A COMBINED EXPERIMENTAL AND NUMERICAL INVESTIGATION OF ROUGHNESS INDUCED SUPERSONIC BOUNDARY LAYER TRANSITION

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Abstract The laminar-turbulent transition of a supersonic flat-plate boundary layer with isolated roughness element is investigated both numerically and experimentally. Experiments are conducted in a Mach 3 low-noise wind tunnel for three different roughness heights of 1mm, 2mm and 4mm respectively. The flow structures in the transitional boundary layer are measured by a nano-based planar laser scattering (NPLS) flow visualization technique. Calculations are implemented in the same wind tunnel conditions using both second-order scheme and fifth-order weighted compact nonlinear scheme (WCNS-E-5) for comparison. Good agreements are achieved between experimental data and high-order solutions, including the turbulent boundary layer structures and quantitative pressure distribution along the plate centerline. However, the second-order scheme is found to be too dissipative to resolve the unsteadiness and small-scale structures in the transitional flow field. It is observed that the shear layer instability appears to be the leading mechanism for transition to turbulence in the wake of roughness element. With increasing height of roughness, the shear layer breaks up earlier and the transition tends to move forward.

EXPERIMENTAL AND NUMERICAL SETUP

The experiments were carried out in a Mach 3 low-noise wind tunnel which runs in an indraft mode. The total pressure and stagnation temperature of the incoming flow were P_0=1atm and T_0=300K, respectively. And other freestream flow parameters are listed in Table 1. A nano-based planar laser scattering (NPLS[1,2]) technique is adopted in current study. NPLS is a flow visualization technique for measuring fine flow structures in high speed and complicated flow fields using nano-particles for tracing. Owning to the excellent following ability of nanoparticles, they can cope with complicated structures in supersonic flow fields and scatter laser light effectively to generate high SNR (signal-to-noise ratio) images. Figure 1 is a sketch of the NPLS testing system. In experiments, a vitreous flat plate with sharp leading edge is used to generate laminar boundary layer. A three-dimensional cylindrical roughness element is located at a distance of 135mm downstream from the leading edge of the flat plate, to trip the boundary layer transition. The undisturbed laminar boundary layer thickness tested at the location of roughness is δ=1.2mm. In this paper, three different roughness height conditions of h=1mm, 2mm and 4mm are tested. Thus the corresponding roughness height to boundary layer thickness ratio h/δ is 0.83, 1.67 and 3.33 respectively.

Numerical simulations are implemented in the same wind tunnel conditions for comparison. The governing equations for the simulation are compressible Navier-Stokes equations. The Navier-Stokes equations are integrated in time with an implicit lower-upper symmetric-Gauss-Seidel (LU-SGS) time-marching algorithm, and dual-time-step subiterations are incorporated into the scheme to achieve second-order temporal accuracy. The discretization of spatial terms of the governing equation is based on the weighted compact nonlinear scheme (WCNS[3.4]), which is a set of high-order cell-centered finite difference schemes. WCNS-E-5, a typical explicit fifth-order one, is adopted in current simulations. Figure 2 is a schematic of the computational domains and figure 3 shows grids near the roughness element. The total number of grid points used in this study is approximately 41millions.

Table 1. Wind tunnel flow parameters

Ma	p(Pa)	T(K)	U(m/s)	μ(Ns/m^2)	Re(m^{-1})
3	2750	107	622.5	7.43×10^{-6}	7.5×10^{6}

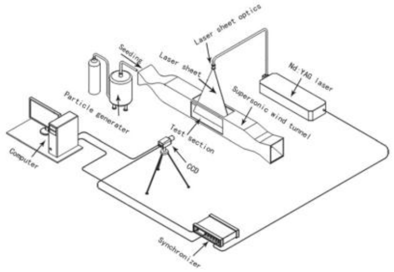


Figure 1. Sketch of the NPLS testing system

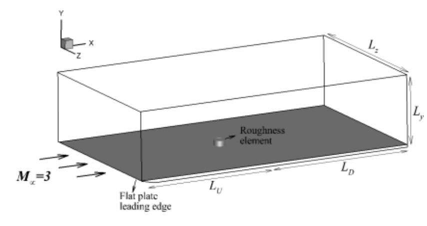


Figure 2. Sketch of the computational domains

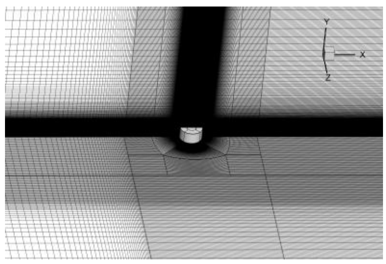
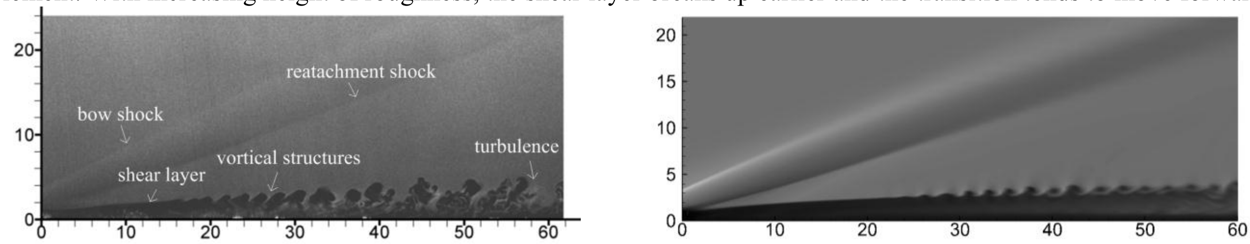


Figure 3. Grids near the roughness element

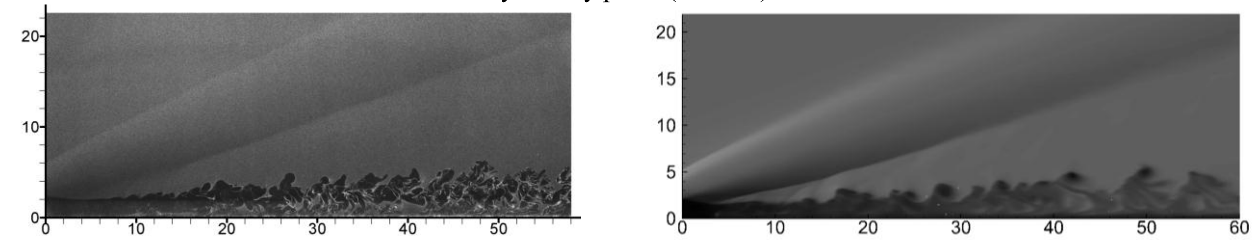
RESULTS

Figures 4-6 show the instantaneous density counters calculated by WCNS-E-5 and the experimental NPLS images for three roughness height respectively, which distinctly reveal the transient flow structures in the wake of roughness element. The NPLS images represent the flow field by gathering the light scattered by the tracing particles in the testing flow field. The flow field with dense tracing particles can generate strong signal, resulting in a high gray scale region in the NPLS image; in contrast, the flow field where particles are sparse corresponds to a low gray scale region. Based on the presupposition that tracer particles are seeded into the freestream uniformly, the gray scale of the NPLS image is proportional to the local density. As illustrated in Figures 4-6, structures of bow shock, reattachment shock, unstable shear layer, and developing turbulent boundary layer are captured in both NPLS images and numerical results. Good agreements are achieved between experimental data and high-order solutions. Very thin shock wave structures and various scales of vortical structures in the transitional boundary layer are identified in the NPLS images, which demonstrates the excellent following ability of the nano-particles for supersonic flow. It is observed in these figures that the shear layer instability appears to be the leading mechanism for transition to turbulence in the wake of roughness element. With increasing height of roughness, the shear layer breaks up earlier and the transition tends to move forward.



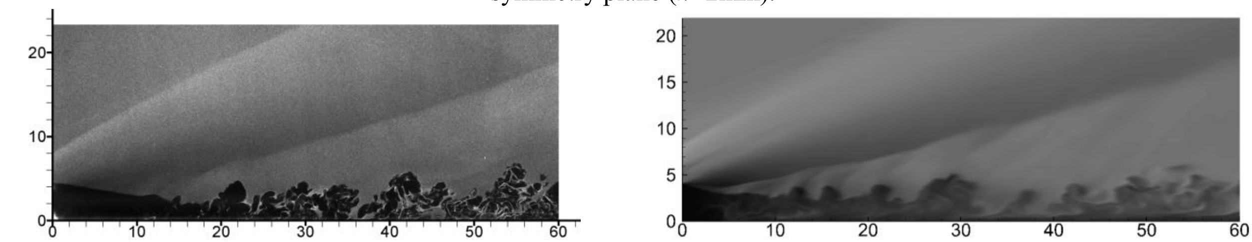
(a) Experimental NPLS image. (b) Density contours computed by WCNS-E-5

Figure 4. Comparison of instantaneous density field between experiment and numerical result of WCNS-E-5 scheme in symmetry plane (*h*=1mm).



(a) Experimental NPLS image. (b) Density contours computed by WCNS-E-5

Figure 5. Comparison of instantaneous density field between experiment and numerical result of WCNS-E-5 scheme in symmetry plane (*h*=2mm).



(a) Experimental NPLS image. (b) Density contours computed by WCNS-E-5

Figure 6. Comparison of instantaneous density field between experiment and numerical result of WCNS-E-5 scheme in symmetry plane (*h*=4mm).

References

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