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Modal Scale Decomposition in Turbulent Flows

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Summary

Modern science in the era of big data and machine learning aims at the extraction of meaningful information from large datasets that typically depict complex dynamical processes. Common characteristics of these systems are non-linear and unsteady dynamics which require specialized techniques to adequately analyze the underlying physics. However, developing interpretable, reliable, and generalizable methods with these properties is a fundamental state-of-the-art challenge in classical data analysis. One strategy related to mathematical and physical applications focuses on the transformation of data into a coordinate system in which data inherent features can be detected more easily, certain effects are decoupled from other mechanisms, or which basically enables novel understanding due to the changed perspective. This approach usually involves a segmentation of the data into modal representations, which are sub-components that provide easier access to the complex processes captured by the data. In this Ph.D. thesis, one of these methods – the empirical mode decomposition – is extended to a sophisticated and comprehensive version for physical applications. Precisely, the developed algorithm is able to process temporally and spatially resolved multi-component data exhibiting non-linear and unsteady physical effects, e.g., a time series of two-dimensional velocity fields. It is demonstrated that the resulting modal functions are coherent in space and time depicting a physically meaningful segmentation of the dynamical processes underlying the given data. The application to academic and real-world relevant fluid dynamical datasets, e.g., in the context of drag reduction of transportation systems like aircraft, highlights its great potential in advancing physically motivated analyses in a broad range of settings. Overall, the findings of this thesis show that the developed approach bears enormous potential in closing the current gap between highly complex data but inadequate analysis tools.

Scientific summary

Turbulent flows are characterized by a complete spectrum of scales. From a spatio-temporal perspective, the interaction of these scales usually involves non-linear and unsteady processes. However, the mathematical and physical limitations of state-of-the-art data analysis tools prohibit an accurate investigation of such dynamics. To close this gap, the two-dimensional noise-assisted multivariate empirical mode decomposition (2D NA-MEMD) is introduced. This data decomposition

method extracts physically meaningful modal representations of the flow field based on the scales inherent to the data. Thus, the approach is data-driven and the modes are adaptively biased towards locally dominant features. The simultaneous decomposition of multiple variates, e.g., spatially resolved velocity components at several time instants, preserves relations between these components in their modal representations such that causal relations can be investigated on a modal basis. For time-resolved data, additional properties like the noise assistance ensure a temporal coherence of the extracted modes in line with their physical dynamics. Consequently, spatially and temporally continuous modal representations of the flow field with an adaptive, scale-based segmentation are obtained that can be used to study non-linear and unsteady dynamics of turbulent flows. This is exemplified in figure 1 showing a streamwise velocity field of a turbulent channel flow and three corresponding modes sorted by their inherent scale size.

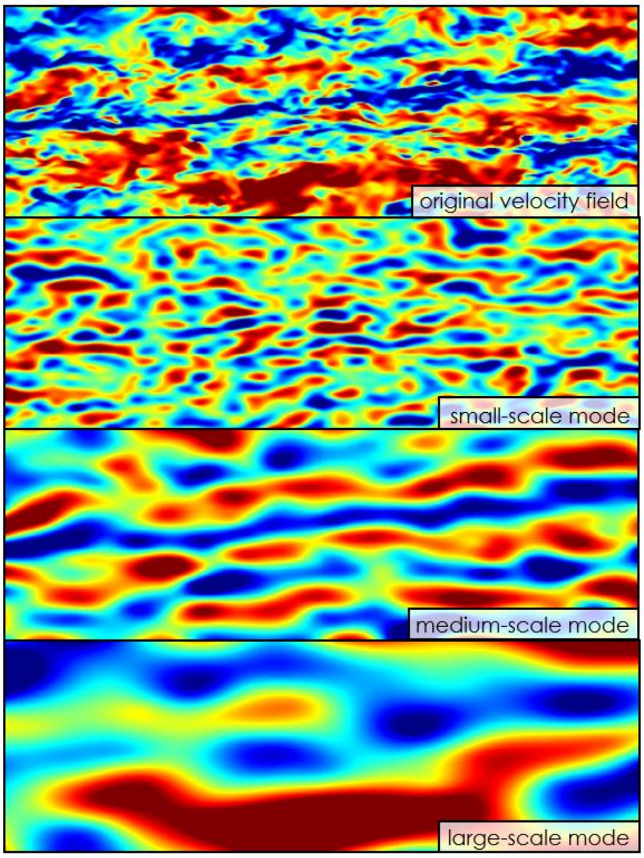

Figure 1: Example of a streamwise velocity field and three corresponding modes obtained by the 2D NA-MEMD

The approach is used in academic and real-world related fluid dynamical applications based on numerically and experimentally obtained data. The datasets cover academic topics related to the fundamental behavior of turbulent wall-bounded flows and engineering inspired research in terms of friction drag reduction in the transportation sector, transonic airfoil buffet flow, and the in-cylinder flow of combustion engines. The 2D NA-MEMD adapts exceptionally well to the variety of studied test cases yielding novel insight into the individual dynamical processes. Overall, the findings of this thesis reveal the enormous potential of the 2D NA-MEMD as a reliable data analysis tool for turbulent flows including their underlying physics and engineering related research. It lays the foundation for future studies aiming at the identification of dynamical flow features that are characterized by complex non-linear and unsteady interactions across different scales.

Validation of the 2D NA-MEMD. Several aspects of the 2D NA-MEMD have been validated based on direct numerical simulation data of a turbulent channel flow. This includes an analysis of the decomposition related hyperparameters, the reconstruction loss, the physical properties of the resulting modes, the computational complexity, and a performance comparison to less sophisticated EMD versions. The latter clearly revealed the 2D NA-MEMD's superiority with respect to the mode mixing phenomenon, the temporal coherence of the modes, and the robustness of the decomposition. More specifically, the 2D NA-MEMD severely reduces mode mixing, i.e., it provides an improved mode separation, due to the filter bank property of the added Gaussian noise. The method also establishes a temporal coherence of the modes although no temporal information is included in the decomposition. This essentially demonstrates the significance of the extracted modal representations in a physical context.

Scale-based interactions in turbulent wall-bounded flows. Research in the last decades has revealed a substantial interaction between near-wall turbulence and outer-layer large-scale motions in turbulent wall-bounded flows. Understanding the different phenomena involved in this scale-based interaction is not only relevant for fundamental research but it can also impact real-world applications that aim at the active manipulation of turbulent flows for the benefit of society. The application of the 2D NA-MEMD provided novel insight into this inner-outer interaction by considering non-linear and unsteady phenomena which are typically not captured by other approaches. For instance, the analysis uncovered a considerable time-dependent behavior of the interaction phenomena with respect to the inner-outer correlation and the associated inclination angle. Regarding the superposition and the interaction via sweeps, the temporal variations were shown to be strongly linked to the rates of high-speed large scales to total large-scale fluctuations.

Friction drag reduction by active wall forcing. The rising awareness of environmental issues substantially increases the necessity to deliver effective drag reduction methods in the transportation sector that meet the challenges of sustainability and conservation of resources. One key aspect that impedes the exploration of the full potential of flow control techniques is the incomplete understanding of the complex fluid dynamical processes. Applying the 2D NA-MEMD to a drag-reduced turbulent boundary layer flow, which was generated by spanwise traveling transversal surface waves, laid the foundation for a comprehensive explanation of the modified physical processes that result in friction drag reduction. That is, it was shown that the introduction of large-scale ejections close to the wall corrupts the mechanism by which highly energetic outer-layer large-scale motions transport high-momentum fluid towards the wall. This substantially reduces the fluctuation intensity at the wall and, in turn, results in friction drag reduction.

Suppressing shock ocscillations on supercritical airfoils in transonic buffet conditions. Within the transonic flight regime, a shock wave/boundary-layer interaction and the corresponding flow separation on the upper wing can induce transonic buffet, which potentially results in a structural fatigue of the wing. Since the underlying mechanisms sustaining the shock wave oscillations during buffet are still not fully uncovered, transonic buffet is of considerable research interest in the aviation sector. The application of the 2D NA-MEMD provided a more accurate description of the phenomenon by precisely capturing the temporal oscillations of the shock wave. In combination with additional post-processing tools like the Hilbert-Huang transform, the complex interplay of differently sized flow features was uncovered. More specifically, it was shown that it is possible to trigger buffet-related shock oscillations in pre-buffet flow conditions based on artificially introduced upstream traveling sound waves. The 2D NA-MEMD revealed that these waves promote an excitation within the flow field that yields a modified buffet cycle. As a result, the shear layer originating from the trailing edge is influenced, which, in turn, modifies the vortex shedding downstream of the airfoil and the buffet feedback cycle. By installing a porous trailing edge, it was further demontrated how the derived knowledge can be used to deploy buffet attenuation strategies to broaden the flight envelope.

Scientific contributions

Research related to this Ph.D. thesis yield seven peer-reviewed publications (two are currently under review) in renowned journals such as the *Journal of Fluid Mechanics* and *Physical Review Fluids*. Moreover, eight contributions to international conferences such as *APS*, *ETC*, *EDRFCM*, *ISPIV*, *TI*, *STAB*, and *TSFP* were accepted and an invited talk at Harvard University was given. Five selected publications are listed in the following.

E. Mäteling, M. Albers, W. Schröder (2023) *How spanwise travelling transversal surface waves change the near-wall flow*. Journal of Fluid Mechanics 957, A30

E. Mäteling, W. Schröder (2022) *Analysis of spatiotemporal inner-outer large-scale interactions in turbulent channel flow by multivariate empirical mode decomposition.* Physical Review Fluids 7 (3), 034603

E. Mäteling, M. Klaas, W. Schröder (2021) *Study on Large-Scale Amplitude Modulation of Near-Wall Small-Scale Structures in Turbulent Wall-Bounded Flows.* New Results in Numerical and Experimental Fluid Mechanics XIII

E. Mäteling, M. Klaas, W. Schröder (2020) *Detection of small-scale/large-scale interactions in turbulent wall-bounded flows*. Physical Review Fluids 5 (11), 114610

E. Mäteling, M. Klaas, W. Schröder (2020) *Simultaneous Stereo PIV and MPS^3 Wall-Shear Stress Measurements in Turbulent Channel Flow.* Optics 1 (1), 40-51