DSMC Simulations of Shock Interaction with Shock-Scale Harmonic Fluctuations

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Abstract. DSMC simulations were performed of the interaction of normal shock waves with perpendicular, shock scale fluctuations in the flow velocity, modeled as one-dimensional harmonic waves in the reference frame of the shock. Wave attenuation was pervasive. However, effects due to interaction between harmonic and molecular fluctuations were observed. At higher Mach numbers and harmonic wave lengths near the mean free path, the shock interaction produced amplification of fluctuating kinetic energy in the shock interior, which did not persist downstream of the shock.

Keywords: DSMC, shock interaction, unsteady wave
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INTRODUCTION

Continuum analysis of interactions of shock waves with unsteady wave structures has been a subject of substantial interest for over a half-century, beginning with Burgers[1] and Kantrowitz[2], who investigated the interaction of a one-dimensional acoustic wave with a normal shock. Recently, Gu et al.[3] studied the interaction of shocks with one-dimensional, nonlinear harmonic waves. However, until now, research on shock/unsteady wave interaction had not been extended to the rarefied flow regime.

Early work on the interaction of shocks with unsteady wave structures was primarily motivated by interest in shock stability and in noise generation due to the interaction of shock waves with turbulence. Much contemporary interest in this topic has been motivated by interest in the effect of shock passage on fluid turbulence itself. To this end, the present work is aimed at understanding the fundamental mechanisms of such shock/turbulence interactions when the smallest scales of turbulence approach the scale of the shock front.

The present investigation focuses on the unsteady interaction of stationary shock waves with a model, turbulence-like flow structure having a length scale on the order of the shock thickness. This approach led previously to the Direct Simulation Monte Carlo (DSMC) method[4] investigation of the interaction of a propagating planar shock wave with a shock-scale, transverse, columnar vortex by Koffi et al.[5]. Koffi et al.[5] demonstrated that coherent turbulent flow structures, represented by the columnar vortex, are weakened during the shock transition but can still be transmitted through the shock. In the same vein, the current DSMC investigation examines the interactions of normal shock waves with perpendicular shock-scale fluctuations modeled as one-dimensional harmonic waves.

High frequency harmonic waves have been simulated previously using DSMC by Hadjiconstantinou and Garcia[6] and by Danforth and Long[7]. In the present case, such waves are generated as macroscopic velocity oscillations in the reference frame of the shock and interact with it. The wavelengths of the oscillations of interest are on the order of the shock thickness.

FLOW MODEL

The one-dimensional flow model employed in this investigation consisted of a standing shock wave initially situated in the center of a computational domain that extended ten mean free paths on both sides of the shock.

Steady supersonic flow approaches the shock from the left side (flowing in the positive x direction). The supersonic inflow velocity to the domain begins to oscillate sinusoidally about a mean, creating a harmonic wave that interacts with the shock and leads to an harmonically oscillating flow in the domain.

The inflow stream velocity is prescribed according to

$$u(0,t) = a(M_s + M_f \sin \omega t) \qquad (1)$$

where $M_f < M_s$. In the above relation, a is the speed of sound in the constant temperature, monatomic inflowing gas, M_s is the shock Mach number (ratio of the mean speed of the incident flow to a), and M_f is the amplitude Mach number of the velocity fluctuations (ratio of the amplitude of the stream velocity oscillations to a). The physical model and flow domain are depicted in Figure 1, where λ is the mean free path in the inflowing gas.

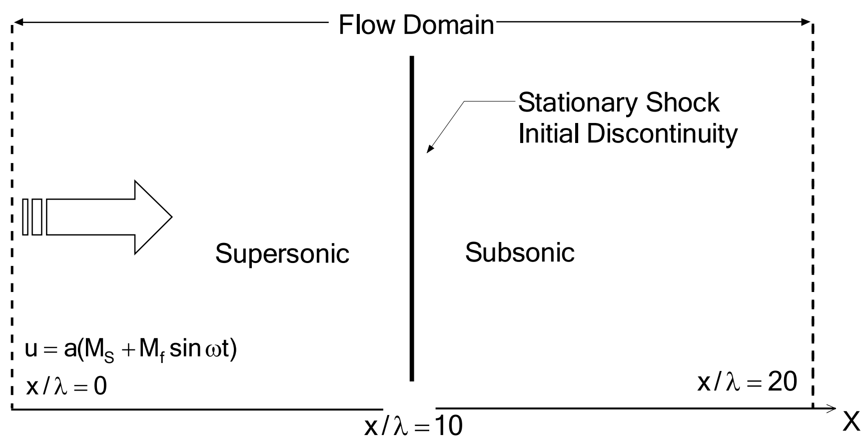

Figure 1. Flow model.

SIMULATION PARAMETERS

Collision-scale, shock/harmonic wave interactions in Argon at an inflow temperature of 273 deg. K. were studied with unsteady DSMC for the model flow. Simulations were performed at inflow number densities corresponding to pressures of p =0.01 atm and p=0.002 atm. The results cover a range of shock Mach numbers and input harmonic wavelengths at these two pressures. For the lower pressure, simulations were carried out from M_s=4 to M_s=8 and for the higher pressure, from M_s=3 to M_s=5. In all cases, M_f = 0.5. For convenience, the input harmonic frequencies were varied by specifying the parameter, n, where $n = 2\pi a/(\omega\lambda)$ is the ratio of the acoustic wavelength of the harmonic wave to the mean free path. It is, therefore, a measure of the ratio of the length scale of the harmonic wave to the shock thickness, as well as a measure of the ratio of collision frequency to oscillation frequency. Simulations were performed at n=0.5. 1.0, 5.0, 10.0, and 20.0.

The initial conditions were taken to be a discontinuous shock jump located at the center of the domain with mean particle velocities on either side of the discontinuity specified by the Rankine-Hugoniot relations for a standing shock. The simulations were started with a steady inflow stream velocity at M_s and a steady shock structure was established before the time varying inflow component of Equation 1 was introduced. The inflow stream of simulated molecules assumed a Maxwellian distribution of thermal velocities at the constant inflow temperature.

For comparative purposes, the simulations were also performed without a shock in the domain and the stream inflow boundary specified by Equation 1, resulting in a harmonically fluctuating supersonic flow within the domain. In all cases, a case appropriate, steady outflow stream boundary was used since, as the results will demonstrate, the influence of the wave at the outflow boundary is negligible.

The simulations employed a Variable Hard Sphere (VHS)[4] collision model. For p=0.01 atm, the time step used was 10^{-10} with 200 cells in the domain and 10 sub-cells per cell. The total number of molecules simulated was 5800. For P=0.002 atm, the time step was $5x10^{-10}$ with 200 cells and the number of molecules simulated was 6600.

RESULTS

Typical sampled stream velocity results are shown in Figure 2 for n=1. The upper graph shows a snapshot in time of the wave as it exists in the domain without a shock. The waveform displays some deviation from a pure sinusoid because of compressibility effects in the interior of the domain and the constant temperature assumption for the inflow stream.

The amount of wave attenuation away from the inflow boundary is clearly seen in the upper graph of Figure 2. The velocity is normalized by its inflow stream mean value, $M_s a$. The structure of such harmonic waves at these collision-scale wavelengths, which correspond to very high frequencies, undergo rapid collisional attenuation as demonstrated in the DSMC computations of Hadjiconstantinou and Garcia[6]. Therefore, not unexpectedly, wave attenuation was the dominant phenomenon observed throughout most of the simulations, including wave interaction with shocks.

The lower graph of Figure 2 compares the rms of the sampled unsteady velocities of the unshocked wave with that of a wave having the same inflow characteristics but encountering a moderate Mach number (M_s=3) shock in the domain. Because of the wave propagating through it, the shock is oscillating rather than standing but its time-averaged position is fixed in space. For this case, there is only a slight effect of the shock interaction on the attenuation of fluctuating kinetic energy contained in the harmonic oscillations, for which the rms sampled velocity (squared) is a proxy. The curve displays a local minimum due to the adjustment effect created by the constant temperature entry condition.

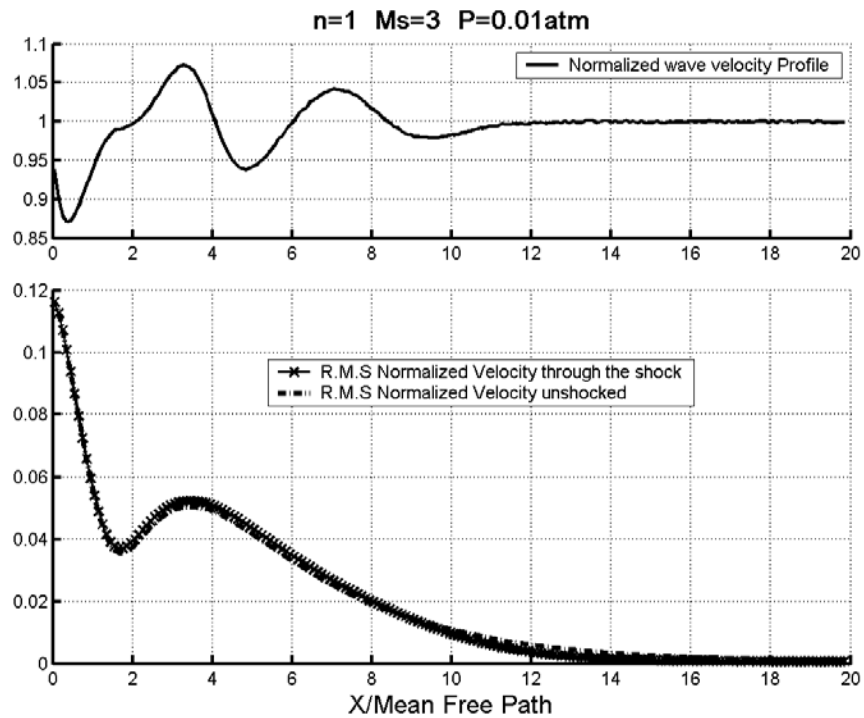

Figure 2 Unshocked instantaneous and rms velocities with Mach 3 shocked velocity.

Figure 3 plots the rms fluctuations of the shocked wave on the same graph as the mean shock profile, where it can be seen that during the shock transition there is no significant effect of the transition on wave attenuation.

As Mach number increased, for n=0.5 and n=1 where the harmonic and thermal scales were closest, pronounced local peaks were observed in the macroscopic rms fluctuating velocity inside the shock. These peaks represent enhancement of the kinetic energy inside the shock over the fluctuating energy at the same location in an unshocked wave. The most prominent manifestation of this phenomenon for the simulation cases occurred at M_s=8 and p=0.002 for n=1. These results are shown in Figures 4 and 5.

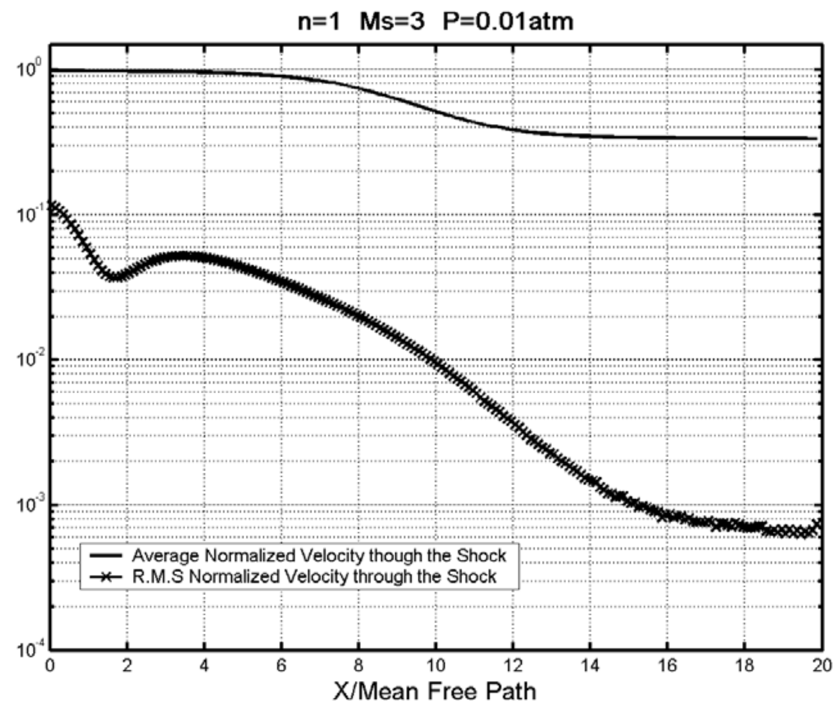

Figure 3 Comparison of average and rms velocity profiles through Mach 3 shock.

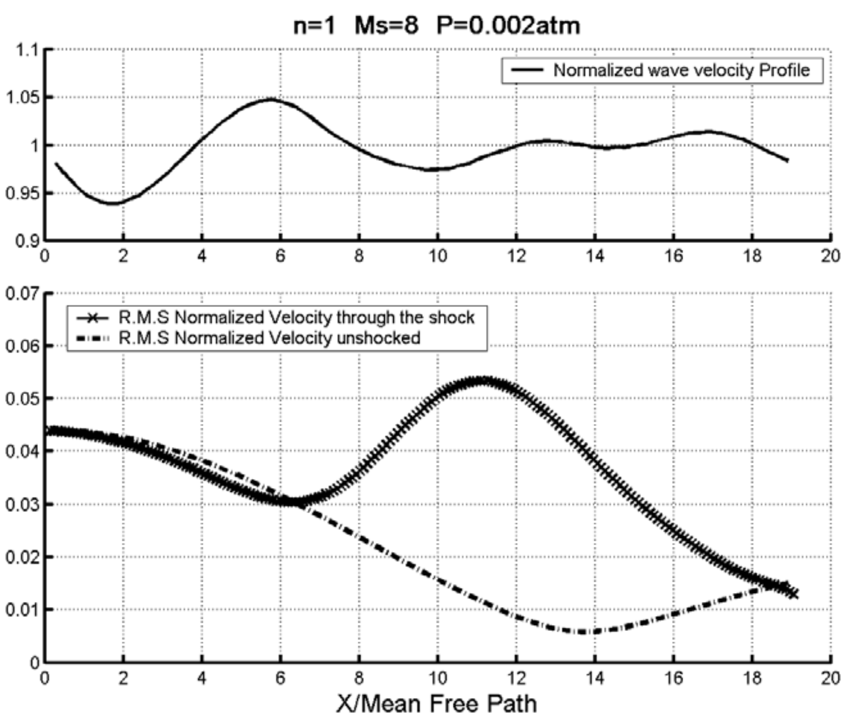

Figure 4 Unshocked instantaneous and rms velocities with Mach 8 shocked velocity.

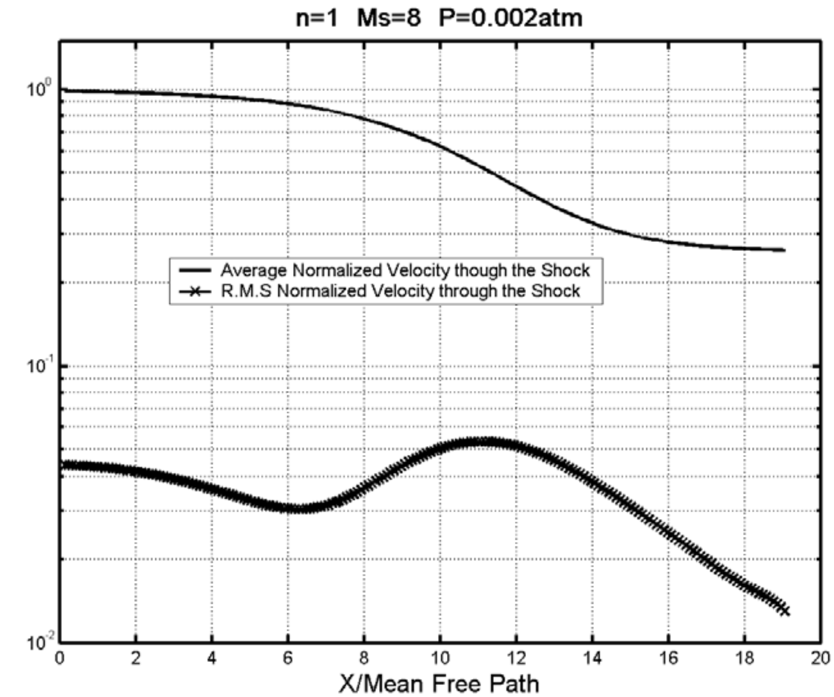

Figure 5 Comparison of average and rms velocity profiles through Mach 8 shock.

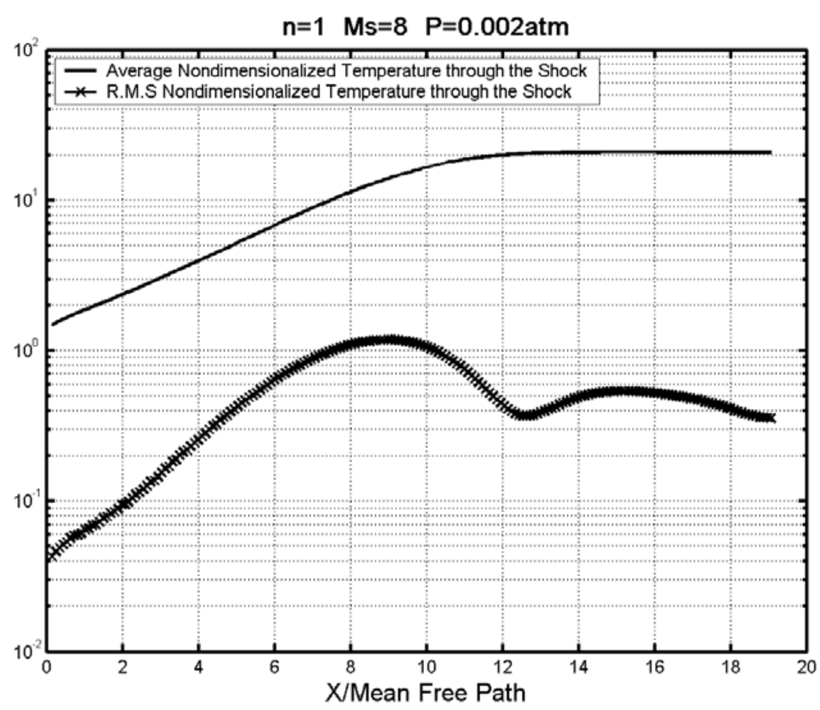

Figure 6 Comparison of average and rms temperature profiles through Mach 8 shock.

The other macroscopic rms sampled variables also exhibited peaking behavior inside the shock, representing amplification of these quantities in the shock interior as shown in Figures 6 and 7 for the temperature and density, respectively. The variables plotted in Figures 6 and 7 were nondimensionalized with their inflow stream constant values. The amplification phenomena do not persist into the region downstream of the shock, where the fluctuations are diminished to the point that they are insignificant.

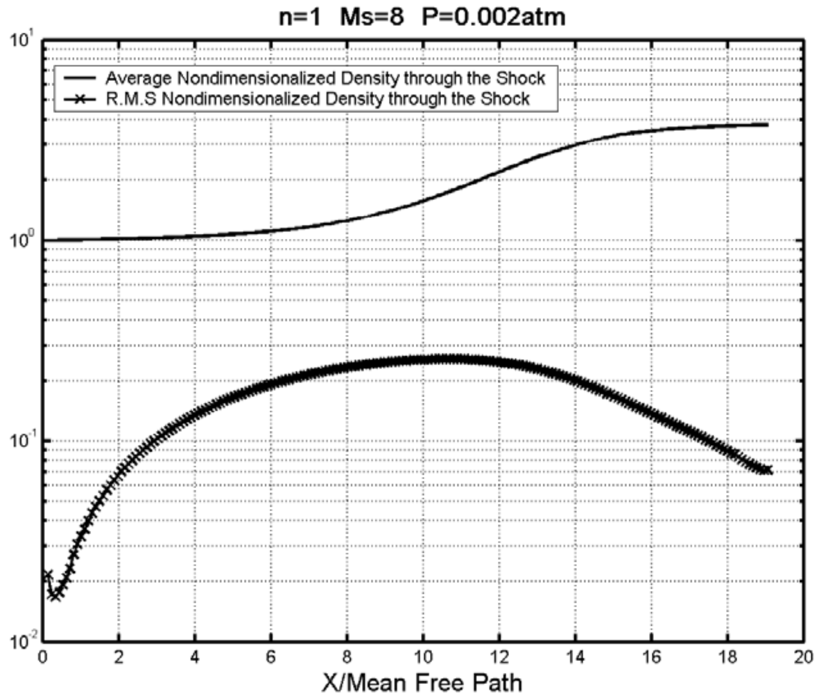

Figure 7 Comparison of average and rms density profiles through Mach 3 shock.

CONCLUSION

The results indicate that there are complex collision-scale interactions between the molecular thermal velocity motions and the flow oscillations in shock interactions when the acoustic wavelength of the flow oscillations approaches the mean free path. They suggest that, at higher Mach numbers, shock-scale turbulent fluctuations interacting with a shock can be amplified in the interior of the shock but, due to wave attenuation effects, they are not transmitted through it. This is a somewhat different result from that for coherent flow structures represented by a columnar vortex, which can persist downstream of the shock.

ACKNOWLEDGMENT

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REFERENCES

1. J. M. Burgers, "On the Transmissions of Sound Waves through a Shock Wave," *Koninklijke Nederlandsche Akademie Van Wetenschappen*, Proc. XLIX,, pp.273-81,1946.
2. A. Kantrowitz, "The Formation and Stability of Normal Shock Waves in Channel Flow," NACA TN 1225, 1947.
3. K. Gu, C. B. Watkins and Y. Andreopoulos, "Shock/Nonlinear Harmonic Wave Interaction," AIAA Paper No. 2006-3547, *Proceedings of the 36th AIAA Fluid Dynamics Conference*, San Francisco, California, June 2006.
4. G. A. Bird, *Molecular Gas Dynamics and the Direct Simulation of Gas Flows*, Clarendon, Oxford, 1994
5. K. Kossi, J-P Njante, C. B. Watkins and Y. Andreopoulos, "Microscale Shock Interaction with Shock-Thickness Scale Vortex using Direct Simulation Monte Carlo," AIAA Paper No. 4898, *Proceedings of the 35th AIAA Fluid Dynamics Conference*, Toronto, Canada, 2005.
6. N. J. Hadjiconstantinou and A. L. Garcia, "Molecular Simulations of Sound Wave Propagation in Simple Gases," *Physics of Fluids*, **13**, 1040-1046, 2001.
7. A. L. Danforth and L. N. Long, "Nonlinear Acoustic Simulations Using Direct Simulation Monte C," *Journal of the Acoustical Society of America*, **116**, 1948-1955, 2004.