of the jet clearly addresses large-scale mixing. Up till now, multi-scale mixing behavior remains relatively unexplored.

The controls in this study are modeled as 12 small hexahedral regions in the domain, that are distributed evenly around the jet circumference with a uniform forcing distribution. Forcing is applied only in the radial direction. Some similarities may exist, e.g., with flap actuators [25], but we selected this type of control mainly for computational reasons (as discussed in detail in Section 2.2). Moreover, radial perturbations are effective in promoting large-scale structures, as the development of primary and secondary vortices in the transition region of a round jet is initiated by the distortions in the azimuthal symmetry of the jet [22,26]. The signal of controls is designed as a finite Fourier series with 10 frequency components varying between $0.5\mathrm{St}_{pm}$ and $5\mathrm{St}_{pm}$ where St_{pm} is the considered preferred mode frequency with a value of $\mathrm{St}_D = 0.33$. Optimization is carried out for coefficients in the Fourier series, yielding 240 degrees of freedom in the control space. Two optimization cases with different initial conditions are considered. One of the cases contains an additional low magnitude random forcing component in its initial condition. Optimizations are conducted for two different initial conditions up to around ten outer iterations, and reductions of about 10% are obtained. Optimized control signals are found to be composed of additional low value multi-frequency components, and they produce flow fields with enhanced irregularity and mixedness.

The structure of this paper is follows. First, we review the gradient-based optimization with continous adjoint method in detail in Section 2. Then the numerical setting is introduced in Section 3. Subsequently, limitations of the adjoint methodology are discussed in Section 4, and results of the optimal control study are presented in Section 5. Finally, conclusions are presented in in Section 6.

2. Optimization with continous adjoint method

In this section, the unsteady jet-flow optimization problem is presented in infinite-dimensional setting.

2.1. Geometrical configuration

Before we present the mathematical details of the jet-flow optimization problem in further sections, we introduce the geometrical details. A descriptive sketch for the three-dimensional computational domain Ω is illustrated in Fig. 1a using a two-dimensional cut at $\theta = 0$, and dimensional specifications for various parts in the domain are summarized in Table 1. The computational domain consists of two parts. A large cylindrical domain Ω_a for the ambient fluid, which extends $L = 8D$ in the axial direction and $R = 5D$ in the radial direction, is attached to a small pipe domain Ω_p with $R_p = 0.5D$ and $L_p = 8D$. The pipe is introduced to allow adjoint fields to exit the ambient domain while moving upstream with negative convection. The observation domain Ω_s to measure the cost functional in the optimization problem is selected to be $\Omega_s = [0, 5D] \times [0, 2\pi] \times [0.6D, 6D]$,