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Numerical Investigation of Multiple Shock/ Turbulent Flow Interaction in a Supersonic Channel

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Abstract. Numerical investigation of multiple shock/turbulent flow interaction is carried out using large eddy simulation for a supersonic channel flow with an inlet free stream Mach number 1.61. Various fundamental mechanisms dictating the flow phenomena including shock train, shear layer and turbulence behavior are investigated. It is found that the existence of the shock train and separated shear layer has an important influence on turbulence features. The turbulence intensities and turbulent kinetic energy (TKE) are strengthened in the region of the multiple shock because of the unsteadiness of the shocks. The investigation on the transport equations of the TKE and the pressure fluctuation reveals that the multiple shock and the roll-up vortices of shear layer can promote the generation of the TKE and the pressure fluctuation. The unsteady behavior of flow field is further analyzed by means of the proper orthogonal decomposition method. It is found that the multiple shock and the separated shear layer dominate the unsteady feature.

AMS subject classifications: 76F65, 76L05, 76F70

Key words: Large eddy simulation, shock train, turbulent flow.

1 Introduction

The characteristics of shock wave/boundary layer interaction for the external flows have been widely investigated [1–5]. Nevertheless, the multiple shock wave/boundary layer interaction for the internal flows is more complicated. The shock train or pseudo-shock structure will form in a variety of devices, such as the straight ducts, diffusers and nozzles [6]. The features of the shock train and multiple shock wave/boundary layer interaction are mainly dependent on the incoming Mach number and the flow confinement [6].

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Based on previous studies [6–8], the interaction between normal shock and boundary layer in the internal flow can be divided into four categories. When the incoming Mach number is supersonic and less than 1.2, the strength of the shock is too weak to induce the boundary layer separation. In this situation, the shock is straight and similar to an inviscid normal shock. When the incoming Mach number increases to 1.2$\sim$1.3, the shock is enhanced to become curve, which is still similar to an inviscid shock. If the incoming Mach number increases again, the shock becomes stronger and induces the boundary layer separation. The separation in turn leads to the bifurcation of the shock. If the incoming Mach number is greater than 1.5, more shocks occur and the shock strain forms.

If the separation caused by the first shock is strong enough, a low-frequency oscillation can be observed [7], which is similar to the breathing motion of the separation bubble in the shock wave/boundary layer interaction [3]. For the shock train structure, the first shock and following shocks all have oscillation phenomena and the oscillation amplitude is enhanced with the increase of the incoming Mach number [7]. The mechanism relevant to the oscillation is still unclear [7–11]. Ikui [7] conducted an experiment in a straight pipe and analyzed the oscillation phenomena of the shocks with the small disturbances upstream the shock. The following experiments [9, 10] indicated that the oscillation is induced by the upstream propagation of the pressure fluctuation along the subsonic region in the downstream of duct. Sugiyama [11] also pointed out that the separation caused by the first shock may be a reasonable explanation of the oscillation of shock train.

The investigation on the shock wave/boundary layer interaction of the internal flow was first conducted for the purpose of designing the supersonic wind tunnels [12]. Then, it is found that the shock train structure is different from the single shock wave/boundary layer interaction [13, 14] and this problem is also studied by numerical simulation and experiment [6]. Among these investigations, the experiments conducted by Carroll [15–18] are prominent. The experiment utilized LDV to collet detailed turbulence statistics in the flow field, which is chosen in this paper for validation.

The numerical simulations of the shock train problem are mainly conducted by means of RANS. Early studies [18–21] used Baldwin-Lomax algebraic model, followed by simulations [22,23] with k–ϵ model, while they all exhibited poor agreement with experimental data. During recent years, some high-fidelity simulations are available [24–26]. Boles [24] conducted a simulation of inlet/isolator configuration with the incoming Mach number $Ma=5$. The hybrid large-eddy simulation (LES)/Reynolds average Navier-Stokes (RANS) model is utilized and a bigger separation region and a stronger shock train structure are observed with respect to experimental result. Koo [25] simulated the unstart process of the inlet/isolator model and over-predicted the separation and the propagation velocity of the unstart shock. Morgan [26] investigated the normal shock train using LES. Although the Reynolds number is lower than that in the experiment, a good agreement of the shock train structure and the quantitative results with experimental data is observed. While for the situation with periodic condition in the spanwise, the position of the shock train is relatively backward with respect to experimental result.

In this paper, an LES technique, which has provided a powerful tool for studying