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LARGE-EDDY SIMULATION OF SHOCK-WAVE / TURBULENT-BOUNDARY-LAYER INTERACTION

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Summary A Large-Eddy Simulation (LES) is conducted to investigate the characteristics of the mean flow and the turbulence structure of the boundary layer along a compression corner. The compression corner has a deflection angle $\beta = 25^0$, and the mean free-stream Mach number is $M_\infty = 2.95$. The Reynolds number based on the incoming boundary layer thickness is $Re_{\delta 0} = 63560$ in accordance with reference experiments. An analysis of the flow computation shows a good agreement with the experiment in terms of mean quantities (shock position, separation zone length, skin friction and surface pressure distributions) and turbulence characteristics. A mechanism of turbulence amplification in the external flow by travelling compression waves is proposed. The existence of three-dimensional large-scale structures (Görtler-type vortices) is shown .

INTRODUCTION

Shock-wave / turbulent-boundary-layer interaction for compression corner flow is a canonical test case for turbulence modelling. Although numerous RANS computations were performed, most of them failed to predict some crucial characteristics. On the other hand DNS computations are too expensive to be applicable for practical configurations. LES is the most appropriate numerical tool since it gives an accurate instantaneous flow representation. Although different subgrid-scale models have been extensively tested throughout the world, most LES computations are still limited to Reynolds numbers which are significantly lower then their experimental counterparts.

The current numerical investigation is aimed at a direct comparison with an available experiment. For this purpose all flow parameters and the flow geometry are matched with the experiment [1]: the free-stream Mach number is $M_\infty = 2.95$, the Reynolds number based on the incoming boundary layer thickness is $Re_{\delta 0} = 63560$, the ramp deflection angle is $\beta = 25^0$. By matching directly the experimental parameters the prediction quality of the employed subgrid-scale model can be assessed without further assumptions. Given a successful validation, the computational results provide an important source to analyse the flow physics in detail.

NUMERICAL TECHNIQUE

For current LES we employ the Approximate Deconvolution Model (ADM) [2] for modelling the sub-grid scales. The conservation equations for the filtered density, momentum and total energy are solved in curvilinear coordinates. A 6-th order compact finite-difference scheme is used for spatial discretization and an explicit low-storage 3-rd order Runge-Kutta scheme is applied for time advancement. Boundary conditions are applied as follows: periodic conditions in the spanwise direction, sponge technique at the outflow [3], non-reflecting condition with sponge layer at the upper boundary, and isothermal condition at the wall. The wall temperature distribution along the streamwise direction in the interaction region is taken from the experiment [1]. The inflow conditions have been generated by a separate flat-plate boundary-layer simulation using the rescaling and recycling procedure described in [4].

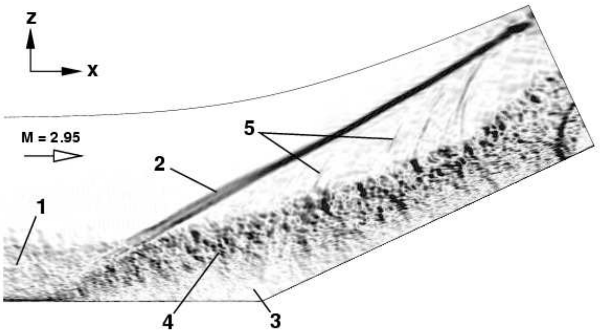

Figure 1. Density gradient averaged in spanwise $\|\nabla\rho\|$ (computed imitation of Schlieren visualization)

The computational domain has a size of $26.6\delta_0 \times 4.2\delta_0 \times 4.1\delta_0$ in streamwise, spanwise and wall normal direction respectively (δ_0 is the boundary layer thickness at inflow) and $701 \times 132 \times 201$ points. The simulation was running over 144 δ_0/U_∞ characteristic time scales. For statistical analysis, the field was sampled 265 times. To further improve statistical data the collection of samples is still in progress.

SIMULATION RESULTS

On Fig. 1 one can clearly identify the main flow field structures in the considered configuration: the undisturbed incoming turbulent boundary layer (1) interacts with the shock wave (2) resulting in the appearance of a separation zone near the corner (3) and a containing shear layer (4). All these flow features were also found in the experiment [1] and all calculated scales (separation zone length, shock position and slope) agree well with the experimental data. Another interesting feature is the existence of weak compression waves (5) above the reattached shear layer. Such waves were observed also

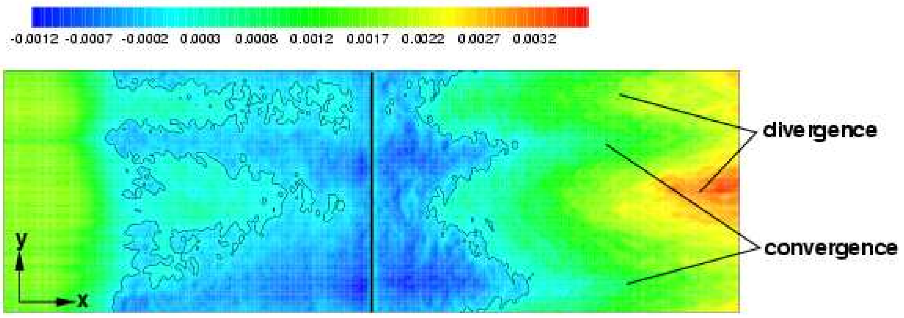

Figure 2. Time-averaged skin friction coefficient distribution at the wall

in previous DNS [3]. Experiments also exhibit compression waves in the described area. The compression waves are probably caused by unsteady motion of the shock wave. They emerge from the shock foot and travel further downstream. It seems that these waves are responsible for the amplification of turbulence levels in the external flow after passing the shock. The shock system unsteadiness itself is a crucial issue for wall loads: due to random shock motion the root mean square of the pressure fluctuations at the wall can reach 20% of mean pressure near the separation line, which agrees with experimentally observed values.

A detailed consideration of the flow field shows indications of large three-dimensional structures. In Figure 2 a time-averaged skin friction coefficient distribution at the wall is shown near the corner. The thin black line indicates $C_f = 0$, the thick vertical line indicates the compression corner position. Two divergence and two convergence lines after reattachment can be clearly seen. Similar oil-flow patterns observed in experiments are associated with Görtler-type vortices. In both cases the vortex width is about $2\delta_0$. Large-scale vortical structures influence mass, turbulence and heat transfer from external flow towards the wall. Eventually, these vortices strongly affect the skin friction distribution: in the reattachment region skin friction can vary along spanwise direction with the amplitude equal to the flat-plate boundary-layer value.

In Figure 3 the skin-friction-coefficient distribution in streamwise direction is shown, open dots denote experimental values, first vertical dotted line indicates the compression corner position, the second vertical dotted line that of the rarefaction corner (not considered in the present simulation). The skin friction coefficient averaged in time and in spanwise direction is denoted by solid line, minimum and maximum values over the spanwise direction are indicated as dashed lines (only in the interaction region). Unfortunately, the spanwise position of the experimental data probes with respect to the large-scale streamwise vortices is unknown.

So far, the turbulence statistics have been analyzed only qualitatively and will be presented more comprehensively durin the conference. Relative growth of density, momentum and velocity fluctuations after interaction were found to agree experimentall data.

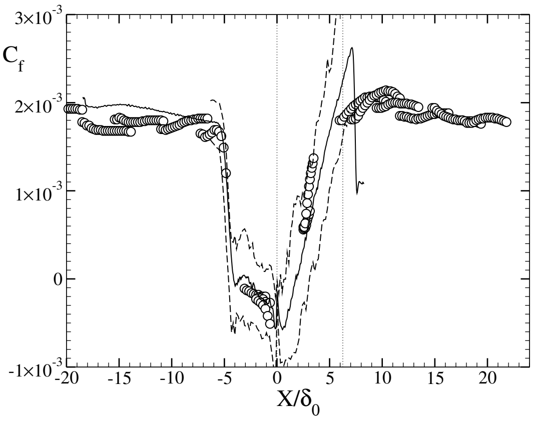

Figure 3. Skin friction coefficient at the wall

CONCLUSIONS

The Large-Eddy Simulation which was performed for flow parameters matching a reference experiment proves the possibility of a correct numerical prediction of shock-wave / turbulent-boundary-layer interaction at compression corners. Its analysis also imposes new requirements for the experiments which should take into account three-dimensional effects. A study of subsequent boundary-layer acceleration in a Prandtl-Meyer rarefaction is currently in progress.

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