Surrogate-based optimization of actuation parameters for active drag reduction in turbulent boundary layer flows

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A significant portion of the energy demand and associated greenhouse gas emissions originate from the transportation sector, with air travel and high-speed rail accounting for a substantial share. Since fuel-burning jet engines will remain the primary propulsion source for large civil aircraft for decades to come and rising energy costs pose an economic challenge for high-speed trains, aerodynamic improvements are needed to reduce energy demand and costs.

A promising technique to actively reduce the aerodynamic viscous drag is the use of spanwise traveling transversal surface waves manipulating the near-wall turbulent boundary layer, which is less well studied than passive techniques such as riblet surfaces. From an optimization perspective, given the flow conditions, e.g., specified by the Reynolds and Mach numbers, the goal is to choose the non-dimensional actuation parameters, i.e., amplitude A^+, wavelength λ^+ and period T^+, such that the drag reduction Δc_d and the net power savings ΔP_{net} are optimized while other aerodynamic properties, such as the lift-to-drag ratio L/D for airfoils, are neutrally or positively affected.

The partially conflicting objectives, i.e., drag reduction and net power savings, are evaluated using wall-resolved Large-Eddy Simulations (LESs) based on the body-fitted deformable structured grid finite volume solver part of the in-house solver framework m-AIA. Since wall-resolved LESs of turbulent boundary layer flows are computationally expensive and the design space of choices is too vast to be sufficiently investigated by grid search methods, two surrogate-based optimization strategies are selected to guide the determination of optimal actuation settings.

First, in previous studies, precomputed LES data of a flat plate approximation are smoothly interpolated using Support Vector Regression (SVR), focusing on the dependence of the drag reduction on the actuation parameters. The resulting SVR model is used to identify the a-priori assumed ridgeline, i.e., the curve connecting the wavelength-parameterized optima locations, by applying symbolic regression. Based on the prior knowledge of self-similarity and the Tomiyama and Fukagata scaling for the local skin friction coefficient, the ridgeline is extrapolated 66% beyond the initial wavelength range, revealing an unexplored and numerically validated optimization potential. [1] [2]

Second, this study focuses on extending the previous optimization pipeline using an SVR-based ridgeline surrogate to an automated optimization loop that addresses the exploration-exploitation trade-off employing Bayesian Optimization (BO) with a Gaussian Process (GP) prior as a surrogate. The prior knowledge utilized for and obtained by the SVR-based ridgeline optimization is incorporated into the GP prior to efficiently guide the optimization of the actuation parameters in a closed-loop.

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[1] Albers et al., *Flow, Turbulence and Combustion* **105**, S. 125 (2020).

[2] Fernex et al., *Physical Review Fluids* **5**, S. 073901 (2020).