Interaction of a Condensed-Phase Explosive Detonation with a Compliant Boundary

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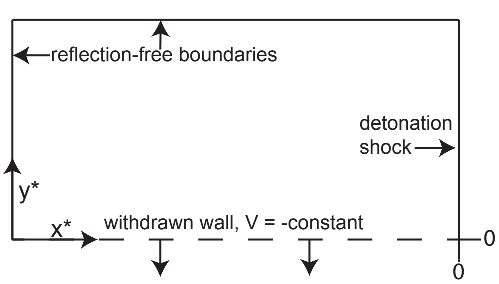
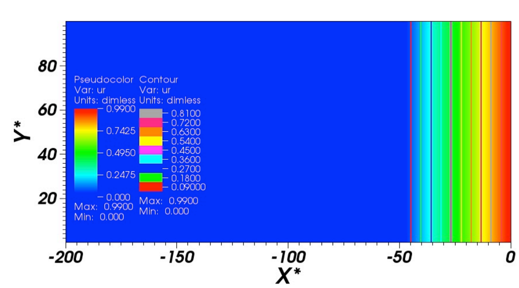
1 Introduction

At the 25th ICDERS, we presented a theory of detonation Mach reflection of a condensed-phase explosive detonation interacting with a rigid wall. In that situation, the oblique interaction of the detonation with the wall compresses and overdrives the detonation. We considered both the case of a Chapman-Jouguet (CJ), instantaneous reaction detonation and a small-resolved-heat-release (SRHR) reaction explosive detonation. In that paper, we showed that a classical Mach reflection structure, including an overdriven detonation Mach shock and a reflected shock, is observed for the case of CJ detonation. However, for the case of a SRHR detonation, the resolved heat-release zone acts to turn the streamlines such that at glancing incidence of the detonation with the wall, a reflected shock is not required to turn the flow. For the SRHR case, the overdriven detonation's lead shock is smooth from the wall through the region of the incident detonation, similar to what is observed in von Neumann Mach reflection. Our theory of glancing-incidence Mach reflection for both the CJ and SRHR detonation cases has recently been published [1]. Here we extend our work to the case of detonation propagating normal to a compliant material boundary (with the parameter tanA from [1] being, tanA = 0.0). Now the detonation compresses the boundary material, which causes the material interface to be deflected outwards, leading to a rarefaction propagating into the detonating explosive.

Here we model the interaction of the detonating explosive with the compliant wall by prescribing the deflection of the boundary between the explosive and the boundary materials. The problem geometry is displayed in Figure 1a), where we use a shock-attached coordinate system to describe the flow (the shock-attached x*-direction coordinate is set to zero at the shock). We impulsively withdraw the wall in the y-direction (downwards) at time $\tau > 0$ to simulate the deflection of the material interface (see Figure 1a)).



a)



b)

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Figure-1) The problem geometry described in terms of an x*-direction, shock-attached coordinate system, is displayed in subfigure a). The locus of the deflected detonation shock corresponds to x*=0 in this shock-attached frame. The initial data for the U-field (the x*-direction velocity, which behaves like a pressure variable) for the case of the SRHR detonation is displayed in subfigure b). For the CJ detonation, the reaction zone region in subfigure b), -50 < x* < 0, shrinks to zero thickness.

The initial state is taken as the CJ-supported steady-state detonation displayed in Figure 1b). We then follow the upward progress of the rarefaction generated by the withdrawal of the bottom boundary. Details on the derivation of the unsteady, transonic small-disturbance (UTSD) equations that we use to describe the CJ and SRHR detonations and the numerical algorithm we use to solve the UTSD equations are found in [1]. Here we replace the x*-direction solver in [1] with an appropriate upwind solver necessary to handle the supersonic flows that develop

$$\frac{1}{2}((\Xi^n_{x*})^2)_{x*} = \frac{1}{2(\Delta x*)^3}\Big(\Big(\max\big((\Xi^n_{i+1,j}-\Xi^n_{i,j}),0.0\big)\Big)^2 + \big(\min\big((\Xi^n_{i+2,j}-\Xi^n_{i+1,j}),0.0\big)\big)^2 - \big(\max\big((\Xi^n_{i,j}-\Xi^n_{i-1,j}),0.0\big)\big)^2 - \big(\min\big((\Xi^n_{i+1,j}-\Xi^n_{i,j}),0.0\big)\big)^2\Big)\,. \tag{1}$$

2 CJ Detonation

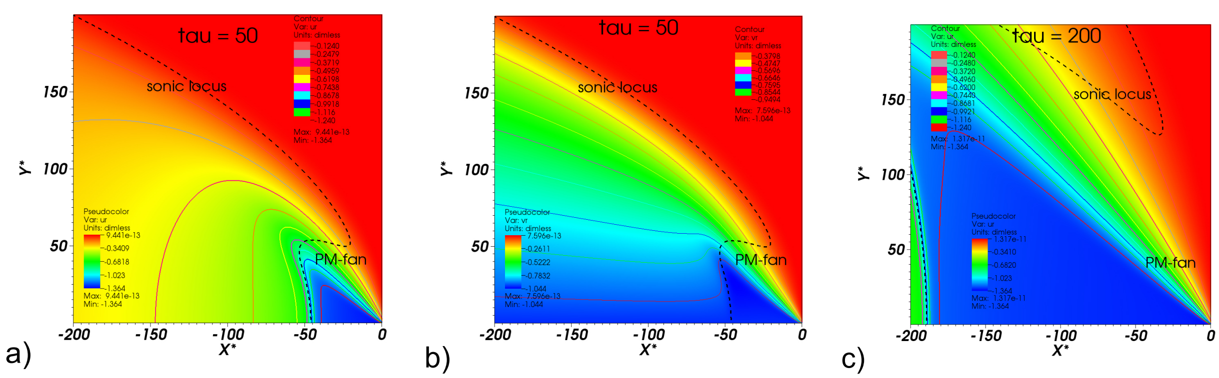
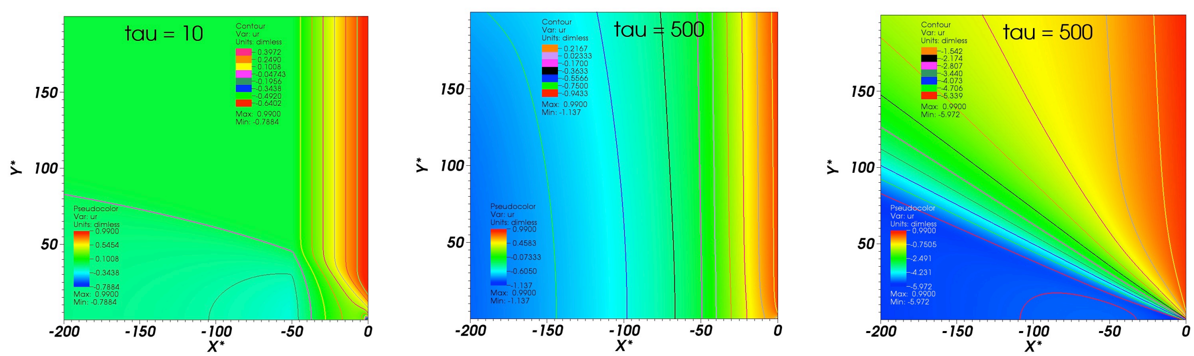


Figure-2) The U and V fields for the instantaneous reaction, CJ detonation model, for the case of V(y*=0) = -1.0. The U and V fields at τ = 50 are displayed in subfigures a) and b), respectively, while the U field at τ = 200 is displayed in subfigure c). The sonic locus is the black dashed line, with the flow being supersonic to the right of the sonic locus. The parameter values are those from [1] for the CJ case, and with tanA = 0.0.

Since the flow is sonic at the CJ detonation shock, we observe the emergence of a Prandtl-Meyer (PM) fan and constant state at the point where the detonation shock meets the bottom boundary. Displayed in Figure-2) are the U and V fields (the x* and y*-direction velocity fields in the shock-attached frame) and the sonic locus for this self-similar flow at τ = 50, and the U-field at τ = 200. The detonation shock remains undisturbed for the CJ detonation case. To connect to the boundary condition at the lower boundary, a supersonic region is observed to grow towards the left as τ increases, with more of the flow occupied by the PM-fan and constant state. The growth of the supersonic region is expected in this scale-free, self-similar problem.

3 SRHR Resolved Reaction Zone Detonation

As a consequence of the presence of a resolved reaction zone, the flow dynamics resulting from the withdrawal of the bottom boundary is changed. When the magnitude of the velocity of the lower boundary is increased to V(y*=0) = -10.0, the PM-singularity seen for the CJ-detonation case is again observed, at least at late times, τ = 500 (see Figure 3c)). However, unlike the CJ-detonation case, the detonation shock is strongly perturbed, with the pressure dropping along the lead shock (x* = 0) as one moves towards y* = 0.0. When the magnitude of the velocity of the lower boundary is decreased to V(y*=0) = -1.0, at early times, τ = 10, one sees the reaction zone being strongly perturbed by the rarefaction coming from the bottom boundary (see Figure 3a)). At late times, τ = 500, the flow near the intersection of the lead detonation shock and lower boundary is relatively smooth and does not show a prominent PM-singularity (see Figure 3b)).



a) b) c)

Figure-3) The U-field for the SRHR, resolved reaction zone detonation. The velocity of the bottom boundary is V(y*=0) = -1.0 in subfigures a) and b), with the magnitude of the velocity increasing to V(y*=0) = -10.0 in subfigure c). The pressure along the lead shock (x*=0) is perturbed by the boundary interaction. The late time flow, τ = 500, is reasonably smooth for V(y*=0) = -1.0, while it is singular when V(y*=0) = -10.0. The parameter values are those from [1] for the SRHR case, and with tanA = 0.0, k = 0.02 and ν = 0.5.

In our paper, we discuss the insensitivity of the CJ case to the value of V(y*=0) < 0.0 and the transitions in behavior we see for the SRHR case as the magnitude of V(y*=0) < 0.0 is changed. Details of the flow near x*=0, y*=0 will be discussed, as well as how the results for the UTSD theory results compare with the analogous Euler equation description of the flow.

References

[1] Bdzil JB, Short M. (2017), Theory of Mach reflection of detonation at glancing incidence., J. Fluid Mech. 811:269.