Mitteilung

Fachgruppe: Hyperschallaerothermodynamik / Turbulenz und Transition

DNS of an oblique-breakdown transition in an oblique-shock/ flat-plate-boundary-layer interaction flow

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Introduction: At the intake of scramjet or ramjet engines and at control surfaces of missiles, complex shock wave/boundary-layer interactions (SWBLI) in the hypersonic and supersonic flow regime occur. The SWBLI significantly influences the flow topology and causes large heat loads in the vicinity of the impinging shock. This is particularly pronounced, when the boundary layer in the interaction region is in a state of laminar-turbulent intermittency [1]. In this study, Direct Numerical Simulations (DNS) are carried out for a SWBLI on a flat plate for oblique shock wave angles of $12.4°$ and $13.0°$ impinging on the plate from above (see fig. 1). A first mode oblique breakdown transition scenario is forced in the simulations by disturbing the boundary-layer flow upstream of the SWBLI. The objective of this study is to investigate and analyze the streamwise development of the relevant eigenmodes of this disturbance. Furthermore, the influence of the disturbance on the skin friction and the heat transfer rate at the wall of the SWBLI is of particular interest.

Methods: The DNS are conducted using the finite-volume flow solver Navier-Stokes Multi-Block (NSMB), which has been successfully utilized in previous DNS studies of hypersonic SWBLI [2]. A fourth-order central scheme is chosen for spatial discretization. Explicit time integration with a three stage Runge-Kutta method is used.

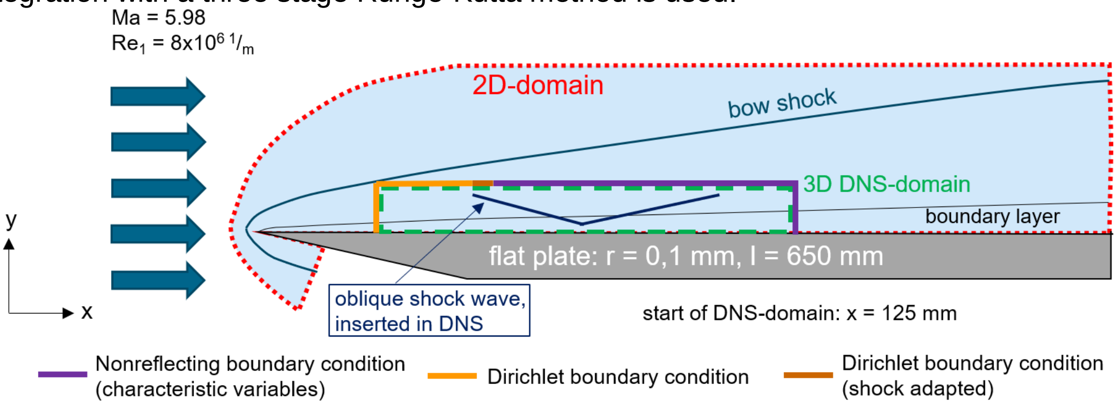

Figure 1: Sketch of the computational domains and boundary conditions: 2D-grid (dashed) and DNS-grid (dotted).

First, a two-dimensional (2D) baseflow solution for the flat-plate boundary-layer flow without shock at Mach number $Ma = 5.98$ and unit Reynolds number $Re_1 = 8 * 10^6\ 1/\mathrm{m}$ is computed on a domain including the leading edge with radius of $r = 0.1$ mm. Second, a restricted domain is used for the three-dimensional (3D) DNS to save computational costs (see fig. 1). Profiles of the flow variables are required for the Dirichlet inflow boundary condition on the left and upper faces upstream of the shock. These values are obtained from the 2D-baseflow solution. The oblique shock wave is introduced into the DNS in the upper left Dirichlet boundary condition by a discontinuity in the flow variables according to the Rankine-Hugoniot equations. A non-reflective boundary condition is applied downstream of the shock at the upper right side of the restricted domain and at the outflow. Periodic boundary conditions are applied in the spanwise direction. Transient perturbation modes are superimposed on the mean-flow values of the inflow boundary condition to force transition. The introduction and streamwise development of the forcing modes have been validated with solutions of Parabolized Stability Equations (PSE) in a previous study [3]. In this study, PSE analyses for the base flow without SWBLI are conducted to find the suitable forcing modes for an oblique breakdown scenario. The highest growth rates throughout the streamwise dimension of the domain for the oblique first modes are found at a frequency of $f = 9\ \mathrm{kHz}$ with a spanwise wavenumber of $\beta = 230\ 1/\mathrm{m}$. In a first step, simulations are carried out on an existing domain to verify the procedure for generating an oblique breakdown scenario. This domain has smaller spanwise extent resulting in a spanwise wavenumber of $\beta = 490\ 1/\mathrm{m}$ and thus a smaller growth rate. Two oblique first modes are imposed in opposite spanwise direction to trigger the oblique breakdown scenario. The maximum amplitude of the perturbation modes is scaled to approximately $3.8\,\%$ of the freestream density. The results of this preliminary investigation are presented below.

Preliminary Results: To illustrate the flow features of the DNS, the magnitude of the density gradient is shown in fig. 2. The boundary-layer thickness increases significantly at the position of the SWBLI. A separation bubble occurs between $x \approx 0.15\ \mathrm{m}$ and $x \approx 0.325\ \mathrm{m}$. In the boundary layer downstream of this separation bubble, small spanwise structures develop, which begin to break down at the end of the DNS domain. In order to analyze the development of different spanwise and temporal modes of the described process, the Fast Fourier Transform (FFT) is used. The results are presented in the final paper.

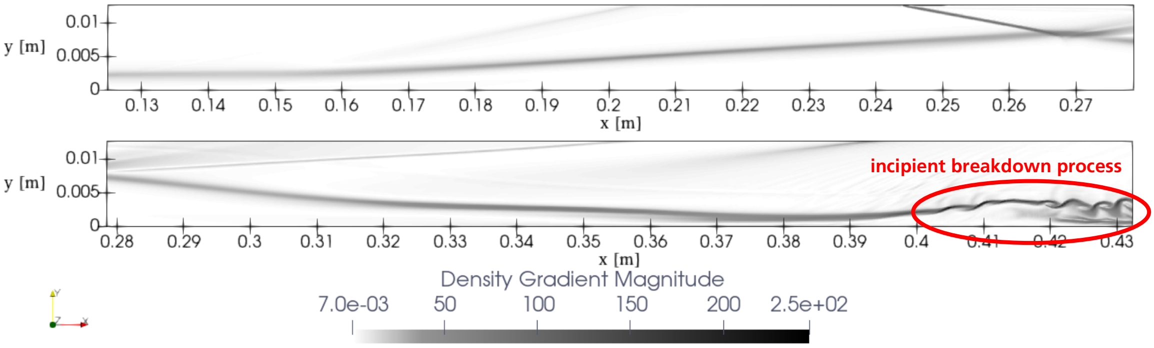

Figure 2: Density gradient magnitude (pseudo-schlieren) on a cut plane at z = 4.5 mm for the 13° shock angle case.

The evolution of the Stanton number St along the streamwise direction is shown in fig. 3. The simulation data shown are mean values (averaged in time and in spanwise direction). Analytical solutions for the laminar and turbulent (Van Driest II transformation [4]) boundary layer are included as a reference. Upstream of $Re_x = 1.1 * 10^6$, the DNS data agree very well with the laminar solution. Downstream of $Re_x = 2.2 * 10^6$, a steep increase in St can be observed, which is caused by both the pressure increase due to the shock and the incipient transition process. The overshoot of St has not reached its maximum yet, indicating, that the transition process is not finished within the DNS domain.

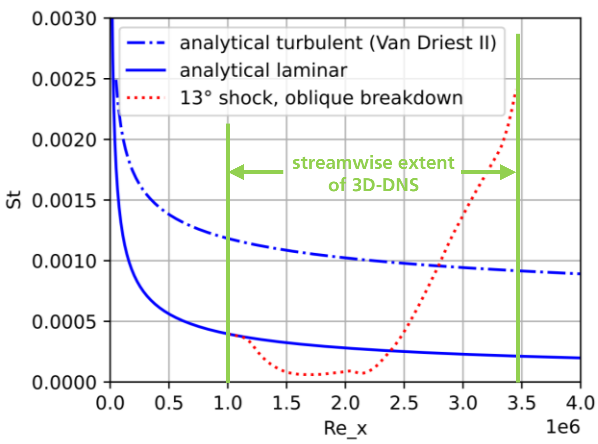

Figure 3: Stanton number development in streamwise direction for the 13° shock angle case.

Between $Re_x = 1.1 * 10^6$ and $Re_x = 2.2 * 10^6$, the effect of the separation bubble is visible. In the final paper, results will be presented for an extended domain to investigate the whole transition process. The spanwise extent of the domain will also be adapted to match the most amplified spanwise wave number determined from PSE.

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