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Zonal Turbulence Modeling and Reduced-Order Methods for Space Launcher Wake Flows Analyses

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Micro Abstract
Turbulent wake flows of generic Ariane 5-like space launcher configurations are investigated using zonal turbulence modeling and reduced-order methods. For two selected, dynamically crucial trajectory stages, i.e., $M_\infty = 0.8$ and $M_\infty = 6$, previously unknown coherent three-dimensional modes are extracted and attributed to the single characteristic frequencies and wave lengths which are responsible for critical side loads on the nozzle structure.

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Introduction

The wake flow of a space launcher continuously changes with the altitude according to the varying freestream and nozzle flow conditions. Due to a complex interaction and superposition of different periodic and stochastic flow phenomena, many aspects of the wake dynamics still are not fully understood and require a fundamental analysis at corresponding points of the flight trajectory. However, in both experimental and numerical investigations many technical difficulties are encountered such as undesired interactions with model supports, limited computational resources, low spatial and temporal resolutions, etc. Besides, the association of every detected distinct frequency with a coherent flow pattern or, more generally, a dynamic mode, hidden in the multiple scales of turbulence, is not straightforward while using conventional post-processing methods.

The motivation for this work is to overcome these issues and to provide new insight into the wake flow phenomena of space launchers at aerodynamically relevant flight regimes. The work focuses on a numerical analysis of turbulent wake flows of generic space launcher configurations at transonic and supersonic freestream conditions using a combination of zonal turbulence modeling and dynamic mode decomposition (DMD). The zonal simulation approach is applied to efficiently obtain time-resolved high-fidelity flow field data. The objective of the subsequent modal analysis is to extract and scrutinize the underlying spatio-temporal modes that are responsible for the characteristic dynamic phenomena.

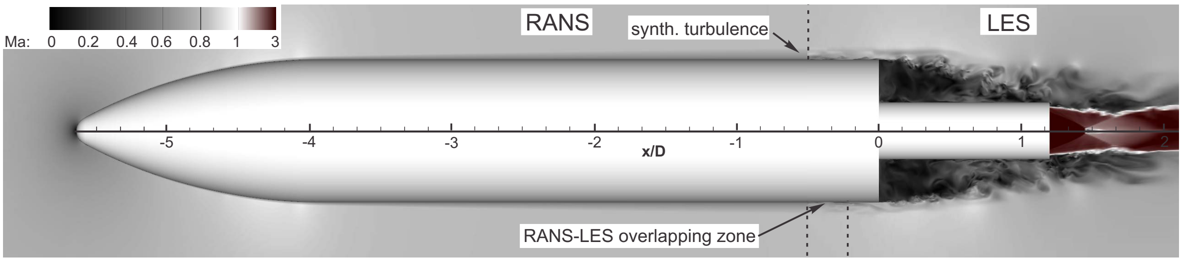
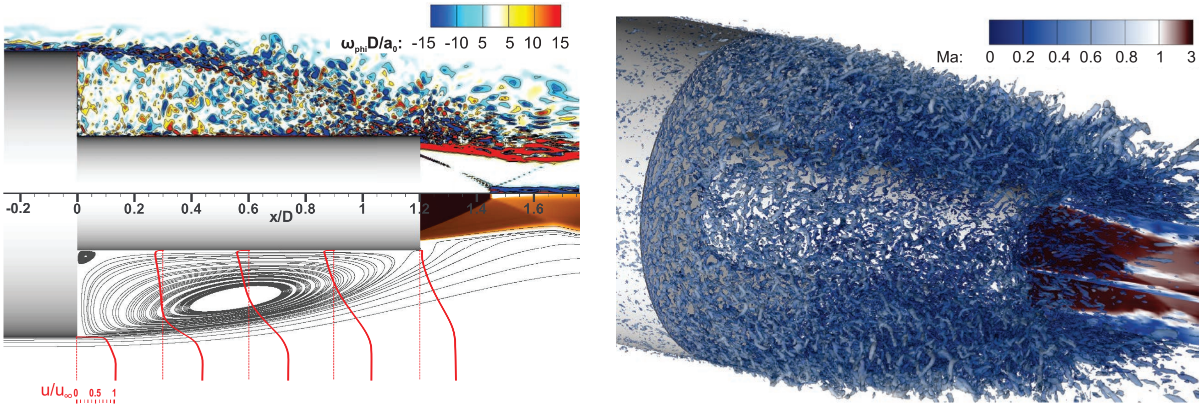


Figure 1. Flow decomposition into RANS and LES zones for the transonic free-flight configuration [5].



(a) (b)

Figure 2. Wake flow topology of the investigated free-flight configuration: (a) instantaneous spanwise vorticity distribution (top); time-averaged axial velocity profiles and streamlines (bottom); (b) coherent structures in the wake visualized using Q criterion ($Q \cdot a_0^2/D^2 = 300$) and color-coded by the Mach number [5].

1 Computational setup

Axisymmetric free-flight configurations generically approximating the main stage of the European Ariane 5 launcher are considered. To model the geometrical boundaries at the tail of the full-scale launcher with a Vulcain-2 engine, a cylindrical nozzle extension with a diameter of $0.4D$ and a length of $1.2D$ is attached to the main body with a reference diameter of $1D$. Inside the nozzle extension, a TIC (truncated ideal contour) nozzle is used.

For the investigations, two trajectory stages at $M_\infty = 0.8$ and $M_\infty = 6.0$ are defined. At the former, strongest buffet loads have been measured on the Vulcain 2 enginge of the full-scale Airane 5 launcher. At the latter, previously unknown high-frequency wall pressure oscillations have been reported. A detailed overview of the freestream and jet flow parameters is given in [4].

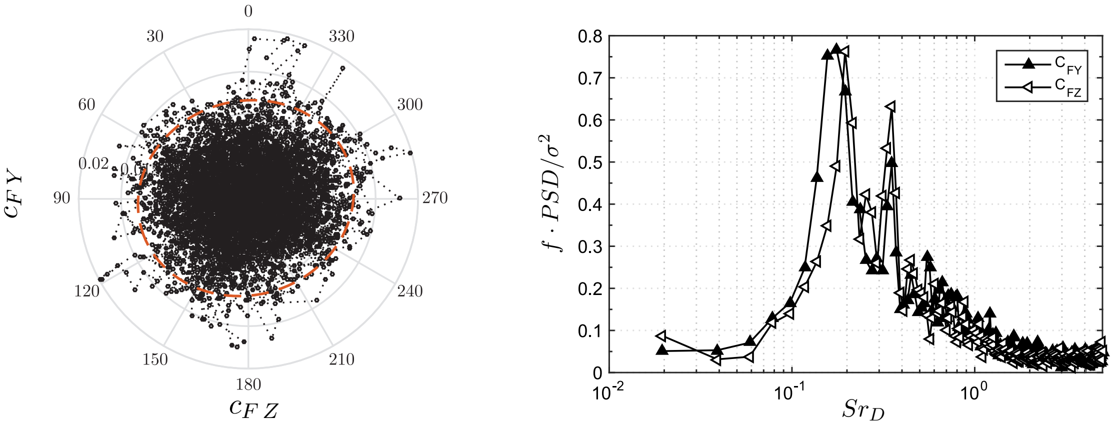
The three-dimensional unsteady flows are computed via a zonal RANS-LES approach in conjunction with the reformulated synthetic turbulence generation (RSTG) method [1,2]. As indicated in Fig. 1, the computational domain is split into zones with an attached flow, e.g., around the main body and inside the nozzle, where the turbulent flow field is predicted by solving the Reynolds Averaged Navier-Stokes (RANS) equations, and a wake zone with an unsteady separated flow computed by the large-eddy simulation (LES). The computations are performed on a structured vertex-centered multi-block grid using an in-house zonal RANS-LES finite-volume flow solver using hybrid parallelization based on MPI, OpenMP, and HDF5.

2 Results

In this abstract, only a brief overview of the major findings for the transonic case is given. More details including the supersonic case will be presented at the conference.

2.1 Transonic wake flow and buffet phenomenon

In Fig. 2 different aspects of the computed wake flow topology for the transonic Ariane 5-like configuration are visualized. The fully turbulent boundary layer separates at the axisymmetric shoulder at $x/D = 0$ and forms a turbulent free-shear layer. The shed shear layer rapidly evolves downstream of the separation due to the shear layer instability, causing the mixing layer and the turbulent structures to grow in size and intensity. Further downstream, the shear layer gradually approaches the nozzle and finally either impinges on its surface or passes over it, depending on the time instance and the azimuthal position. This behavior induces non-axisymmetric side loads with a pronounced temporal periodicity known as the buffet phenomenon. The variation of the



(a) (b)

Figure 3. (a) Scatter plot of the instantaneous side loads on the nozzle structure in polar coordinates with the $\alpha = 95$ confidence ellipse drawn by dashed red line; (b) premultiplied normalized power spectral density ($f \cdot PSD/\sigma^2$) of the side load components ($\sigma_{c_{FY}} = 4.9 \cdot 10^{-3}$, $\sigma_{c_{FZ}} = 5.1 \cdot 10^{-3}$) [5].

side load vector in time along with the spectral analysis of its components is shown in Fig. 3. This conventional statistical analysis, however, doesn't provide direct information on the underlying dynamic modes hidden in the multiple spatio-temporal scales of turbulence. Therefore, to identify coherent flow patterns responsible for the buffet phenomenon, a reduced-order analysis based on dynamic mode decomposition (DMD) is performed.

2.2 Reduced-order analysis

An optimized DMD algorithm by Schmid [3] with a preprocessing step based on singular value decomposition (SVD) is used. As a result, the high-dimensional flow field $v(x, y, z, t)$ is projected onto a set of spatial modes, which can be represented by

$$v(x,y,z,t) = \textstyle\sum_{n=1}^{N} a_n \exp{(\lambda_n t)} \phi_n(x,y,z), \tag{1}$$

where ϕ_n is the spatial mode, a_n is the amplitude, λ_n is the complex frequency of the respective mode, and N is the number of the flow field snapshots. The resulting DMD spectrum, i.e., the frequency-based distribution ($Sr_D(\lambda_n) = \Im(\lambda_n)/2\pi$) of the amplitudes a_n normalized by the mean mode amplitude a_0 and the individual damping $|\mu_n|^{-N} = |exp(\lambda_n \Delta t)|^{-N}$ to identify the most stable modes, is shown in Fig. 4. Three stable modes of interest are identified, frequencies of which closely match the characteristic peaks in the wall pressure spectra [5]. The three-dimensional shape of the extracted pressure modes is illustrated in Fig. 5. A detailed analysis of

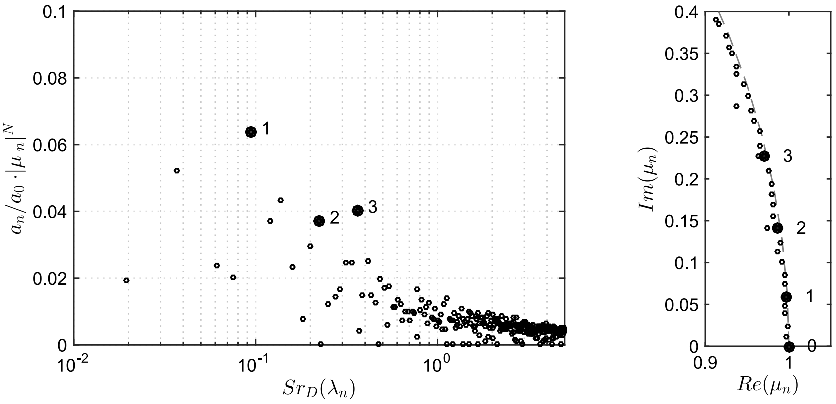


Figure 4. Normalized DMD-spectrum of the velocity and pressure field in the physical frequency domain(left); Ritz eigenvalues $\mu_n = exp(\lambda_n \Delta t)$ plotted with respect to the unit circle (right) [5].

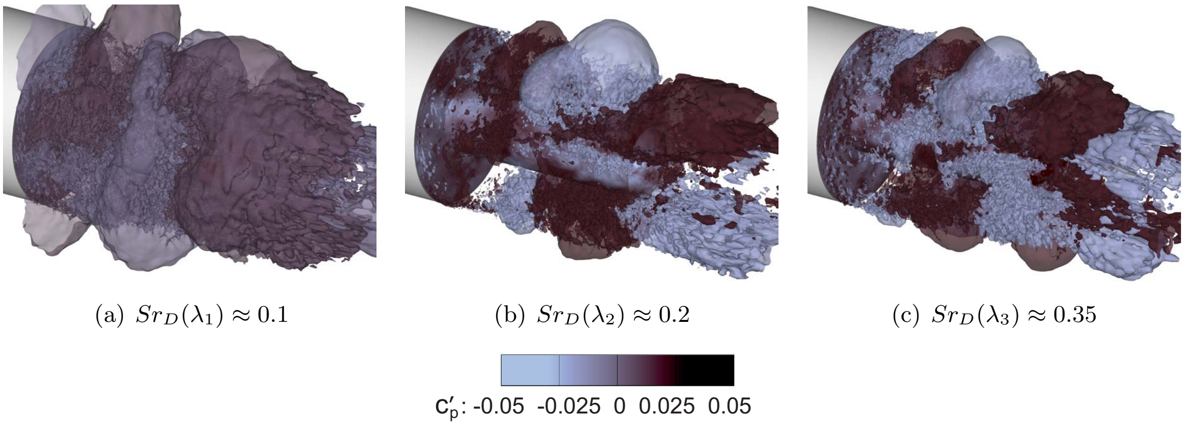

(a) $Sr_D(\lambda_1) \approx 0.1$ (b) $Sr_D(\lambda_2) \approx 0.2$ (c) $Sr_D(\lambda_3) \approx 0.35$

Figure 5. Reduced-order modeled pressure field for the three characteristic frequencies: (a) $Sr_D(\lambda_1) \approx 0.1$, (b) $Sr_D(\lambda_2) \approx 0.2$, (c) $Sr_D(\lambda_3) \approx 0.35$. Time instances at the beginning (top) and after one quarter (bottom) of the respective period are shown [5].

the reduced-order model based on the extracted pressure and velocity modes (not shown here for space limitation reasons) reveals that the transonic buffet phenomenon is caused by elongated closed-loop vortices tat are shed in alternating sequence from azimuthally opposite positions and locked in phase with a low-frequency cross-pumping motion of the recirculation region. For further details the reader is referred to [5].

Conclusions

A complimentary methodology for an extended analysis of turbulent wake flows of space launchers is developed and applied to a generic Ariane 5-like configuration at aerodynamically crucial trajectory stages, i.e., $M_\infty = 0.8$ and $M_\infty = 6.0$. It is shown that the transonic wake is essentially dominated by three-dimensional modes which induce strongly periodic side loads on the nozzle structure, known as the buffet phenomenon. More details on the physical origin of these modes as well as the results for the supersonic trajectory stage will be presented at the conference.

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