A High-Order Shock-Fitting Non-Equilibrium Flow Solver for DNS of Strong Shock and Turbulence Interactions

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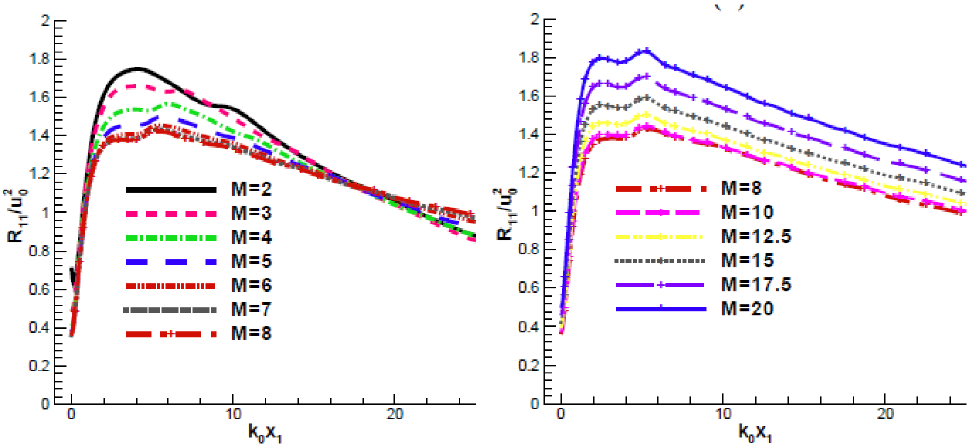
Abstract: The problem of strong shock and turbulence has proven to be very complex to understand with existing tools. Furthermore, thermo-chemically non-equilibrium effects including internal energy excitations, translation-vibration energy relaxation, and chemical reactions among different species need to be considered for flow behind strong shocks. In this paper, a unique approach of using a shock-fitting and shock-capturing method is proposed. The main shock is treated by a shock-fitting method as a sharp boundary of the computational domain. The rest of weak or secondary shocks induced by interactions of the main shock and freestream turbulence are captured by shock-capturing schemes. We will develop a high-order shock-fitting non-equilibrium flow solver and apply it to strong shock and turbulence interactions with thermo-chemically non-equilibrium effects.

Keywords: Shock and Turbulence Interaction, High-Order Shock-Fitting Method, Non-Equilibrium Flow.

1 Introduction

Many important scientific and engineering applications involve complex interactions between strong shock and turbulent flow, such as volcanic eruptions, detonations, shock wave lithotripsy to break up kidney stones, supernova explosion, as well as the implosion of a cryogenic fuel capsule for inertial confinement fusion. The underlying physics in strong shock and turbulence interaction is essential for better understanding of such applications. Unfortunately, these processes are strongly nonlinear and proven to be very complex to understand with existing tools. In addition, gas temperature increases dramatically behind strong shocks so that thermo-chemically non-equilibrium effects become important, which includes internal energy excitations, translation-vibration energy relaxation, and chemical reactions among different species.



(a) M = 2-8 *(b) M = 8 - 20*

Fig. 1. The amplification in streamwise velocity fluctuations at different shock Mach number [1]

Numerical simulations for such problems have been very limited due to the shortcomings of current numerical methods as well as the requirements of large computational resources. Popular shock-capturing schemes are not very accurate as they inherently use numerical dissipation in the whole computational domain. Moreover, spurious numerical oscillations have also been observed when solving strong shock and turbulence interaction problems with shock-capturing schemes [2]. Recently, Rawat and Zhong [1] conducted a series of DNS studies on strong shock and turbulence interactions, with the main focus on high shock Mach number cases. Figure 1 shows the amplification in streamwise velocity fluctuations for cases with different shock Mach number. It was observed to decrease for weaker than Mach 8 shocks, which is in accordance with the linear theory results. This trend, however, reverses for stronger shocks. Same trends were observed for turbulent kinetic energy. However, thermo-chemically non-equilibrium effects are neglected in their simulations.

2 Problem Statement

A schematic of strong shock and turbulence interaction is shown in Fig. 2. In such flows, the coupling between the shock wave and turbulent flow is very strong. Complex linear and nonlinear mechanisms are involved which alter the dynamics of the shock motion and can cause considerable changes in the structure of turbulence and its statistical properties.

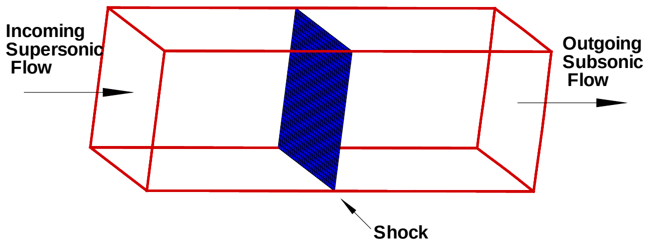


Fig. 2. A schematic of typical setting of strong shock and turbulence interaction.

In this paper, a unique approach of using a shock-fitting and shock-capturing method is proposed. The main shock is treated by a shock-fitting method as a sharp boundary of the computational domain. The rest of weak or secondary shocks induced by interactions of the main shock and freestream turbulence are captured by shock-capturing schemes. The code will be implemented based on a two-temperature model. It is assumed that translational and rotational energy modes are in equilibrium at the translational temperature whereas vibration energy and electronic energy are in equilibrium at the vibration temperature. The specific models for 5-species air has been well tested.

3 Conclusion and Future Work

In this paper, we will develop a high-order shock-fitting non-equilibrium flow solver and apply it to strong shock and turbulence interactions with thermo-chemically non-equilibrium effects. Thermo-chemically non-equilibrium effects are to be considered in the new high-order solver, which will lead to a better understanding of the underlying physics in strong shock and turbulence interaction.

References

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