Turbulence control—From model-based to machine learned

Bernd R. Noack
Harbin Institute of Technology, China
bernd.noack@hit.edu.cn

Abstract

Turbulence control is a critical enabler of aerodynamic drag reduction, lift increase, mixing enhancement, and noise reduction. Current and future applications have epic proportion: cars, trucks, trains, airplanes, wind turbines, medical devices, combustion, chemical reactors, just to name a few. A key feature, opportunity and technical challenge is the inherent nonlinearity of the actuation response [1]. For instance, excitation at a given frequency will affect also other frequencies. This frequency cross-talk is not accessible in any linear control framework.

In these lectures, we discuss a spectrum of turbulence control strategies. Starting point is human-learned nonlinear model-based control explaining the dynamics with one or few dominant frequencies [2] in analytical detail. This path follows the traditional control philosophy

$$\text{understanding} \mapsto \text{modeling} \mapsto \text{control} \mapsto \text{tuning in experiment},$$

may work beautifully for simple dynamics but is less suited for the jungle of nonlinear surprises.

Recently, artificial intelligence / machine learning has opened a game-changing elegant new avenue [3]: the automated model-free discovery and exploitation of unknown nonlinear interactions directly in the plant. This avenue leads to the new faster, easier (student-proof) paradigm,

$$\text{experiment} \mapsto \text{control} \mapsto \text{modeling} \mapsto \text{understanding},$$

with numerous success stories in experiments. In between the extremes of model-based and model-free strategy, cluster-based networks emerge as enabler for automated modeling *and* control. The following topics will be discussed:

(1) **Model-based control (part 1).**
   a) Reduced-order modeling—POD Galerkin method.
   b) Modeling and control of a single frequency dynamics.
   c) Modeling and control of two/multiple frequency dynamics.

(2) **Model-free machine learning control (part 2).**
   a) Control as regression problem—Genetic programming.
   b) Machine learning control.
   c) Control landscapes—Cartographing the learning.

(3) **Cluster-based control (part 3).**
   a) Coarse-graining snapshots—Clustering.
   b) Cluster-based modeling.
   c) Cluster-based control.

(4) **Principles of control (part 4).**
   a) Physical actuation mechanisms.
   b) Pairing methods with problems.
   c) Good practices for the experiment.

Reading material: Our review article [1] provides the roadmap for the spectrum of turbulence control methods taught in this class. Model-based and model-free flow control are described in detail in our Springer textbooks [2, 3].

POD-based reduced-order modeling (part 1) is covered in the classics by Holmes et al. [4]. An inspired hands-on introduction of control methods is provided by Aström & Murray [5]. Burkov [6] is an excellent primer of machine learning as basis for part 2–4. Evolutionary algorithms (part 2) are beautifully described in the short book of Wahde [7].

Perhaps the best start is our review article [1]. The machine learning primer [6] will be useful for any modern research beyond these lectures. From there on, the recommended reading may be based on time and interest.

References

[1] S. L. Brunton and B. R. Noack. Closed-loop turbulence control: Progress and challenges. *Appl. Mech. Rev.*, 67(5):050801:01–48, 2015.

[2] B. R. Noack, M. Morzyński, and G. Tadmor. *Reduced-Order Modelling for Flow Control*, volume 528 of *CISM Courses and Lectures*. Springer-Verlag, Vienna, 2011.

[3] T. Duriez, S. L. Brunton, and B. R. Noack. *Machine Learning Control — Taming Nonlinear Dynamics and Turbulence*, volume 116 of *Fluid Mechanics and Its Applications*. Springer-Verlag, 2017.

[4] P. Holmes, J. L. Lumley, G. Berkooz, and C. W. Rowley. *Turbulence, Coherent Structures, Dynamical Systems and Symmetry*. Cambridge University Press, Cambridge, 2nd paperback edition, 2012.

[5] K. J. Åström and R. M. Murray. *Feedback Systems: An Introduction for Scientists and Engineers*. Princeton University Press, Princeton, 2010.

[6] Andriy Burkov. *The Hundred-Page Machine Learning Book*. Andriy Burkov, 2019.

[7] M. Wahde. *Biologically Inspired Optimization Methods: An Introduction*. WIT Press, 2008.