ABSTRACT

In most engineering applications of explosives, the detonation reaction-zone length, $\eta_r$, is orders of magnitude shorter than is a typical system dimension. Yet, it is observed that the finiteness of the reaction-zone length does influence the propagation of the detonation (e.g., the speed of propagation). To deal with these effects in simulations of systems, one has two alternatives: 1) a direct numerical simulation (DNS) using adaptive mesh refinement (AMR) on a resolvable, physically appropriate model or 2) a subscale model of the reaction zone that properly describes how the detonation front responds to changes in the flow in which the reaction zone finds itself embedded. In this lecture, I’ll review our development of a subscale model for detonation, something we call detonation shock dynamics (DSD).

What sets our modeling strategy apart from those for other combustion interface submodels is the supersonic nature of the combustion wave. For submodels of subsonic combustion, preheat ahead of the reaction front plays a dominant role in defining the combustion zone and the regression speed of the reaction front. In these models the thickness of the reaction front itself can be ignored. For detonation, on the other hand, the combustion zone is synonymous with the reaction front. The reaction zone neither preconditions the unburnt material nor is it influenced by the flow of the burnt products of combustion. It is causally insulated from both. Detonation communicates with its’ surroundings laterally, principally through the ”sides” of the reaction zone. Thus, the interplay between the length scale for the reaction zone, $\eta_r$, and the geometrical length scales of the explosive region is fundamental in detonation submodels and defines the dimensionless parameter used to develop rational detonation submodels. This interaction sets both the local speed of propagation and the ”thermodynamic state” (pressure, density, etc.) that is deposited with the combustion products as they leave the reaction zone.

DSD propagation submodels come in a number of flavors. Shared in common though, is the feature that all are asymptotic models, rationally derived from the multi-dimensional Euler equations (or other appropriate equations) in the limit of 1) weak shock curvature $(\eta_r \tilde{k} = k = O(\epsilon) << 1$, where $\tilde{k}$ is the curvature of the detonation shock) and 2) slow time evolution, measured in terms of the scaled time, $|\epsilon|^\nu \tilde{t}$. All these models have two components: 1) the front propagation submodel and 2) a submodel for depositing the proper ”thermodynamic state” with the combustion products exiting the reaction zone.
The first class of models to be developed and most widely used in engineering applications is the family of $D_n(\kappa)$-models, where $D_n$ is the propagation speed and $\kappa$ is the scaled shock curvature. This type of model assumes a quasi-static and local dependence of $D_n$ on the reaction-zone dynamics. To deposit the "proper" detonation state with the reaction products as they exit into the flow following the reaction zone, we use a pseudo reaction zone model that mimics the reaction zone in that we can control the exit flow state. By construction, the leading edge of this submodel remains synchronized with the location of the front propagation model. It is constructed to be conserving of mass, momentum and energy. The "thermodynamic state" of the combustion products depends principally on the value of $D_n$ and to a lesser extent on the interaction of the real physical shock curvature, $\kappa$, with the length of the pseudo reaction zone. The equation of state (EOS) of the reaction products is that of the "true" (measured) EOS. The detailed structure of the reaction zone, however, is artificial. Given that neither the dependence of the exit "thermodynamic state" on $D_n$ nor the structure of the reaction zone is known for condensed phase explosives, the model is consistent with explosive’s known properties, and importantly is conservative. In my presentation, I will describe the properties of both aspects of these submodels, discuss their numerical implementation and show results.

Detailed comparison of DNS results with those of the $D_n(\kappa)$ model, using a model reaction zone problem for which all EOS and reaction rate information is specified, reveals discrepancies between them. After discussing these differences, I will go on to present work on higher-order propagation models that include explicit time dependence and nonlocal effects. These extended models derive a propagation law $D_n(\kappa, DD_n/Dt, \partial^2 D_n/\partial \xi^2)$, where $D/Dt$ denotes a time rate of change and $\partial^2/\partial \xi^2$ describes a spatial rate of change with arclength along the shock front, $\xi$. I will also describe some of the mathematical properties of these higher-order models. Finally, I will outline some directions for future work.