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Computational simulations of microscale shock–vortex interaction using a mixed discontinuous Galerkin method

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ABSTRACT

This study extensively investigates the physics of microscale shock–vortex interaction of argon gas by solving conservation laws with non-Newtonian constitutive relations. In order to solve the conservation laws and associated implicit type second-order constitutive equations of viscous stress and heat flux numerically, a mixed discontinuous Galerkin (DG) formulation is developed. Three major characteristics are found in the microscale shock–vortex interaction in thermal nonequilibrium: the absence of quadrupolar acoustic wave structure, which is the major feature in macroscale near-equilibrium; the increase in the dissipation rate during the strong interaction; and the decrease in enstrophy during the weak interaction. Moreover, we show that the strong shock–vortex interaction in high shock or vortex Mach numbers can cause an increase in enstrophy. We also find the viscous effect to be dominant in the net vorticity generation. Among shock and vortex parameters, the shock Mach number, vortex Mach number and vortex size turn out to play a critical role in the deformation of the vortex and the strength of interaction, which in turn govern the evolution of vorticity due to the viscous effects, the change in the dissipation rate and the increase or decrease in enstrophy during the interaction.

1. Introduction

Shock–vortex interactions have been extensively investigated in the past decades because they can provide fundamental knowledge on flow physics of high speed gas flows. The shock wave and the vortex are deformed and/or disrupted during the interaction, and it alters or destroys the shock wave and the vortex structure. Most of the previous studies on this problem have been conducted for the purpose of understanding the noise production mechanism and deformation of the shock wave and vortex. Since thermal nonequilibrium effects are in general negligible at the macroscale, virtually all the previous studies are based on compressible Euler or Navier–Stokes–Fourier (NSF) equations [1–6], which are derived from the Boltzmann equation with the assumption of near-thermal-equilibrium, for analyzing the physical phenomena.

Previous computational investigations showed that strong shock–vortex interactions cause significant shock deformation and result in the formation of secondary shock structures [1]. Subsequently, Inoue and Hattori [3] predicted that a third sound wave was generated in the interaction of an initially planar shockwave and a single vortex. Later, Zhang and Shu [7] reported that additional sound waves would be generated in the subsequent secondary (and tertiary) interactions involving reflected shocks, shock lets, and the deformed vortex. In addition, Chatterjee and Vijayaraj [8] captured multiple acoustic waves, quadrupolar in nature and with successive layout of phase. The number of acoustic waves captured was more than the maximum of three reported in previous studies. The additional sound waves are due to acoustic addition from the rotating elliptical vortex following the interaction. Chang et al. [9] studied various cases of shock–vortex interactions. These studies found that the most remarkable flow elements of the shock–vortex interaction are the induced expansion wave and shock wave.

Although numerous computational studies have been conducted on the shock–vortex interaction at the macroscale, the microscale shock–vortex interaction in thermal nonequilibrium is not yet well understood. Up to now, only a few microscale cases involving limited Mach and Knudsen numbers have been conducted by Koffi et al. using direct simulation Monte Carlo (DSMC) [10,11]. That study showed that, within the range of the parameters considered, the viscous attenuation of the vortex was found to dominate the gas flow in the microscale shock–vortex interaction. At microscale, the attenuation overwhelmed the enstrophy generation, which is in stark contrast to the enstrophy production in the macroscale shock–vortex interaction. However, critical

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