Physics-Based Low Order Galerkin Models in Fluid Dynamics & Flow Control

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The order and complexity of computational fluid dynamic (CFD) models can be staggering. Yet while this complexity reflects the intricate multi-scale dynamics CFD models attempt to resolve, it is also a common observation in many practical cases that large scale flow structures are governed by a manageable, and relatively simple set of dynamic rules. Hence the wide spread quest to produce low order models for fluid flow systems: Models that encapsulate an insight into key governing mechanisms and that are useful for a systematic design procedures of feedback control laws.

The proper orthogonal decomposition (POD), where Galerkin mode-sets are extracted from CFD or experimental data, is perhaps the most common approach. Yet, in their original forms, these nonlinear models are, all too often, very fragile and their domain of validity is limited to a small neighborhood of an attractor or a fixed point and nominal flow conditions, and even there, the accuracy of their dynamic predictions leaves much to be desired. In this, first of a two part talk with B. R. Noack we provide an overview of our effort to uncover a model structure that maintains the POD simplicity but possesses the robustness and dynamic range that are essential for control design. One key premise, underlying our approach is that for a successful, low order model of a physical phenomenon, it is essential to effectively represent the dominant physical mechanisms.

We thus focus on the distillation of simplified versions of the governing physical first principles. A second premise is a realization that while standard Galerkin models are focused on a spatially and temporally limited ranges of length scales, dominating flow unsteadiness, both longer and smaller scales are essential for ample models of energy supply and consumption. Yet a third principle is the realization that governing flow structures deform along transients. Indeed, such deformations are typically the very objective of flow control. The bilateral interactions of unsteady fluctuations and mean field variations are essential to the Navier-Stokes representation of the transition from an unstable steady solution to an attractor. A mean field model, essentially, a single state version of the Reynolds average equation, is established as an indispensable counterpart, representing these interactions at the Galerkin level.

Cutting through long outstanding Gordian knot, a novel finite time thermodynamics (FTT) model provides a statistical closure to time-averaged energy dynamics of Galerkin modes, and gives rise to physically based, nonlinear sub-grid turbulence models, where standard linear modal eddy viscosities fail. Interestingly, the integration of both the mean field and sub-grid representations give rise to stability ensuring Landau-like models, while making connections with the classical theories of Landau and Stuart, on the one hand, and of

Boltzmann, Jaynes and Kraichnan, on the other hand. The work described in this talk is a collaborative effort of the authors with many colleagues and students. Those most closely related to the discussed material are (alphabetically) B. Ahlborn, D. Bissex, T. Colonius, R. King, D. R. Luchtenburg, A. Mishra, M. Morzynski, B. Mutschke, M. Pastoor, C. W. Rowley, Z. Rusak and D. R. Williams. The work was supported by the US NSF and AFOSR.