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# Turbulence Control — Better, Faster and Easier with Machine Learning

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Closed-loop turbulence control has current and future engineering applications of truly epic proportions, including cars, trains, airplanes, jet noise, air conditioning, medical applications, wind turbines, combustors, and energy systems, i.e., well-known topics presented in this conference. 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.

Recently, Artificial Intelligence (AI) / Machine Learning (ML) has opened game-changing new avenues [2]: the automated model-free discovery and exploitation of unknown nonlinear actuation mechanisms directly in the plant. In this talk, we review recent successes on these avenues towards *broadband frequency turbulence control with distributed actuation/sensing*. Presented examples focus on drag reduction of bluff bodies with multiple actuators and multiple sensors. The journey includes (1) handcrafted insightful deep mean-field modeling explaining complex flow dynamics [3], (2) automated cluster-based modeling for broadband turbulence [4], (3) automated gradient-enriched machine learning control for fast learning of general nonlinear multiple input multiple output feedback laws [5] and concludes with (4) a preview of smart skin separation control customizing engineering needs.

The presented work involves Guy Cornejo Maceda, Nan Deng, Daniel Fernex, Songqi Li, Francois Lusseyran, Marek Morzyński, Luc Pastur and Richard Semaan.

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[2] Brunton, S. L., Noack, B. R. & Koumoutaskos, P. 2020 *Ann. Rev. Fluid Mech.* **52**:477–508.
[3] Deng, N., Noack, B. R., Morzyński, M., & Pastur, L. R. 2020 Low-order model for successive bifurcations of the fluidic pinball. *J. Fluid Mech.* **884**, A37:1–41.
[4] Fernex, D., Noack, B. R. & Semaan, R. 2021 *Science Advances* **7**(25), eabf5006:1...10.
[5] Cornejo Maceda, G. Y., Li, Y., Lusseyran, F., Morzyński, M. & Noack, B. R. 2021 *J. Fluid Mech.* A42:1–43.