New model simulates phenomena in a shock wave

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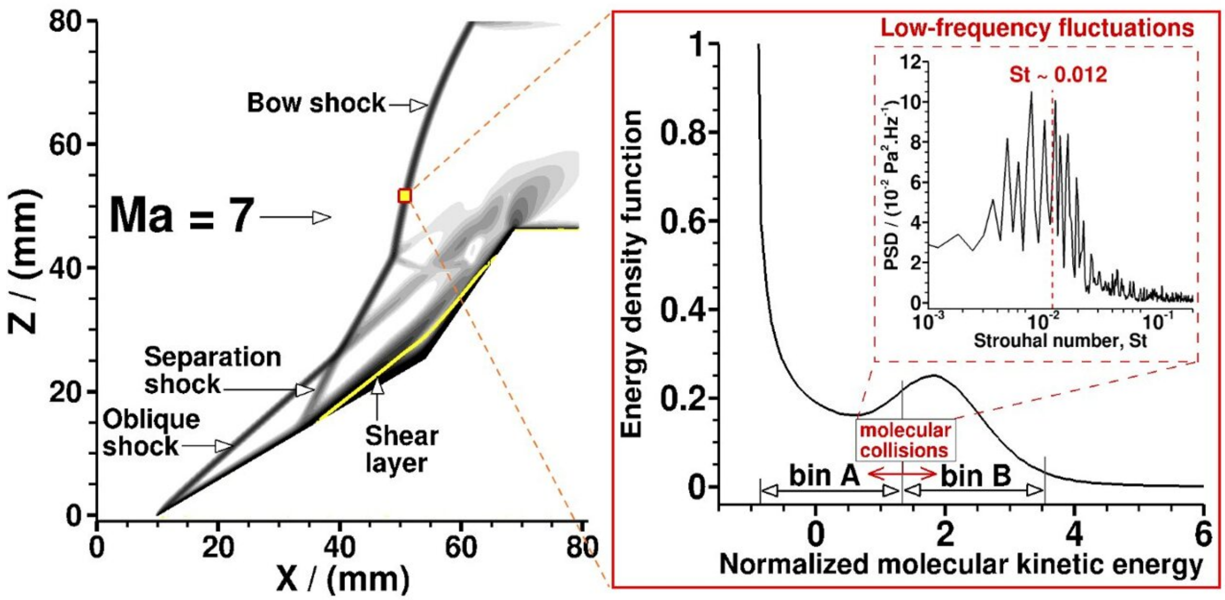

Left: shock-wave/boundary-layer interactions in a Mach 7 flow over a ouble-wedge configuration. Right: a bimodal energy distribution function of particles in the bow shock. Molecular collisions between the low energy bin A and high energy bin B cause low-frequency fluctuations having Strouhal number on the order of 0.012. Credit: University of Illinois Dept. of Aerospace Engineering

Much of the study in the field of hypersonics focuses on understanding the disturbances in the flow of gases near the surface of the vehicle—the boundary layer—rather than what's happening in the shock, which typically occurs in the front of the vehicle.

Researchers at the University of Illinois Urbana-Champaign and Liverpool developed a model to understand the origins of molecular fluctuations in the shock and found them to be at much lower frequencies than in the boundary layer flow.

"In the shock, two streams of particles coexist. There are high energy particles coming from upstream of the shock—the undisturbed gas or free stream. And there are low energy particles from downstream—those that are in the vicinity of the vehicle wall. By simulating the bimodal particle energy distributions, our model correctly predicts the fluctuation frequencies to be two orders of magnitude lower in the shock versus those in the upstream," said Saurabh Sawant, a doctoral student in the Department of Aerospace Engineering.

The study characterizes the fluctuations in the shock waves of vehicles traveling at speeds of Mach 2 to 10 and is modeled in one dimension.

Professor Deborah Levin, Sawant's adviser and co-author of the research, said modeling a shock to this level of fidelity in two or three dimensions is both computationally expensive and much more complicated.

"However, a one-dimensional detached shock is a good approximation to a very strong shock," she said. "It's going to teach us something and it's easier for us to observe molecular fluctuations in a one-dimension shock."

According to Sawant, almost all researchers use the same set of equations known as Navier-Stokes to model shock-dominated flows. But this approach cannot be used to study molecular fluctuations in a flow.

This study is the first to use a different, novel approach.

"The Navier Stokes equations apply in certain regions of the flow, but not quite as well in the shock. We used more general equations that govern the variation of velocity distribution functions in a flow field," he said.

Levin added, "It's a simulation technique of computational particles that represents a solution of the Boltzmann equation because no one can solve the Boltzmann equation directly for something as complicated as this."

Although shocks are difficult to model, Levin said they are important in terms of understanding the disturbances in the flow because of the effects it may have on flow stability.

"You might have a vehicle set on a trajectory and a flap is employed," she said. "Suddenly, the forces acting on the vehicle become unsteady. Instead of being in a kind of regime where you have either laminar flow or fully turbulent flow, it is somewhere in between and hard to control."

One stimulus for the study came from the paper's third author, Professor Vassilios Theofilis from the University of Liverpool, who is a world-renowned expert in stability theory.

"We used to say that the strong shock in the front of the vehicle is stable. Nothing to talk about. Very boring from a stability point of view," Levin said. "We understood that researchers who study the transition are more excited about the instabilities that occur with more complicated flows, but he noticed fluctuations in the direct simulation Monte Carlo particle data. And he said, you know, we really need to look at this very, very carefully, and he was right."

She said other researchers who study hypersonics are beginning to pay attention to this paper and another companion paper and want to use what Sawant has derived.

The study, "A kinetic approach to studying low-frequency molecular fluctuations in a one-dimensional shock," by Saurabh Sawant and Deborah Levin from UIUC, and Vassilios Theofilis from the University of Liverpool, is published as Editor's pick in *Physics of Fluids*.

The companion paper, "Analytical prediction of low-frequency fluctuations inside a one-dimensional shock," is also written by Sawant, Levin, and Theofilis. It is published in *Theoretical and Computational Fluid Dynamics*.

More information: Saurabh S. Sawant et al, A kinetic approach to studying low-frequency molecular fluctuations in a one-dimensional shock, *Physics of Fluids* (2021). DOI: 10.1063/5.0065971

Saurabh S. Sawant et al, Analytical prediction of low-frequency fluctuations inside a one-dimensional shock, *Theoretical and Computational Fluid Dynamics* (2021). DOI: 10.1007/s00162-021-00589-5

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