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Understanding Curved Detonation Waves

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A wave curve is the set of final states to which an initial state may be connected by a traveling wave. In gas dynamics, for example, the wave curve consists of the shock Hugoniot curve for compressive waves and the rarefaction curve for expansive waves. In this paper, we discuss the wave curve for an undriven planar detonation and for general planar detonations. We then extend the wave curve concept to detonations in converging and diverging geometry. We also discuss the application of these wave curves to the numerical computation of detonation problems.

An undriven planar detonation wave is self-sustaining and propagates at a constant Chapman-Jouguet (or CJ) velocity which is a characteristic of the explosive. Since the wave is not influenced by the region behind it, the state at the end of the reaction zone must be sonic with respect to the detonation front. The speed of this wave and the state behind it are uniquely determined by applying algebraic jump conditions representing the conservation of mass, momentum and energy through the reaction zone along with the condition that the flow must be sonic at the end of the reaction zone. This calculation is independent of reaction rate and length of the reaction zone. It can be assumed that the reaction rate is infinite and the reaction zone is infinitesimally thin. The undriven planar detonation wave has been used as the basis of a computational method called programmed burn. In this technique, a detonation wave in 2-D is propagated using a Huygen's wave construction with the CJ velocity, and the physical state behind the detonation is set to the sonic CJ state.

If a planar detonation wave is overdriven, one can attain greater detonation speeds and pressures behind the detonation than in the CJ case. For each detonation speed above the CJ speed, there are two solutions to the algebraic equations for the jump conditions yielding an ambiguity for the state behind the detonation. This ambiguity ' resolved by applying the Zeldovich von Neumann Doering (ZND) model. Here, the detonation is modeled as a traveling reactive wave with a finite reaction rate. This turns the partial differential equations (PDEs) for reactive flow into ordinary differential equations (ODEs). The shock initiating the detonation takes the initial state to a higher pressure state on the unburned Hugoniot curve. As the reaction proceeds, the states in the reaction zone move down a line in the specific volume pressure plane (called the Rayleigh line) determined by conservation of mass and momentum. The states in the reaction zone can be written as algebraic functions of the reaction progress variable which is determined as a function of position by solving an ODE. Since the chemical reaction is irreversible, the progress of the reaction must increase monotonically and determines the strong or high pressure solution to the jump equations. Thus, the model yields a one-parameter family of solutions corresponding to the strong detonation portion of the planar wave curve. This branch joins up with the CJ point as the detonation speed is reduced to the CJ speed. There is no detonation solution for wave speeds below CJ. Since the flow is sonic at the CJ point, a rarefaction (Taylor wave) may be attached to the CJ state to connect to lower pressure states in the behind flow, thus completing the planar detonation wave curve. This wave curve can extend the programmed burn model to describe overdriven detonation waves as well as the CJ detonation wave. Numerical computations using the planar detonation wave curve have been performed using the random choice and front tracking methods.

The front tracking method is a general algorithm that is capable of accounting for the analytic properties of a front and the coupling of the front to the surrounding flow. The method superimposes one dimensional grids for the fronts over a two dimensional grid for the interior solution. In addition to applying a finite difference scheme in the interior, the front is propagated by solving a non-local Riemann problem. The solution to the Riemann problem is determined by the wave curve. Thus, the wave curve contains the analytic properties which characterize the front.

In curved geometry the reaction zone is influenced by the nonlinear coupling of the geometry and the chemistry. For example, it is well known that the propagation of a detonation wave through a rate stick proceeds at a lower speed than the planar CJ wave speed. When the width of the reaction zone is small compared to the radius of curvature of the front, the time and length scales for the reaction zone are much smaller than those for the flow in the reaction products. The detonation wave can be approximated as quasi steady with the reaction zone equilibrating adiabatically to changes in the flow behind the wave. This quasi-steady approximation reduces the system of PDEs to a system of ODEs which represent the generalization of the ZND model equations to include the effect of geometry to first order in the ratio of the reaction zone width to the radius of curvature of the front. The quasi-steady equations have been used to determine the detonation speed of an undriven detonation wave as a function of front curvature. In this case, there is a sonic point within the reaction zone, and the flow is supersonic behind the detonation.

An algorithm called detonation shock dynamics accounts for the relationship between the velocity of an undriven detonation wave and the front curvature. A detonation front can be propagated using this method, but the state behind the wave needs to be set consistent with the conservation laws. The algorithm applies to the propagation of underdriven diverging detonation waves but not to overdriven detonation waves.

The quasi-steady approximation ODEs can be applied to obtain the state behind a detonation wave, and thus to determine the complete wave curve for detonations in converging and diverging geometry. In contrast to a planar detonation wave, a curved detonation wave satisfies modified jump conditions. These jump conditions are similar to the planar jump conditions but also contain terms involving the local curvature and the amount of each conserved quantity in the reaction zone. In addition, the width of the reaction zone comes into play. The jump conditions reduce to the planar jump conditions as the curvature goes to zero.

In this paper, we review the planar wave curve and the solution of to the quasi-steady model equations. Examples of typical detonation wave curves for both converging and diverging geometry are presented, and the wave structures that arise are discussed. We also describe the application of the modified jump conditions to numerical computations in the context of the front tracking method.