Ray-tracked Dynamics of Detonation Wave Fronts during Critical Diffraction

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1 Introduction

Diffraction of gaseous detonations at a sudden area change has persistently been a topic of interest, due to its practical importance in engine applications involving detonation transmission scenarios and also for detonation quenching purposes relevant to the industrial explosion mitigation. It can provide an unambiguous measure of the mixture detonability, since the critical tube diameter or channel size permitting successful transmission is uniquely defined for a given mixture and scales with the detonation reaction zone thickness. During the diffraction process, detonations are typically characterized by the events of local failure and re-initiation, which can either result in the successful transmission (supercritical regime) or complete quenching (sub-critical regime) of detonations depending on the initial thermodynamic conditions. Near the critical regime, non-steady events are usually observed, as reported in the recent experimental works [1,2]. While these stochastic events can control the stochasticity of the diffraction process, their relative importance in quantitatively affecting the detonation limits is not clear.

Nakayama et al. [3] have studied the dynamics of curved detonations propagating in curved channels. They have suggested that the dynamics can be uniquely described by a speed-curvature relation. Radulescu's group [4–6] have also isolated cellular detonations with constant mean curvature in exponentially diverging channels in order to establish the speed-mean curvature relationship. The maximum curvature data obtained from these analyses have been used to predict detonation failure in diffraction experiments quite successfully [2], although the quasi-steady assumption for the near-axis detonation dynamics was not verified experimentally. In the present study, we wish to establish the dynamics of diffracting detonations and comment on the relevance of a quasi-steady model to predict detonation critical diffraction criterion and the detonation front dynamics on and off-axis. In order to reconstruct the dynamics of the lead shock (speed, curvature and acceleration), we use our recently proposed curved ray-tracking method for building shock rays normal to the curved fronts, thereby permitting the easy access to extracting speeds and curvature of the fronts [7]. These new data thus permit to determine the relevance of a unique speed-curvature relation to the detonation diffraction problem.

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2 Detonation Dynamics during Critical Diffraction

The present work involves the authors' previously reported low-pressure experiments of $2H_2/O_2/2Ar$ detonations diffracting around a 90° corner with a sudden area change [1], which were conducted in a narrow channel with the height and depth of 203 mm and 19 mm, respectively. The exit slot before diffraction was 38 mm in height, and the whole evolution process was visualized by employing the high-speed schlieren technique. At each pressure condition, experiments were repeated 10 times for determining the probability of successful detonation transmission near the limit. One can also refer to the authors' work [1] for more details on these diffraction experiments. In the present study, we examined 10 repeated critical diffraction experiments performed at the initial pressure of 19.7 kPa (i.e., Exp#1–#10), with 10/10 successful transmission; below this pressure, the $2H_2/O_2/2Ar$ detonations cannot successfully transmit during the diffraction stage with 10/10 frequency and some of the experiments led to sub-critical outcome.

Regarding the 10 successfully transmitted diffraction experiments, we first digitally recorded the location of each detonation front in sequential frames. From these fronts, we then applied our recently proposed curved ray-tracking method [7] to construct a system of shock rays, which are the trajectories of a point normal to the leading shock [8]. It is worth noting that such a curved ray-tracking approach has been demonstrated to have a higher order of accuracy and much larger convergence rate than the traditional forward or backward straight-ray methods. One can refer to our recent work [7] for more details of the presently employed curved ray-tracking methodology for tracing the shock rays. Figure 1 shows examples of both the experimentally obtained diffracting detonation fronts (left column) and the digitally post-processed fronts with the tracked rays (right column). Although all the 10 experiments were conducted at the same initial pressure, stochastic elements can result in some different events during the diffraction stage. For example, one can readily recognize from the composite schlieren images of the four experiments in Fig. 1 the differences manifested in the extent and location of the local decoupling and re-initiation phenomena.

Along the built shock rays (i.e., Ray 0–3), we then evaluated the normal detonation speed with respect to time for all the 10 experiments, as shown in Fig. 2. The instantaneous velocity was averaged among three consecutive frames using the second-order differentiation method, i.e., $D(n) = \Delta x/\Delta t = (x[n+1] - x[n-1])/\,2\Delta t$, where x is the ray length, Δx the distance and Δt the time spacing between two neighbouring frames. From these velocity profiles, it is clear that the leading shock near the top wall decayed gradually, while those further away from the axis decoupled more rapidly as a result of the penetration of the expansion waves generated at the corner. This can also be qualitatively observed from the superimposed schlieren images in Fig. 1. For Ray 0 on the top wall, while in most of the experiments the detonation speeds decayed to about $0.8D_{CJ}$, minimum speed around $0.5D_{CJ}$ were measured in several experiments, suggesting a significant local decoupling of the leading shock from the trailing reaction front along the axis for these cases. For rays away from the top wall, i.e., Ray 1–3, the initial decrease and subsequent increase of the leading shock speeds signify the occurrence of local re-initiation events of detonations. Another interesting point to note is the time instant before the increase of the leading shock speeds. While the leading shock speed along Ray 1 begins to increase around 70 μs, such a re-acceleration takes place at about 60 μs and 80 μs for Ray 2 and Ray 3, respectively. It can thus be qualitatively inferred that the local re-initiation of detonations tend to initially occur in Zone B between Ray 1 and Ray 2, and that the re-initiation position appears to be more likely closer to Ray 2.

In addition to the detonation front speeds along the established rays, we further extracted the front curvature in each ray tube from the definition [8]

$$\kappa[n] = \frac{1}{A}\frac{dA}{dx} \approx \frac{1}{A[n]}\frac{A[n+1] - A[n-1]}{x[n+1] - x[n-1]} \tag{1}$$

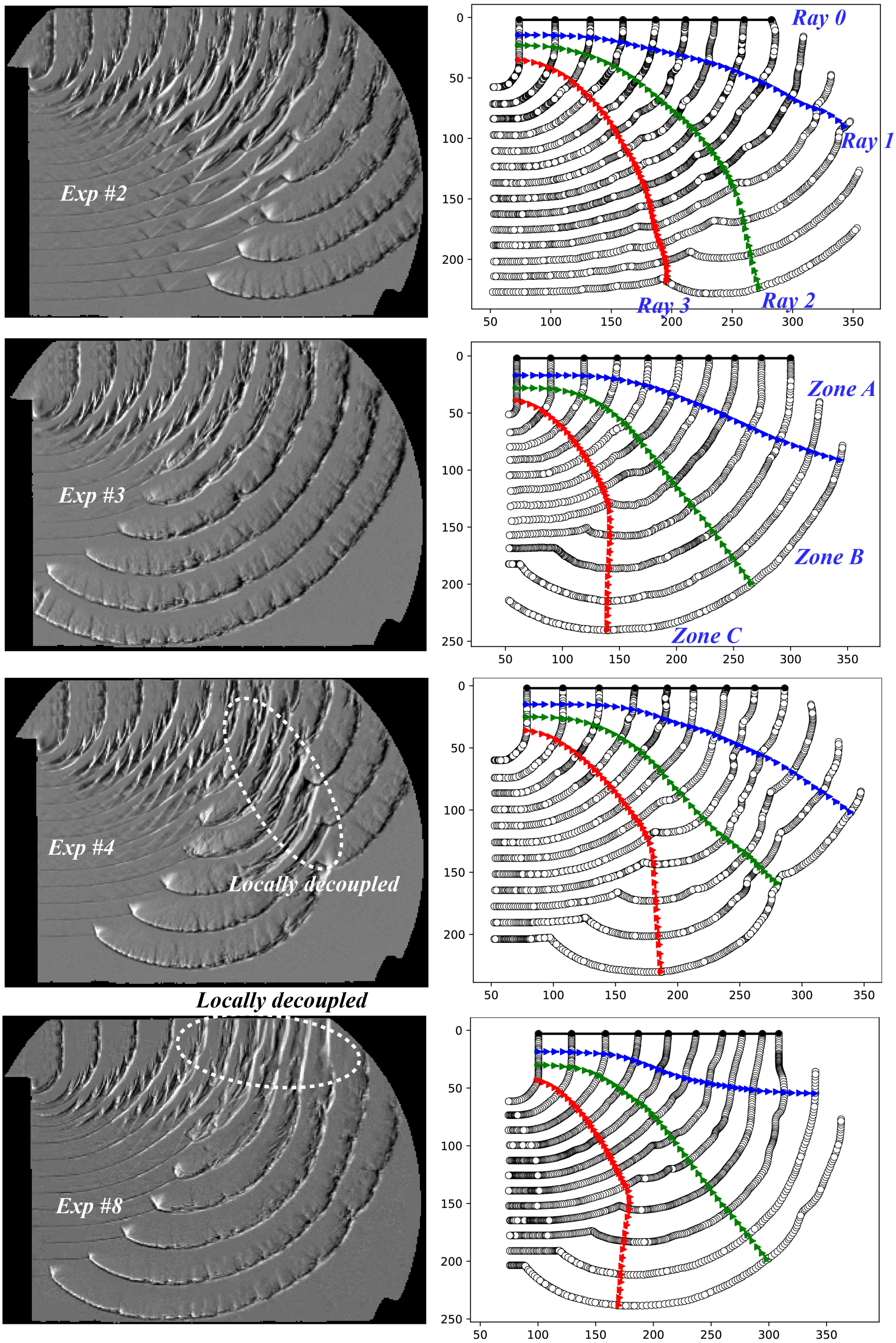

Figure 1: Examples of the superimposed $2H_2/O_2/2Ar$ detonation fronts during critical diffraction and the digitally post-processed rays. Note that the time interval between two successive detonation fronts is 12.9 μs.

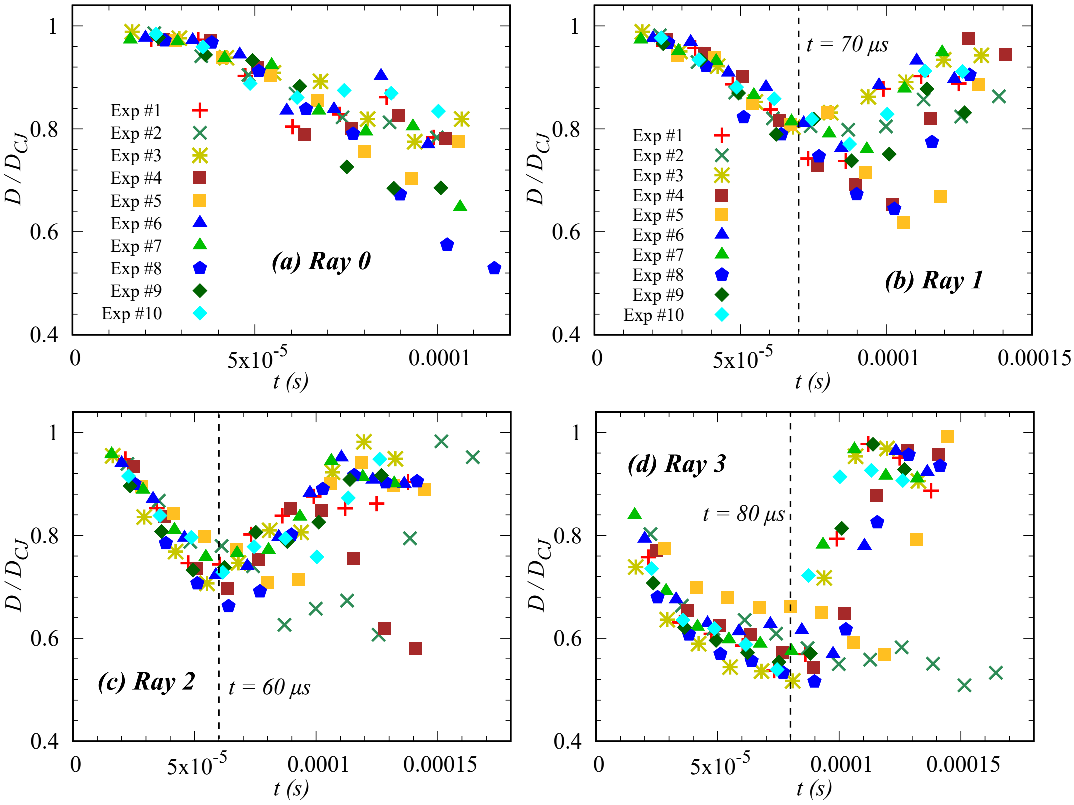

Figure 2: Evolution of detonation front speeds along different rays.

where A is the detonation front area in each ray tube between two neighbouring rays. Figure 3 shows the compiled curvature of the diffracting detonation fronts in each ray tube with respect to the ray length averaged among the two neighbouring rays. It is evident that the curvature of detonation fronts in both the ray tubes close to the axis (i.e., Zone A and B) shows the trend to increase first and then decrease. This is due to the weakening effect of the expansion waves in curving the diffracting detonation fronts and thus decreasing the propagation speeds. As such, the front curvature increases until the detonation is either locally quenched or re-initiated. While for those in Zone C, which is close to the sharp corner, the shock front curvature generally decreases in Fig. 3c. It is clear that the maximum curvature permitting the successful transmission of detonations in the present configuration is approximately 15–25 m^{-1}.

Finally, we compiled the detonation speed (obtained by averaging both the side rays in the corresponding ray tube), normalized by the Chapman-Jouguet (CJ) value, against the ZND detonation induction zone length (Δ_i) normalized curvature

$$\kappa_{eff}\Delta_i = (\kappa + \phi_{BL})\,\Delta_i \tag{2}$$

where κ_{eff} is the total curvature, including both contributions from the diffracting front area change and also from the boundary-layer effects. $\phi_{BL} = 5.5\ \mathrm{m}^{-1}$ is the boundary-layer-induced curvature in the present narrow channel, as measured by Xiao & Radulescu [5] for the same channel and mixture. These ray-tube-based characteristic $D/D_{CJ}-\kappa_{eff}\Delta_i$ relationships have been illustrated in Fig. 4. Also shown are the quasi-steady ramp experiments results of the detonation speed dependence on lateral strain rate measured by Xiao & Radulescu [5] for the same mixture, and the generalized ZND model predictions made using the detailed San Diego mechanism. The comparative results indicate that for the detonation segments in Zone A, their macro-scale dynamics generally follow those measured by Xiao & Radulescu [5] in the quasi-steady diverging detonation experiments, except for the parts involving the local decoupling events. While for Zone B and C, dynamics of detonations demonstrate much larger scatters

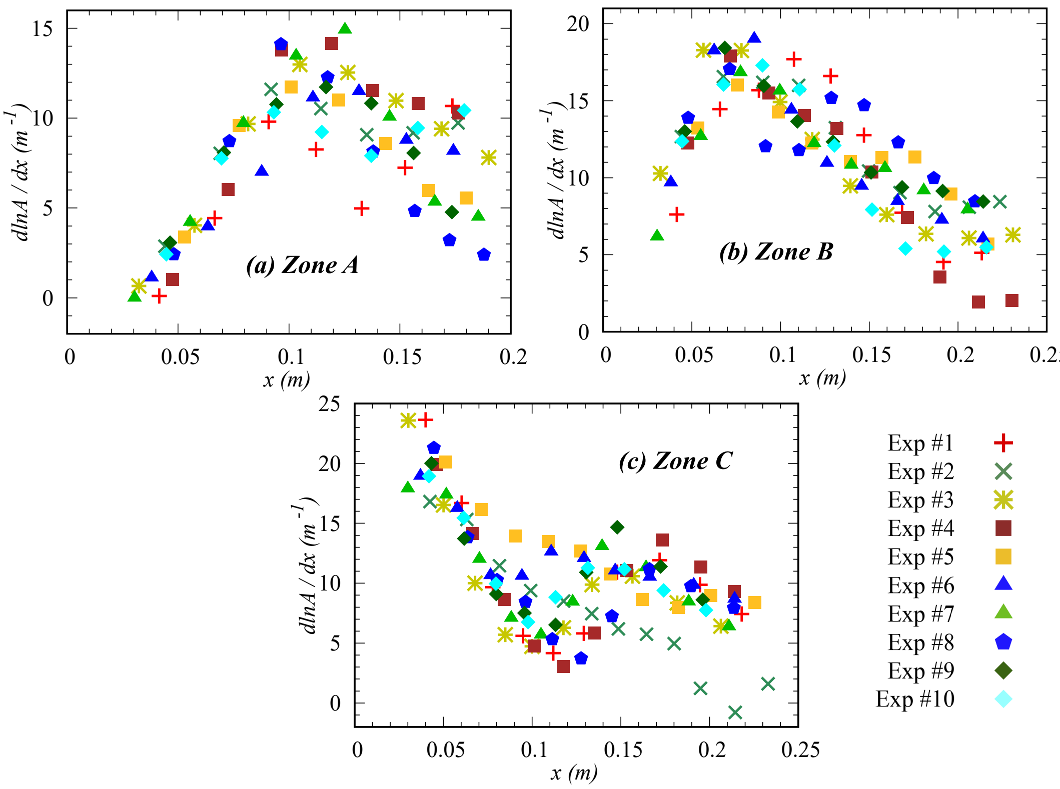

Figure 3: Evolution of detonation front curvature with respect to distance in each ray tube.

around the established quasi-steady ones due to the more prominent effects of detonation quenching and re-initiation. It is worth noting that the compiled diffracting detonation limits $(\kappa_{eff}\Delta_i)_{max}$ in Fig.4c appear to coincide well with the limiting range of the quasi-steady ramp experiments.

3 Conclusion

The present work revisited the detonation diffraction phenomenon from the $D-\kappa$ perspective. By applying the curved ray-tracking method to post-process the authors' previously reported critical diffraction experiments of hydrogen-oxygen-argon detonations, a system of shock rays was constructed and as a result, the detonation front normal speed along rays and also the front curvature in each ray tube were extracted. Analyses of these ray dynamics demonstrate the local events of re-initiating detonations more likely to occur in Zone B and the maximum curvature permitting the successful transmission to be 15–25 m^{-1} in the present configuration. The ray-tube-based $D(\kappa)$ relationships were compiled and shown to be in relatively good agreement with those established from the quasi-steady ramp experiments in terms of the macro-scale dynamics of detonations before failure. The local quenching and re-initiation elements appear to lead to large scatters of the dynamics with significant discrepancies from the quasi-steady description.

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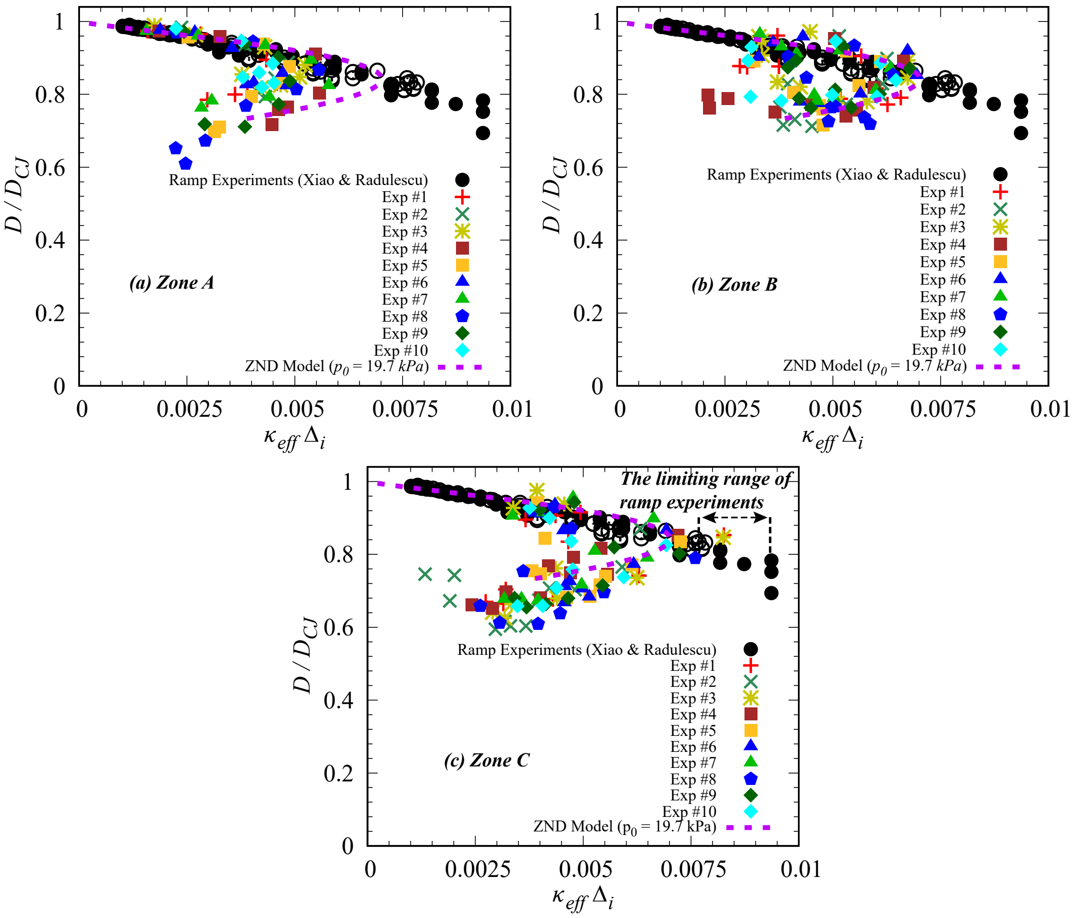

Figure 4: The ray-tube-based $D(\kappa)$ relationships of diffracting detonations in different regions, in comparison with those obtained from the quasi-steady ramp experiments [5] and the generalized ZND model.

References

[1] Mével R, Xiao Q, Radulescu M. Hydrogen-oxygen-argon detonation diffraction in a narrow channel. (2017) In 26th ICDERS.

[2] Zangene F, Xiao Q, Radulescu M. (2023). Critical diffraction of irregular structure detonations and their predictability from experimentally obtained $D - K$ data. Proc. Combust. Inst.

[3] Nakayama H, Kasahara J, Matsuo A, Funaki I. (2013). Front shock behavior of stable curved detonation waves in rectangular-cross-section curved channels. Proc. Combust. Inst. 34(2):1939-1947.

[4] Radulescu MI, Borzou B. Dynamics of detonations with a constant mean flow divergence. (2018). J. Fluid Mech. 845:346-377.

[5] Xiao Q, Radulescu MI. (2020). Dynamics of hydrogen–oxygen–argon cellular detonations with a constant mean lateral strain rate. Combust. Flame. 215:437-57.

[6] Xiao Q, Radulescu MI. (2020). Role of instability on the limits of laterally strained detonation waves. Combustion and Flame. Combust. Flame. 220:410-428.

[7] Xiao Q, Mével R, Gallier S, Radulescu MI. (2022). Ray-tracking methods for characterizing the dynamics of curved detonation. Phys. Fluids. 34(6):066104.

[8] Whitham GB. (2011). Linear and nonlinear waves. John Wiley & Sons.

[9] Radulescu MI, Mével R, Xiao Q, Gallier S. (2021). On the self-similarity of diffracting gaseous detonations and the critical channel width problem. Phys. Fluids. 33(6):066106.