DATA DRIVEN ANALYSIS OF UNSTEADY SEPARATED FLOWS

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Abstract

Extracting meaningful information from flow field data, identifying interpretable and generalizable patterns, and in turn, revealing the essential system dynamics has remained a challenging problem in fluid dynamics domain. The complexity is further enhanced in cases where the underlying physics is high dimensional, nonlinear and having multiple spatio-temporal scales such as in the case of natural flapping-wing flight. Analysis, comprehension, characterization, modelling and prediction of aerodynamic characteristics of such transient flow configurations associated with low Reynolds number (Re) flight in general and plunging flight in particular constitutes the primary goal of the proposed research. The objectives have been realised by leveraging state of the art techniques in the field of data science, thereby augmenting both quantitative and qualitative understanding of the fundamental physical mechanisms associated with dynamics of separated flows, which are not evident in conventional paradigms of study. High fidelity direct numerical simulations (DNS) of low Re flow past stationary as well as plunging flat plate at various angles of attack (α) provides data for analysis.

For the static case, with gradual increase in α, multiple flow regimes and bifurcations up to chaotic state are observed, and with further increase in α, inverse transitions from chaos back to periodicity have been detected. Frequency spectra, phase space diagrams and recurrence plots have been used to visualize these regime transitions, while recurrence quantification analysis (RQA) has been used to quantify the chaos. Proper orthogonal decomposition (POD) and dynamic mode decomposition (DMD) are employed along with the FFT results to not only identify the relevant flow features but also quantify their individual contributions to unsteady aerodynamic loads. While the results are encouraging for datasets corresponding to periodic regimes, these methods appear inadequate when aperiodicity or chaos sets in. A novel framework combining the empirical mode decomposition (EMD) with the Physically Informed multi-resolution DMD (PImrDMD) technique to handle the chaotic flow regime has been proposed. The study concludes that the proposed framework successfully establishes a connect between flow field dynamics and aerodynamic characteristics even for a chaotic regime and thus identifies the coherent structures responsible for the sudden transients while also revealing information about their frequencies as well as time of occurrence. Data from the aforementioned analysis techniques are also used to quantitatively examine the mechanism causing regime transitions. It is discovered that the number of growth modes progressively increases as α increases, and the advent of chaos may be associated with the growth modes outnumbering the decay modes.

The analysis of the plunging case is executed in five stages. First, fast Fourier transforms (FFT) is used to determine the essential frequencies that contribute to the lift and drag forces. Second, modal decomposition of the flow field is performed to extract the physically significant coherent structures. While a standard DMD method is incorporated for analysis of static case, the challenges related to the moving boundaries in the plunging case are addressed through hybrid DMD (HDMD). Regarding the selection of HDMD modes, it is established that the standard methodology of mode selection based on amplitudes isn't always ideal and that not all “dominant” modes are the modes of “relevance”, a fact overlooked by the traditional approach of mode selection. Furthermore, the link between the POD, HDMD and Spectral Proper orthogonal Decomposition (SPOD) modes are investigated, demonstrating the commonalities between the energetic and the dynamically relevant flow features. Third, dynamic interlinking between the wake dynamics and the surface properties on the plate is demonstrated by observing the relationship between the key dynamical modes seen on the plate with those in the flow field obtained in the second stage. Important events in the flow-field have been discovered to have their signatures on the plate. Fourth, exploiting the known patterns of dynamical significance from the previous two stages combined with the recent work on compressed sensing, key locations on the plate as well as in the flow field that capture most of the relevant dynamics are identified using the sparse sensor algorithm. Accurate reconstruction of the snapshot using data from only 10 sensor points out of over 1.2 million nodes demonstrates the effectiveness of the technique. Finally, in the fifth step, a robust nonlinear low-dimensional model based on “Sparse Identification of Nonlinear Dynamics” (SINDy) algorithm is developed with inputs from HDMD coefficients as well as time series data from sensor points to forecast the lift coefficient. This model outperforms the classical Theodorsen's model, producing significantly better results and obtaining higher accuracy in capturing both low and high frequency patterns. The current study has successfully evaluated the utility of data-driven techniques for learning complicated flow physics purely from data, and it can be a critical framework that might be adopted, expanded, and implemented to effectively monitor and control variety of fluid flow applications.