Mitteilung

Fachgruppe: Hochagile Konfigurationen

Limits of quasiconical symmetry in 3D shock-boundary layer interaction at a single fin on a flat plate

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Introduction : Quasiconical symmetry in 3D-STBLI

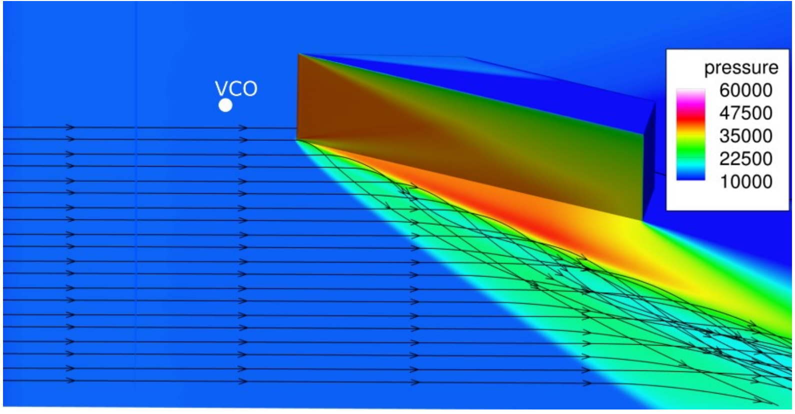

Figure 1: RANS distribution of wall pressure [Pa] in the interaction region of a single fin and streamlines within the boundary layer on the incoming flow forming a separation vortex. (Mach 3, $ß = 16°$, $Re_1 = 45x10^6/m$)

Three dimensional shock-wave turbulent boundary layer interactions (3D-STBLI) of a single fin, mounted on a flat plate, are investigated. This configuration is known to create a quasi-conical flowflield, where most flow properties solely depend on the conical angles and not on the distance to the virtual conical origin (VCO) [1]. The prerequisite for this symmetry is the plane compression shock, which is generated at a semi-infinite sharp fin in an inviscid flow. This symmetry is known to be broken for viscous fluids in the vincinity of the leading edge of the fin, resulting in an «inception region». Furthermore, the finite height on the fin causes a deformation and weakening of the shock front, which propagates downstream to the plate surface, as can be seen in Fig. 1. Between those two effects lies an alleged zone of conical symmetry. This symmetry was demonstrated to exist for the lambda shock system (main shock, separation shock and rear shock) with conical shadowgraphy [2] as well as for the surface pressure distribution. Several other flowfield quantities are assumed to follow this symmetry in recent publications (like [3]), although this has not yet been explicitly proven.

Using experimental methods to measure wall shear stress and heat flux distributions, we can now quantitatively investigate the deviations from a perfect conical symmetry. This helps to prove several assumptions of quasiconical behaviour right, suggest corrections or assume uncertainities of the quasiconical approach.

Experimental Methods

The experiments were conducted at the Rohrwindkanal Göttingen (RWG), which is a Ludwieg tube facility. The experiments were conducted at Mach numbers of 3 and 5 for a constant unit Reynolds number of $Re_1 = 45×10^6/m$. Two alternative fin geometries were tested on the rotating insert of the model, varying the fin angle $ß$ and leading edge radius R in discrete steps. Wall pressure, wall shear stress and heat flux on the flat-plate surface were measured in the RWG in three separate test campaigns. Figure 2 (left) shows an image of the fin inclined at $ß = 16°$on the turntable, which is equipped with 211 pressure taps for measuring the wall pressure distribution. The skin-friction coefficient C_f was measured with oil film interferometry (OFI). A typical OFI-interferogram can be seen in Fig. 2 (center). The inverse determination of the skin friction coefficient from the thin film equation [4] requires knowledge of the change in the oil film thickness distribution over time from an OFI test as well as the path of the limiting streamlines, which are obtained in a separate wind tunnel run. Each wind tunnel experiment only yields a small evaluable area and several data sets need to be combined to obtain a nearly complete 2D distribution of wall shear stress amplitude and direction. Finally, the heat flux was measured using quantitative infrared thermography (QIRT), whereby the temporal development of the model surface temperature (Fig. 2, right) is documented and processed.

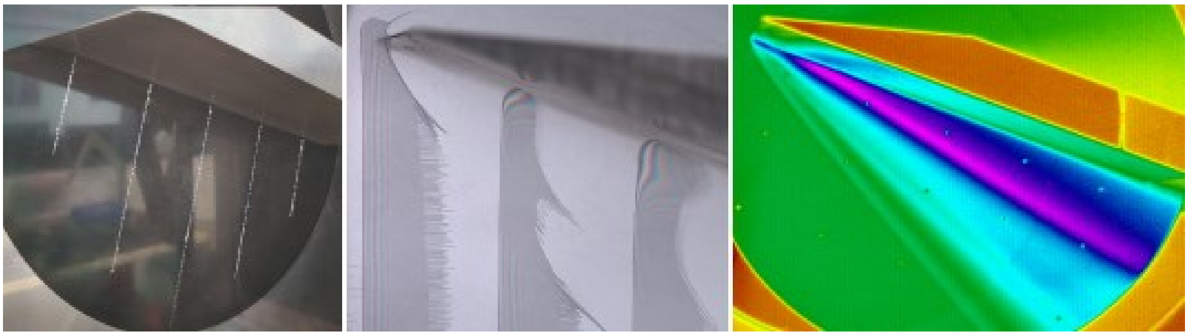

Figure 2: Three experimental methods, consisting of pressure taps (left), Oil film Interferometry (center) and quantitative infrared thermography showing the model surface temperature (right).

Sample Results

Figure 3 shows the normalised peak values of the wall pressure, the skin friction coefficient C_f and the Stanton number *St* along the conical rows as a function of the distance to the fin leading edge *x'*. The inception region can be clearly seen as a steep climb of the Stanton number (red line) up to *x'* = 65 mm in this configuration. But even at higher distances no perfectly constant values are measured, as is typically assumed within the quasiconical symmetry. Furthermore, this behavior changes with the model geometry. In the case of Mach 3, the quasiconical symmetry is not preserved near the rear edge of the fin and the peak values tend to decrease. At a Mach number of 5, the measured values stay nearly constant for a longer distance but the impact of a changed geometry of the leading edge is very strong. A blunt leading edge of the fin with curvature radius of only 0.8 mm can double the size of the inception region.

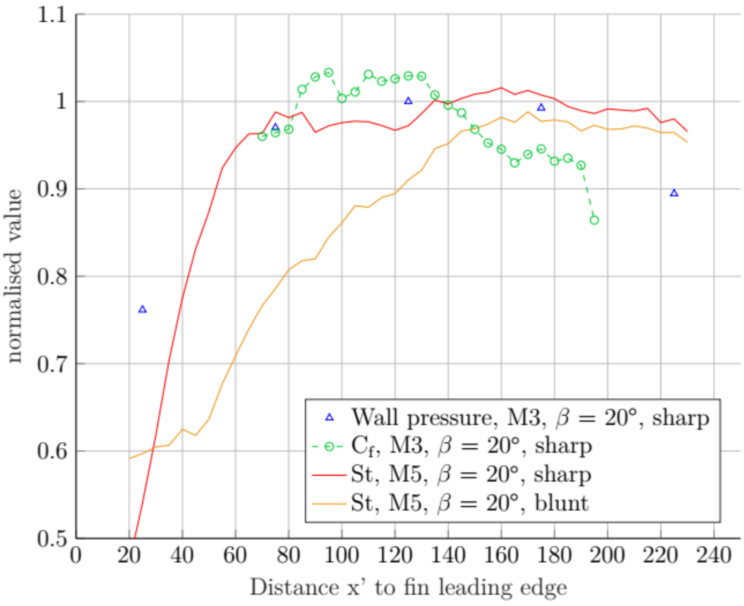

Figure 3: Sample results of peak values of the wall pressure, friction coefficient (both at Mach 3) and Stanton number (at Mach 5) over the distance to the fin leading edge.

Literature

[1] Adler, M. C., and Gaitonde, D. V. Flow similarity in strong swept shock/turbulent-boundary-layer interactions. *AIAA Journal 57*, 4 (2019), 1579– 1593

[2] Alvi, F., and Settles, G. Structure of swept shock wave/boundary-layer interactions using conical shadowgraphy. In *21st Fluid Dynamics, Plasma Dynamics and Lasers Conference* (1990), American Institute of Aeronautics and Astronautics.

[3] Baldwin, A., Mears, L., Alvi, F., Kumar, R., and Naughton, J. Effect of swept shockwave boundary-layer interaction strength on surface skin friction. *AIAA Journal* 61, 4 (2023), 1608–1622

[4] Brown, J., and Naughton, J. The thin oil film equation. *No. NAS 1.15:208767* (1999)