# Numerical and experimental investigation of a transonic space launcher wake

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## 1. Introduction

The results are obtained within a sub project of the SFB TRR 40 program (founded 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. The overall objective is to develop technological foundations for the design of thermally and mechanically highly loaded components of future space transportation systems. The interaction between the shear layer and the nozzle in the wake of the launcher is particularly important. This reattachment causes strong wall pressure fluctuations which lead to increased dynamic loads for the nozzle structure. The loads are strongest in the transonic regime and the characteristic frequencies of the pressure fluctuations may interfere with the structural modes of the nozzle leading to so called buffeting. Hannemann et al. [2] showed that shedding of large wake vortices is the driving force for the aerodynamic unsteady phenomena.

For the design of next generation space launchers it is essential, on the one hand, to develop efficient and reliable numerical tools and, on the other hand, to achieve accurate experimental results with sufficiently high spatial and temporal resolution for the validation. Therefore, a combined numerical and experimental investigation of a generic space launcher model's wake flow is conducted. The simulations and measurements were performed on a blunt axisymmetric space launcher model, sketched in figure 1. The configuration consists of a 36° cone with a spherical nose of $R = 5\,\mathrm{mm}$ and a cylindrical part with a length of 164.3 mm and a diameter of $d = 54\,\mathrm{mm}$. The total length, from nose to base, is 231.3 mm. The analyzed data sets were achieved at a Mach number of $\mathrm{Ma} = 0.7$ and a Reynolds number based on the forebody's diameter $d = 54\,\mathrm{mm}$ of $\mathrm{Re}_d = 10^6$.

## 2. Computational approach

The time-resolved numerical computations of the flow field around the generic rocket configuration are performed by the Institute of Aerodynamics, RWTH Aachen University using a zonal RANS/LES approach. The integration domain around the rocket configuration is split into a main body zone with an attached flow where the turbulent flow field is predicted by solving the Reynolds averaged Navier-Stokes (RANS) equations and a wake zone where the highly unsteady separated flow is time-resolving computed by the large-eddy simulation (LES). The required transition from the RANS to LES zone is obtained by applying a synthetic turbulence generation (STG) method according to Roidl et al. [3]. In this approach, turbulent structures are generated in the inflow plane of the overlapping RANS/LES region as a superposition of coherent vortices via form functions which meet specific spatial and temporal characteristics. As a result, the velocity signal is composed of an averaged velocity component which is provided from the upstream RANS solution and the normalized stochastic fluctuations $u'_m$ which are subjected to a Cholesky decomposition to assign the values of the Reynolds-stress tensor. To minimize the transition zone between the RANS and LES domains, body forces $f_i$ are added to the wall-normal momentum equation at a number of control planes at different streamwise positions to match the turbulent flow properties of the LES with the given RANS values as shown in Figure 2.

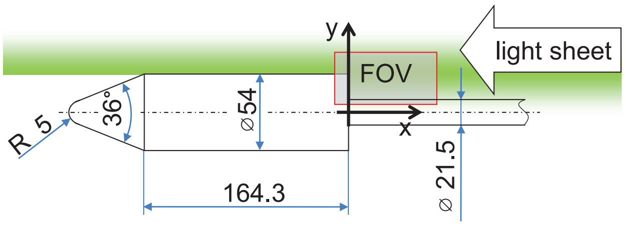


Figure 1: Axisymmetric space launcher model with rear sting. The laser light sheet and the field of view (FOV) for high-repetition rate PIV measurements are illustrated. Numerical values are given in mm.

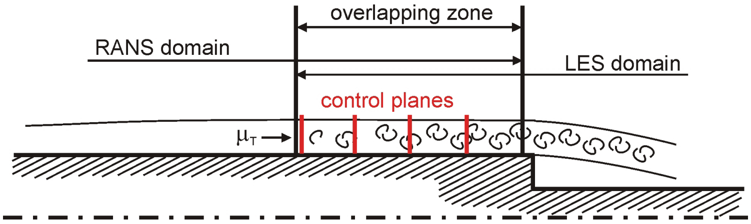


Figure 2: RANS/LES overlapping zone with control planes.

## 3. Experimental approach

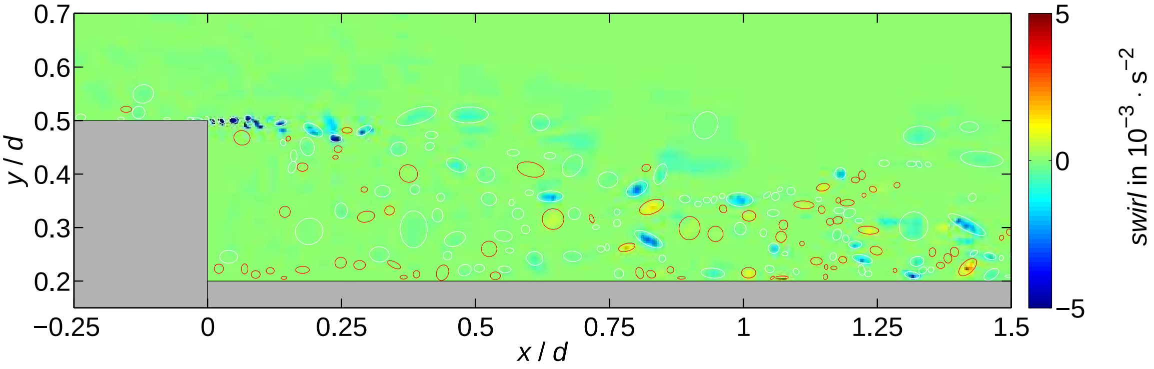
High-repetition-rate PIV measurements were performed in the Trisonic Wind tunnel at the Bundeswehr University in Munich (TWM). The flow is seeded with DEHS tracer particles with a mean diameter of 1 $\mu$m. The particles in the plane of symmetry were illuminated by a light sheet using a Quantronix Darwin Duo Nd:YLF double-pulse laser with a laser energy of 11 mJ per cavity at 2 kHz. The light sheet thickness in the focal plane is $\approx$ 1 mm for the chosen setup. The recordings were captured by using a *Phantom v*12 high repetition rate CMOS camera (by Vision Research Inc). For a reduced image size of $1,280 \times 400$ px, more than 5,000 double frame PIV images could be captured during one wind tunnel run. The recording rate and the time between the laser-pulses was adjusted to 2,000 image pairs per second and 3 $\mu$s, respectively. A *Makro.Planar T*.2/100 objective lens (by Carl Zeiss AG) with a focal length of 100 mm and a f-number of 2.8 was mounted in front of the camera. In total 21,500 PIV image pairs were acquired in four wind tunnel runs. More details about the measurement setup as well as on the TWM facility can be found in [1].

## 4. Results

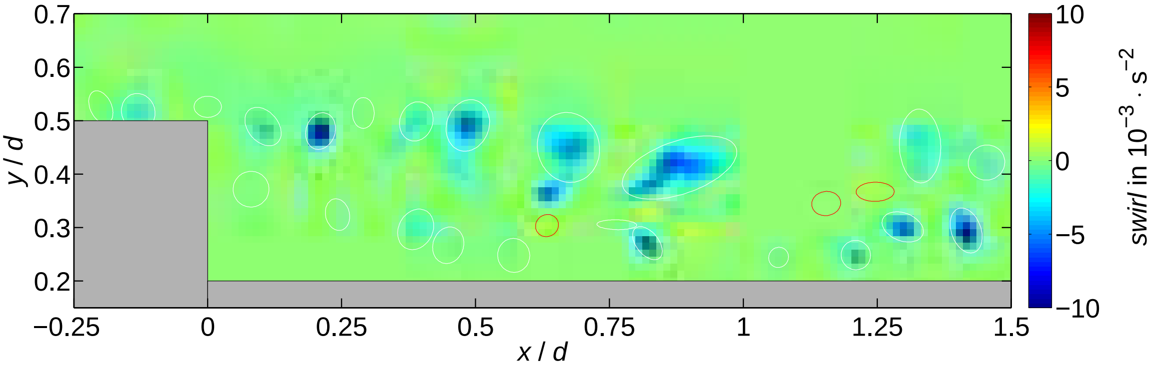
A very important aspect is the formation of shear layer vortices and their motion in the separated region. To analyze the capability of LES and PIV to resolve the relevant scales in instantaneous time steps, the vortices in the space launcher model's wake were detected and their size distribution was investigated.

For the large-eddy simulation 495 velocity fields in the plane of symmetry, each with 27,800 data points, are considered here. Unlike the PIV data, the LES-mesh is adapted to the topology of the flow, to increase the resolution in regions with strong gradients. Figure 3a shows a characteristic snapshot of the vortex distribution in the space launcher model's wake. More than 200 vortices are detected in each LES velocity field. A significant fraction of them has a counter-clockwise rotation direction, indicated by the red ellipsis in Fig. 3a. In order to compare the LES and PIV results, the LES resolution was artificially reduced by averaging over a window of $0.05{\cdot}d{\times}0.05{\cdot}d$. The detected vortices in this averaged field are shown in Fig. 3b. The PIV measurements yield 21,500 vector fields with $160 \times 50 = 8,000$ data points on a regular grid. The spatial resolution (distance between independent vectors) is $\approx 0.05 \cdot d$, which is not sufficient to resolve the small shear layer vortices. Only large scale vortices can be detected reliably. The vortex distribution for a characteristic velocity field is shown in Fig. 3c. It can be seen that the averaged LES data results in a similar number and size of the detected vortices as the PIV data.

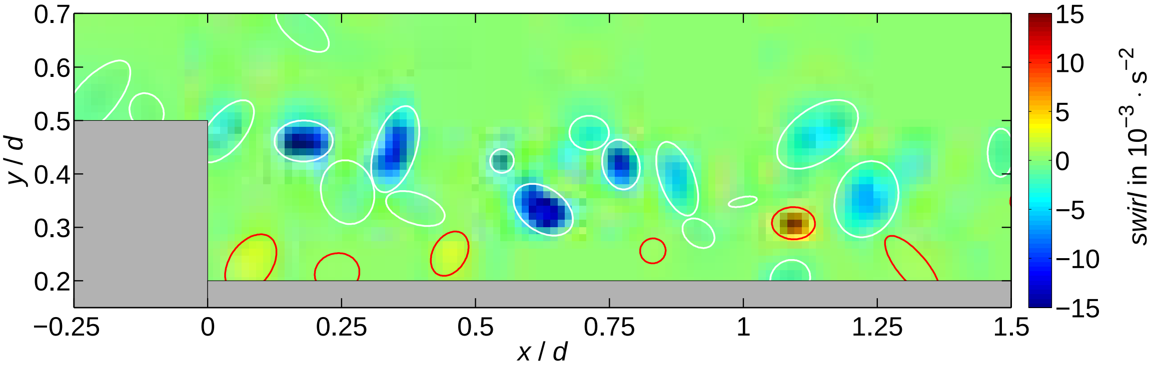
A histogram of the major axis length $L_1$ of the cross section of the detected vortices is shown in Fig. 4. For the



(a) LES



(b) averaged LES



(c) PIV

Figure 3: Characteristic vortex distribution in the space launcher model's wake for LES (a), for averaged LES matching the PIV resolution (b), and for an experimental PIV velocity field (c).

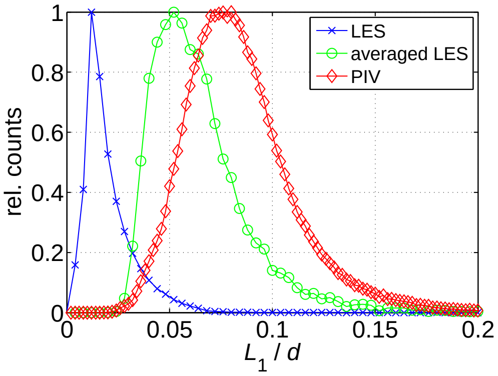


Figure 4: Histogram of the vortex size distribution for detected vortices from LES data, from averaged LES data and from PIV data.

LES data the vortex size with highest probability is around 0.01 times the main body diameter, whereas for the PIV data this value is shifted to $0.08 \cdot d$ due to the limited resolution of PIV. Furthermore, the average LES data, which matches the PIV resolution, still detects smaller vortices than found in the PIV data. This effect is most likely due to the measurement noise which complicates the detection of small vortices.

The conference paper will additionally show a detailed comparison of the mean velocity distribution and of the Reynolds stresses distribution. It will be demonstrated that statistical values can be reliably estimated from the PIV data with sufficiently high resolution.

## Acknowledgments

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