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Advanced PIV techniques for the temporal and spatial characterization of turbulent structures in high speed flows

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Abstract:

The investigation of compressible turbulent flows, which has a high relevance to the domain of aeronautical vehicle applications, provides an environment of particular challenge to the experimental approach. In view of the high Reynolds numbers character of these flows, a large range of spatial and temporal scales is encountered, while moreover the high convective velocities introduce that structures pass at very high frequency in the Eularian observation frame of stationary measurement probes. This sets high demands on the frequency response of for example the hot-wire technique. In addition, the high-speed wind tunnel environment usually puts further limitations on the measurement capabilities, in view of restricted access and limited measurement times, in comparison to the low-speed flow regime.

Understanding the structure of turbulence, unsteady and three-dimensional by nature, has traditionally been progressing gradually through a combined use of quantitative probe measurements (LDA and HWA) in combination with high-speed qualitative flow visualization. The application of PIV has introduced the possibility of capturing the instantaneous spatial flow organization in a quantitative sense, which has been extremely helpful in further characterizing in particular the large-scale structure of turbulent flows. Although planar PIV (2C or 3C) allows the measurement of the instantaneous velocity field in a planar cross section of the flow, the repetition rate of the measurement is insufficient to follow the temporal flow development. The advent of high-speed PIV systems (with kHz repetition rate) permits time-resolved capabilities for flows at relatively low speeds, but are still insufficient for flows at supersonic or hypersonic speeds.

The present communication discusses a number of recent developments that intend to enhance the capabilities of PIV technique for the temporal and spatial characterization of turbulence in high speed flows, notably Dual-PIV and Tomographic-PIV, and their application in the study of a turbulent boundary layer and a shock wave turbulent boundary layer interaction, at Mach numbers near 2 [1-4].

Tomographic-PIV was applied to characterize the turbulence large scale structures in the boundary layer [2] as well as the instantaneous 3D flow organization of the SWBL interaction [3]. Results of the tomographic-PIV experiments in the turbulent boundary layer reveal the formation of packets of smaller and larger hairpin vortices, related to large-scale elongated low speed structures, similar as has been observed in low-speed flows (Fig.1). In the shock-interaction investigation a clear deformation of the shock front in response to these large-scale structures in the incoming boundary layer is observed, resulting in a variation in streamwise location as well as a spanwise rippling of, in particular, the reflected shock foot (Fig.2).

Dual-PIV experiments, using two PIV systems separated by orthogonal polarization and with tunable short delay (down to 1 microsecond) have been carried out to investigate temporal development of the interaction flow field, allowing estimates of time-correlations and associated time scales, convective velocities and accelerations [4]. Results of the experiments confirm the discrepancy in time scales between the incoming boundary layer and the reflected shock region, see Fig.3, which is in global agreement with results reported elsewhere in literature. The potential of the dual-PIV technique for characterizing the temporal development of the flow is under further study.

References

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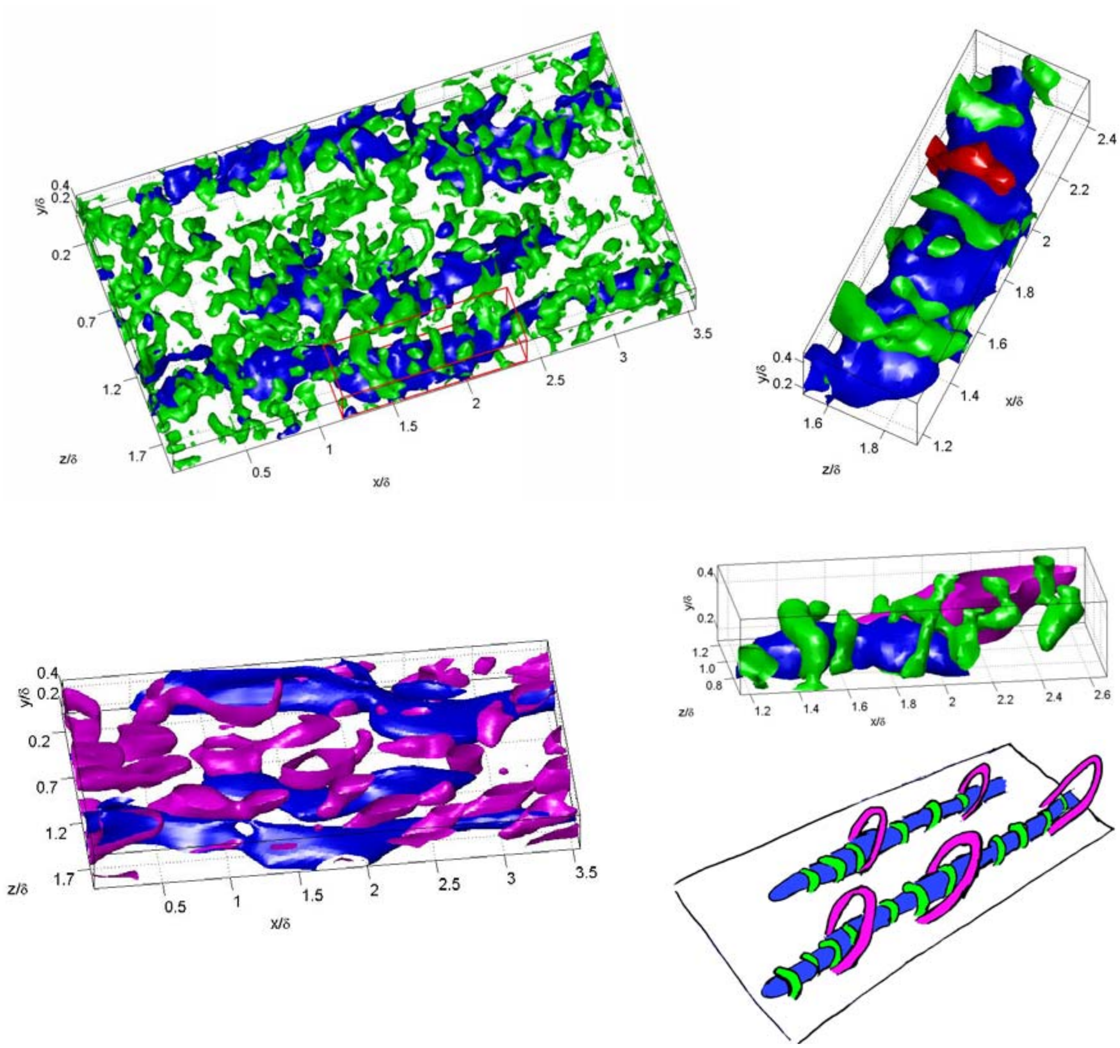

Figure 1: Results of tomographic PIV investigation of a turbulent boundary layer at Mach 2.
Top Left: Instantaneous vortex distribution (green) and low speed zones (blue);
Top Right:Enlargement of the sub-volume indicated by the red box showing arch vortices around a low speed zone;
Bottom Left:Large-scale vortical structures (magenta) detected by wall-normal swirling motion are revealed after low-pass spatial filtering of the velocity field.
Bottom Right: Composite assembly and conceptual sketch of the large-scale (magenta) and smaller-scale hairpins (green) around the low-speed zones (blue).

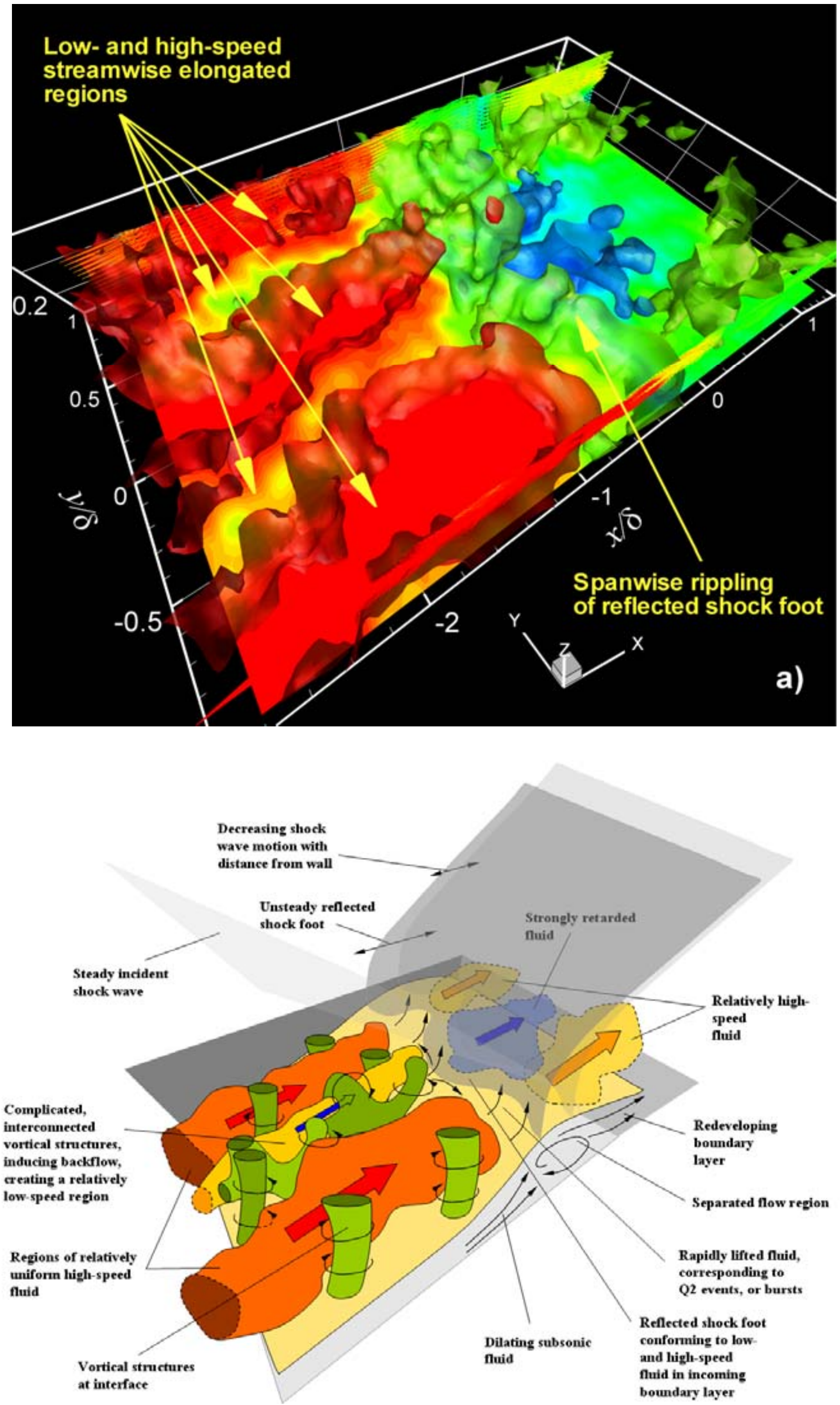

Figure 2: Results of tomographic PIV of the SWBLI investigation: instantaneous 3D flow field and conceptual model.

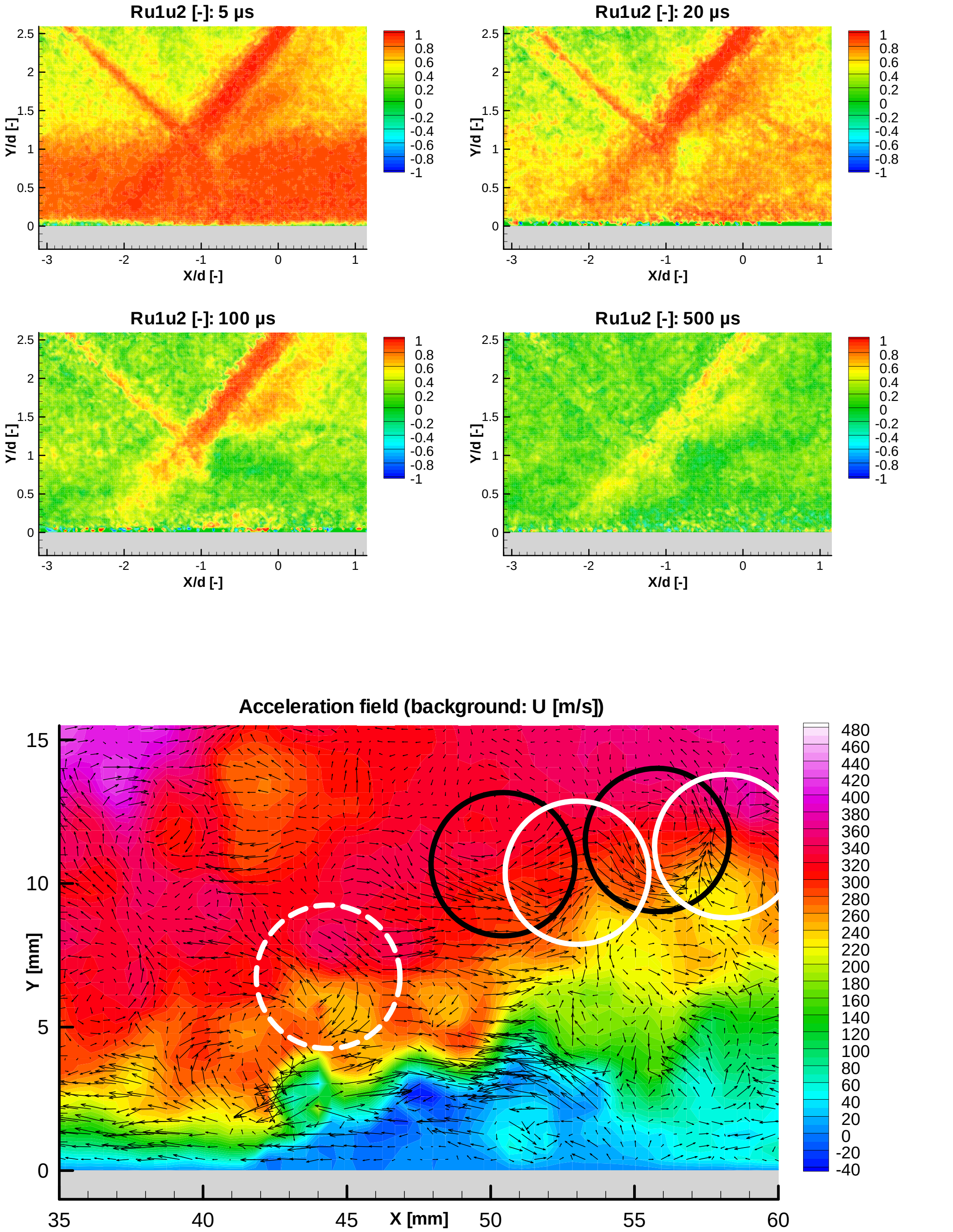

Figure 3: Results of Dual-PIV measurements:
Top: Time-correlation coefficient for different values of the time delay.
Bottom: Local acceleration field (time delay 10 µs), arrows indicate acceleration, background colour represents velocity, circles indicate identified vortex cores.