A new Koopman-inspired approach to match flow field excitation with consequent structure responses for nonlinear fluid-structure interactions

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Abstract. This work presents a novel method to form constitutive fluid-to-structure, excitation-to-response correspondences for insights into nonlinear fluid-structure interactions (FSI). It combines temporal orthogonality and phenomenological visualization, serving as a Koopman-inspired, POD-projected, and machine-learning-embedded method that can be seen as an advanced Discrete Fourier/Z-Transform. Successful implementation with a prism wake with homogenous and anisotropic turbulence attests to its capability to handle a broad spectrum of problems involving nonlinear and stochastic dynamics.

Introduction

One long-standing difficulty of fluid-structure interactions (FSI) is the inability to match a flow field excitation with consequent structure response(s). There is yet an effective method to perform the task because of FSI's multi-dimensional complexities, involving many research frontiers like fluid mechanics, structural dynamics, nonlinearity, dimensionality, turbulence, stochasticity and chaos, and so on.

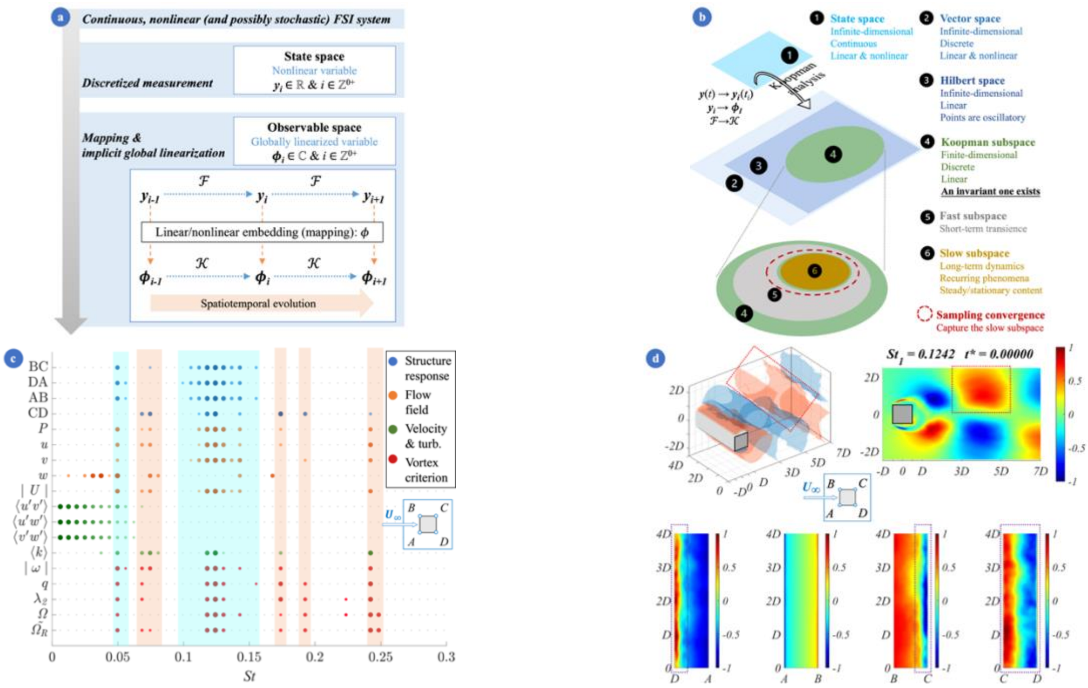

Figure 1: a) an overview of the Koopman theory; b) space transformations and mappings performed by Koopman algorithms; c) A demonstration of the multi-observable frequency-matching procedure to establish six dominant fluid-structure correspondences in the prism wake example; d) a snapshot of the dynamic Koopman mode showing the phenomenological content of matched flow field excitation and resultant structure surface pressures at St = 0.1242, the underlying mechanism is the formation of separation-induced asymmetric wall jets, shear-layer-triggered separation bubbles and reversed flows, reattachment as a result of excessive curvature and bubble enclosure, and eventual shedding of longitudinal substructure (i.e., rolls) as a part of a Karman vortex.

Results and discussion

Inspired by applied Koopmanism (Fig, 1a) [1], the authors developed and successfully actualized a data-driven approach to overcome the problem. The procedure begins with a series of space transformations and an implicit, globally optimal linearization, isolating orthogonal eigen tuples from spatiotemporally entangled raw measurements (Fig. 1b). Afterwards, the Koopman model distributes the dynamical content onto a discretized, sampling-independent Fourier spectrum, on which constitutive fluid-structure correspondence can be established by multi-observable frequency-matching (Fig. 1c). Finally, each fluid-structure pair can be visualized by the newly proposed dynamic Koopman mode, providing phenomenological information for full disclosures of underlying mechanisms (Fig. 1d). This method's data-driven nature means it can be applied to a broad spectrum of FSI cases, opening windows for new fluid mechanics insights. It also shows promise in control problems because each observed response can now be traced back to its excitation origin.

References

[1] Budišić, M., Mohr, R., Mezić, I. (2012) Applied Koopmanism. Chaos **22(4)** 047510.