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Analysis of characteristic wake flow modes on a generic transonic backward-facing step configuration

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ABSTRACT

To gain insight into characteristic wake flow modes, which among others are responsible for asymmetrical loads on the engine extensions of space launchers at transonic speeds, combined experimental and numerical investigations of a turbulent wake flow are performed at $Ma_\infty = 0.8$ and $Re_h = 1.8 \cdot 10^5$. The experiments are conducted at the Bundeswehr University Munich using planar PIV and wall pressure measurements, while the numerical investigations are performed by the Institute of Aerodynamics at RWTH Aachen University using a zonal RANS–LES approach and dynamic mode decomposition (DMD). The analysis is done on a planar space launcher configuration that consists of a backward-facing step with a long shock-free forebody avoiding undesired shock-boundary-layer interactions upstream of the analyzed wake flow region. The investigated wake flow is characterized by a highly unsteady behavior of the shear layer shedding from the forebody and subsequently reattaching onto the splitter plate. The strong variation of the reattachment positions in the spanwise and the streamwise direction leads to pronounced wall pressure oscillations and consequently, structural loads. By means of a classical statistical analysis, i.e., spatial and temporal Fourier transforms and two-point correlations of experimental and numerical data, one spatial coherent scale with a spanwise wavelength of $\lambda_z \approx 2h$ and two characteristic frequencies of $Sr_h \approx 0.01$ and $Sr_h \approx 0.07$ have been obtained for the investigated wake flow problem. To clarify the coherent fluid motion dominating the detected spatio-temporal behavior, a DMD algorithm is applied to the time-resolved three-dimensional streamwise velocity field. The frequencies of the first two extracted stable sparsity DMD modes closely coincide with the characteristic peaks in the wall pressure spectra. The analysis of the three-dimensional shape of the extracted DMD modes reveals that the detected wake flow behavior is caused by a pronounced low-frequency cross-pumping motion of the recirculation region and a high-frequency cross-flapping motion of the shear layer, respectively. Both wake flow modes feature a pronounced nearly-periodical variation in the spanwise direction with an approximate spanwise wavelength of two step heights. Thus, the extracted underlying wake modes clearly explain the occurrence of corresponding peaks in the wall pressure spectra, the periodical formation of wedge-shaped reattachment regions on the splitter plate, and the detection of finger-like structures in the PIV experiments.

1. Introduction

The presented investigations are performed within the framework of the German Transregional Collaborative Research Center TRR 40 funded by the German Research Foundation which focuses on the analysis and modeling of coupled liquid rocket propulsion systems and their integration into the space transportation system. It is known that during the first trajectory stages up to an altitude of several thousands of meters, the wake flow of a classical space launcher such as Ariane 5 is determined by the separation and subsequent reattachment of the shear layer shed from the launcher's main body onto the nozzle structure. Particularly at transonic speeds, when the pressure fluctuations feature the highest nominal amplitudes, the shear layer impinging on the nozzle can excite critical structural vibrations which are known as the buffeting phenomenon and under unfavorable conditions can lead to a complete loss of the vehicle. However, due to a superposition of locally different periodic and stochastic flow phenomena

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an accurate prediction of the buffeting loads is still a difficult task, which leads to increased safety margins and consequently, reduced launcher efficiency. Therefore, for the design of future efficient space launcher systems, reduced order models based on accurate time-resolved numerical simulations validated by high-fidelity experimental investigations are required to provide detailed insight into the wake flow phenomena, to develop methods of their controllability, and to ultimately reduce aerodynamic loads on the nozzle structure without penalizing the launcher's efficiency.

Due to its high practical relevance, still not fully understood physics, and steady development of time-resolved measurement and simulation techniques, the transonic wake flow of space launchers has attracted more and more attention of different research communities in recent years. For instance, Deprés et al. [1], Meliga & Reijasse [2], Deck & Thorigny [3], Weiss et al. [4], Hannemann et al. [5], Schrijer et al. [6], Statnikov et al. [7], Pain et al. [8], Scharnowski et al. [9], Lüedeke et al. [10], Schwane [11], and many others carried out detailed experimental and numerical investigations on several wind tunnel and free flight configurations ranging from simplified generic cylinders up to precisely scaled models of the real European Ariane 5 launcher including the solid boosters. By using classical data-based statistical analyses, i.e., mean and root-mean-square distributions, spectra and correlation analysis, the characteristic frequencies of the wake flow and their variation with changing geometry parameters could be successfully detected. However, due to the superposition of locally different periodic and stochastic flow phenomena, the association of every single detected distinct frequency range with a certain wake flow phenomenon is not straightforward and is often rather based on experience and best practice than on a stringent post-processing method.

Relatively new promising approaches appropriate for extended diagnostic purposes are the modal decomposition methods such as proper orthogonal decomposition (POD) or dynamic mode decomposition (DMD), since they allow the separation of coherent multi-dimensional flow patterns from the stochastic turbulent background. For instance, Marié et al. [12] successfully applied POD to 2D-PIV and wall pressure measurements in the transonic wake of a 1:60 scaled Ariane 5 wind tunnel model to identify the most energetic modes in the motion of the transonic shear layer that are responsible for dynamic loads on the nozzle. Likewise, by using POD on a snapshot sequence from high-speed 2D-PIV measurements, Schrijer et al. [13] visualized the two most energetic linearly-independent modes in the wake of an axisymmetric backward-facing step configuration, i.e., pulsatile growth and collapse of the separated region as well as momentum exchange across the shear layer. Statnikov et al. [14] used DMD for an extended analysis of the wake flow dynamics of a generic axisymmetric Ariane 5 configuration at supersonic free flight conditions computed via a zonal RANS–LES method and determined three distinct modes of the recirculation cavity, i.e., pumping, swinging, and flapping.

However, the spanwise or azimuthal structures of the wake modes are still not understood in detail, although the existence of a pronounced wake flow three-dimensionality has been indirectly proven for different planar and axisymmetric configurations. For instance, Ginoux [15] observed a spanwise variation of the heat transfer and skin friction in the wake of a backward-facing step and a hollow cylinder flare geometry in the wind tunnel tests at $M_\infty = 5.3$. Linear stability analyses reveal the occurrence of intrinsic spanwise instabilities for laminar flows past backward-facing steps, e.g., Barkley et al. [16] and Beaudoin et al. [17]. For turbulent wakes of space launchers, Deprés et al. [1] in their experimental and Deck & Thorigny [3] in their numerical investigations of transonic axisymmetric configurations detected an antiphase relationship between the wall pressure signals located at $\Delta\varphi = 180°$, attributed to an antisymmetric mode resulting in strong side loads.

Despite the importance of the knowledge of the true three-dimensional shape of the wake modes, the promising modal decomposition techniques have been mostly applied to investigate only the wake dynamics in one longitudinal slice. One reason for this is the technical difficulty to capture the unsteady three-dimensional flow field experimentally by optical measurement techniques. As an alternative, the three-dimensional field data can be generated by numerical simulations, which, however, requires the use of expensive time and scale resolving simulation methods, which again have to be validated with experimental data. Finally, the post-processing of the collected time-resolved three-dimensional flow field stored in the so-called snapshot matrix is computationally and logistically much more difficult compared to a quasi-two-dimensional case.

In this study, to provide a first modal analysis of the true three-dimensional turbulent transonic wake, DMD is applied to the three-dimensional velocity field of a planar space launcher configuration at $Ma_\infty = 0.8$ computed using a time-resolved zonal RANS–LES approach. A planar configuration is chosen to allow a straightforward comparison of the results of the three-dimensional modal analysis based on numerical data with experimental PIV measurements performed in the transverse plane over the splitter plate. However, due to the use of a planar configuration, the obtained results cannot be directly transferred to axisymmetric cases, since for instance no helical modes exist and the characteristic frequencies or the azimuthal wave lengths may differ quantitatively. Nevertheless, wake modes of the planar backward-facing step and of its axisymmetric equivalent feature many similarities resulting from the sole presence of the abrupt clearly defined separation line and the reattachment of the unstable shear layer on the lower wall, no matter whether straight or curved, which is discussed in the last section.

The paper is organized as follows. In Section 2, the experimental setup is presented along with the respective geometry and flow parameters. In Section 3, brief descriptions of the applied zonal RANS/LES method, the used computational grids, and the dynamic mode decomposition algorithm are provided. In Section 4, the results of the performed analysis are presented. After a general characterization of the flow topology and validation with experimental data, the dominant length and time scales of the wake dynamics are determined using spatial and temporal Fourier transforms and two-point correlations of experimental and numerical data. To complete the analysis, dynamic mode decomposition is applied to the three-dimensional streamwise velocity field to clarify the origin of the detected coherent scales and to illustrate the underlying spatio-temporal fluid motion. Finally, a summary of the results as well as the conclusions including a comparison with existing modal analyses of axisymmetric transonic wake flows are given in Section 5.

2. Experimental approach

The PIV measurements were performed in the Trisonic Wind Tunnel at the Bundeswehr University in Munich (TWM). The TWM facility is a blow-down type wind tunnel with a 300 mm 675 mm ($w \times h$) test section, with a stable operating range of Mach numbers from 0.2 to 3.0. It has two tanks that can be pressurized up to 20 bar above ambient pressure, holding a total volume of 356 m^3 of dry air. To control the Reynolds number, the total pressure in the test section is varied between 1.2 and 5 bar. The facility is discussed in detail in [18]. The freestream conditions for the presented investigations on the transonic turbulent wake at $Ma_\infty = 0.8$ are summarized in Table 1.

A spanwise horizontal planar field of view (FOV) located at 25% of the step height was evaluated. The PIV setup consisted of a double pulse PIV laser with 100 mJ per pulse, an sCMOS camera