Vortical Flow Interaction on Airborne High Speed Vehicles

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Introduction

High maneuverability is a mandatory requirement of state-of-the-art airborne high speed vehicles like missiles and fixed-wing aircrafts. This requirement demands maneuvers at high angles of attack which lead to large flow separations and the formation of multiple vortices (Figure 1 and 2). Regardless of the number of vortices, the vortices and their footprint on the surface pressure distribution of the vehicle have a strong impact on the aerodynamic forces and moments and thus on the flight stability of the vehicle. The evolution of the vortices is often affected by interactions among these vortices (vortex / vortex-interaction) and the interaction with vehicle components (vortex / vehicle component-interaction). At high speeds (M > 0.85), shock waves occur, which can additionally lead to a vortex / shock interaction. The interaction can range from simply influencing the vortex trajectory to a complete vortex merge, changing significantly the trajectory and strength of the vortices, and thus the footprint of the vortex on the vehicle surface and vehicle components. In the worst case, vortex burst can occur. Vortex burst, also called vortex breakdown, is characterized by an abrupt change of the vortex trajectory and topology, respectively, often including an internal stagnation point and an expansion of the vortical structure, which goes along with a pressure rise (Bubble-type breakdown [1]). On a delta wing, vortex breakdown often occurs at first on one side of the vehicle, leading to a highly asymmetric flow field and surface pressure distribution. Important factors for the different kinds of interactions are the vortex size and strength, which are changing with angle of attack, roll and sideslip angle, and Mach number. The different kinds of vortex-interaction mentioned above have been investigated for decades, but important aspects of the vortex-interaction flow physics are still not well understood. Therefore, a non-confidential NATO Science and Technology Organization (STO) working group (AVT 316) [2] has been established recently to improve the prediction of vortex-interaction. Numerical simulation can help to get a deeper insight into the flow physics. However, for this purpose the roll-up and the evolution of the vortices have to be modelled with a certain accuracy, since this affects the trajectory, strength, and size of the vortices. In this respect, standard turbulence models are often inadequate [3]. Considering vortex-interaction with a shock wave or a vehicle component, both the development of the attached vortex as well as the evolution of the separated vortex in downstream direction towards the interaction zone is of importance. However, standard turbulence models have been proven to be too dissipative to correctly reproduce vortex evolution [2,3]. Therefore, the aim of this project is to investigate the application of state-of-the-art scale-resolving methods like DDES and IDDES to these kinds of flows. Furthermore, the performance of a seven equation Reynolds stress model will be investigated. In the final report, a comparison of the results of eddy-resolving methods with the results of Reynolds-Averaged Navier-Stokes (RANS) simula-tions, using standard 1 and 2 equation turbulence models, will be made.

Results and Methods

For a generic double-delta wing configuration and a generic missile configuration, steady state (RANS) and time accurate flow simulations (URANS), as well as scale resolving simulations have been carried out with the DLR-TAU Code in this study. TAU is a hybrid structured/unstructured finite volume flow solver for the compressible Reynolds-Averaged Navier-Stokes-equations. The most demanding steady state computation needed about 15,000 Core-h (1,920 cores) and the scale resolving simulations consumed on average 500,000 Core-h (1,200 cores) to converge. The latter statement demonstrates the need for SupermucNG's HPC. In total, 5 Terabyte of data was analyzed and stored external yet.

Missiles

Regarding the investigations on the missile configuration, simulations with a state-of-the-art seven equation turbulence model have been performed in a first step. The aim is to investigate the influence of the computational grid topology and the fineness of the grid on the vortex topology, and the influence of the grid properties on the numerical dissipation, respectively. In Figure 1, the vortex dominated flow that evolves at the missile at a Mach number of 0.85, an angle of attack

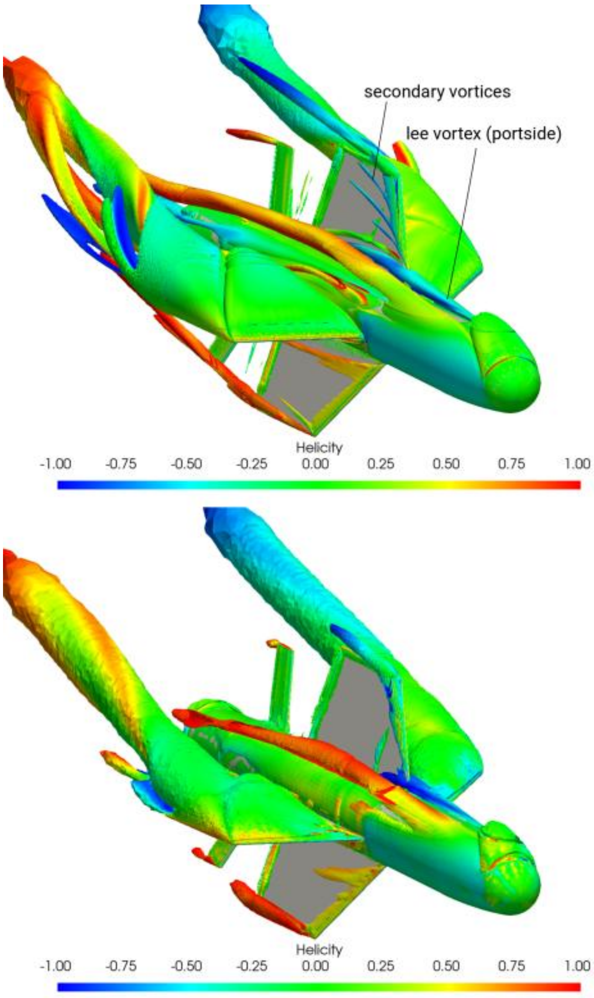

Figure 1: Visualization of the vortex topology using λ_2 criterion isosurface and helicity (top: fine grid ($\approx 100^6$ grid nodes), bottom: corse grid ($\approx 12^6$ grid nodes)).

(AoA) of 17.5° and a roll angle of 45° is visualized using the Q-criterion and the helicity. In the upper illustration (fine grid), secondary vortices on the wing are visible in addition to the large scale vortices. In the lower figure, however, they are missing due to the coarseness of the grid and the resulting greater numerical dissipation compared to the fine grid. This affects all vortices, such as the leeward vortex on the port side. Figure 1 illustrates how the strength of this vortex changes significantly with the grid fineness. However, this vortex has a strong influence on the rolling moment due to its interaction with the wing. Hence a correct determination of the vortex evolution is essential for simulation based aerodynamic data.

Delta Wings

The studies on delta wings were performed on the DLR F22 planform, a generic triple delta configuration with sharp leading edges. In a first step, URANS simulations for Mach numbers between M = 0.5 and M = 1.41 and AoA between $\alpha = 8°$ and $\alpha = 28°$ were performed to identify suitable flow conditions for the investigation of vortex-interactions. In a second step, scale resolving IDDES simulations were carried out for selected flow conditions. For the evaluation of the results, the unsteady simulations were averaged over a period of at least 50 convective time units. In Fig. 2, the λ_2 criterion is used to visualize the vortex topology of an averaged IDDES simulation at M = 0.85, AoA = 16°. At these flow conditions, three primary vortices develop: at the forebody, the strake and the main wing, respectively. Vortex merging between the inboard and midboard vortex can be observed on the strake, and both the inboard and the midboard vortex interact with shocks forming on the wing. While the inboard vortex is barely disturbed by the shock interaction, the vortex core velocity of the midboard vortex drops significantly, leading to vortex breakdown. This can be seen in Figure 3, where the streamwise development of the velocity deficit δ is plotted for the inboard, and midboard vortex. Both URANS and IDDES simulations predict vortex breakdown after the interaction of the midboard vortex and the shock. However, the shock position strongly varies between the two approaches.

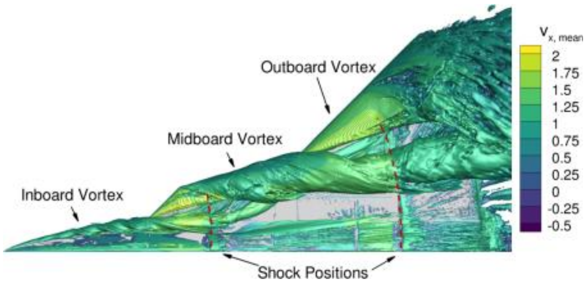

Figure 2: Vortex topology on delta wing configuration at M=0.85, AoA=16°, visualized by an isosurface of the λ_2 criterion.

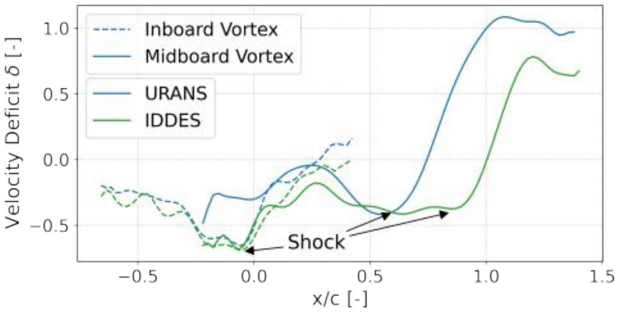

Figure 3: Comparison of velocity deficit in the vortex core between URANS and IDDES.

Ongoing Research / Outlook

Regarding the missile configuration, IDDES simulations will be undertaken to investigate how not only the grid influences the evolution of the vortices and their interactions, but also the treatment of turbulence. This is still addressed in the context of this project. But, it is also a possible starting point for a follow-up project. Based on the results for the delta wing configuration, in a next step, and beyond, it is planned to perform IDDES simulations of analytical vortices in order to more closely study the vortex-shock interaction itself.

References and Links

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[3] Braun, S., et al. Numerical simulation of vortex roll-up processes using the ssg/lrr-w model. In New Results in Numerical and Experimental Fluid Mechanics X, pages 481–491. Springer, 2016.