Cellular Structure in an Oblique Detonation Wave

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1 Introduction

Initiation and stabilization of Oblique Detonation Waves (ODW) by conical bodies have been observed in supersonic flows of premixed combustible gas, with the oblique detonations exhibiting evidence of cellular structure in the wave fronts [1, 2]. Viguier et al. [3] were able to obtain experimental smoke foils recording the cellular structure of an ODW stabilized on a gasdynamic wedge driven by faster detonation in adjacent gas. The mechanism responsible for cellular structure in oblique detonations, and whether it is equivalent to cellular structure in normal detonations, has to be thoroughly investigated. In order to numerically simulate and properly resolve the structure and substructures (e.g. triple points, transverse waves, shock waves and slip lines) of a detonation, previous studies [4–6] have shown that a sufficient resolution is required. In the present work, numerical simulations of an ODW attached to a wedge are conducted. The purpose is to show a method to visualize the cellular pattern of the ODW structure. The obtained cellular structure is also compared to that of a normal detonation wave with an equivalent degree of overdrive. The ultimate goal is to determine whether the dynamic detonation parameters, such as the characteristic cell size, is the same for normal and oblique detonation waves.

The cellular structure of a normal detonation wave is presented as a schematic on the left-hand side of Fig. 1. For a standing normal detonation, there is an incoming freestream at the CJ velocity. One can imagine a smoke foil on the background translating in the same direction and at the same speed as the freestream and the illustrated cellular pattern would be obtained. The arrows refer to the relative velocity direction of two triple points. The left- and right-propagating waves can be differentiated from such a pattern. By applying the same concept to a standing ODW, the cellular pattern shown on the right-hand side of Fig. 1 would be obtained. In this case, the freestream velocity is larger than the CJ value. The black arrows correspond to the velocity direction of two triple points relative to each other, while the red arrows show their velocity direction relative to the non-moving wedge. One can see that the left- and right-propagating waves are swept away from the wedge tip by the tangential velocity component of the freestream. The cell size λ from this schematic is measured by the width of a cell, parallel to the detonation front.

2 Numerical model

The Amrita computational environment developed by James J. Quirk [7] is used to solve the reactive Euler equations in the numerical domain. The ideal gas assumption is used and the chemistry is modeled

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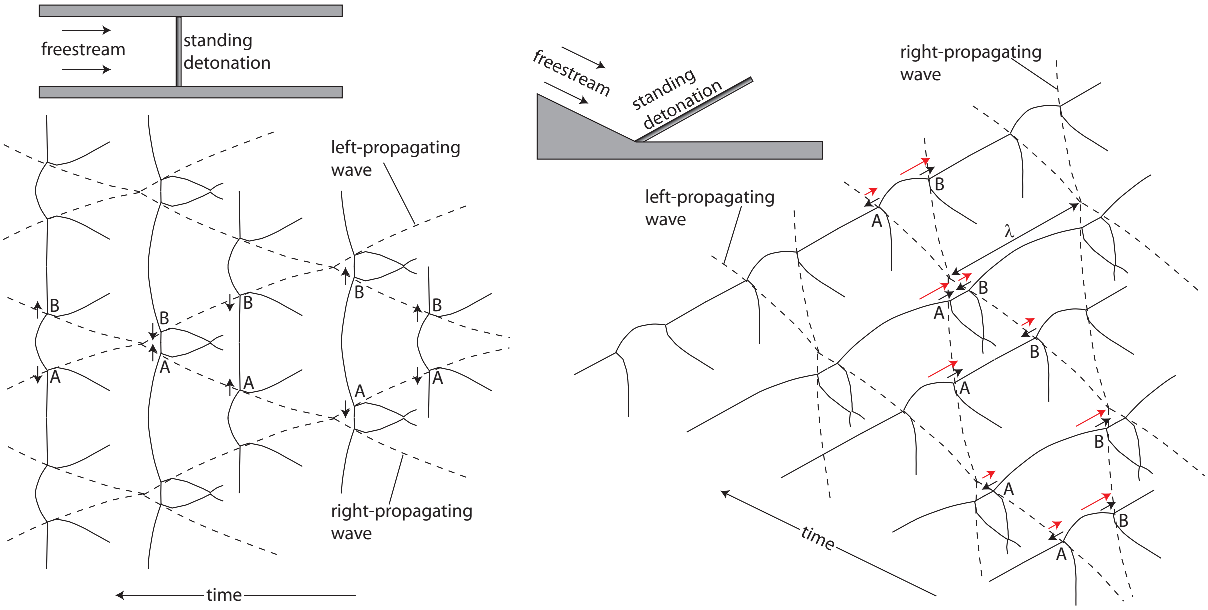

Figure 1: Schematic of the triple point trajectory in an ODW

with an irreversible one-step Arrhenius equation. Amrita employs a hierarchical system of mesh patches according to a mesh refinement scheme defined by the user. The coarsest mesh, which covers the entire numerical domain, is set such that there is one grid point per half-reaction length. Mesh refinement is automatically applied at the locations of steep gradient to correctly resolve the flowfield. The most refined grid level corresponds to 128 grid points per half-reaction length of a CJ detonation wave (Δ_{CJ}). The Lax-Friedrichs solver was used to evaluate the fluxes in the Euler equations. Figure 2 shows the numerical domain and the boundary conditions used in the simulations of ODWs initiated by a wedge. The width of the domain is 100 Δ_{CJ}. The flow conditions are normalized with the freestream pressure and density and are defined as:

$$p = 1, \quad \rho = 1, \quad u = 8, \quad \theta = 25^\circ, \quad Z = 0,$$

where p is the pressure, ρ is the density, u is the x-velocity component, θ is the wedge angle and Z is the reaction progress variable (the flow is in chemical equilibrium when $Z = 0$). In this study, the value of the specific heat ratio is $\gamma = 1.3$ and the non-dimensional parameters of the chemistry model are $Q = 10$ and $E = 30$. The complete numerical domain is initialized with the freestream values and the flow features evolve by marching in time. It can be shown that using the above flow conditions, the ODW angle is 40° with respect with the freestream flow direction. The normal velocity component is thus 5.14, providing a degree of overdrive of $d = (u_n/u_{CJ})^2 = 1.62$. Due to faster kinetics in an overdriven detonation, compared to a CJ detonation, the most refined grid level corresponds to 11 grid points per half-reaction lengths of the overdriven detonation (Δ_{OD}).

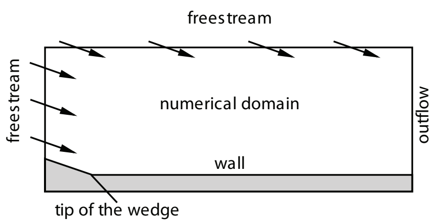

Figure 2: Numerical domain and boundary conditions

In the simulation of a normal detonation wave propagating in a rectangular channel, the flow is initial-

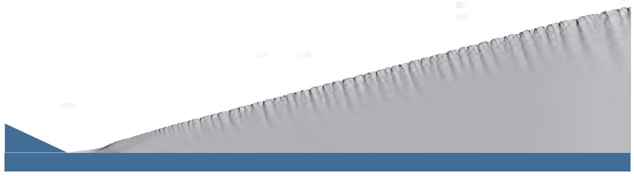

Figure 3: Pressure contours of an ODW attached to a 25° wedge

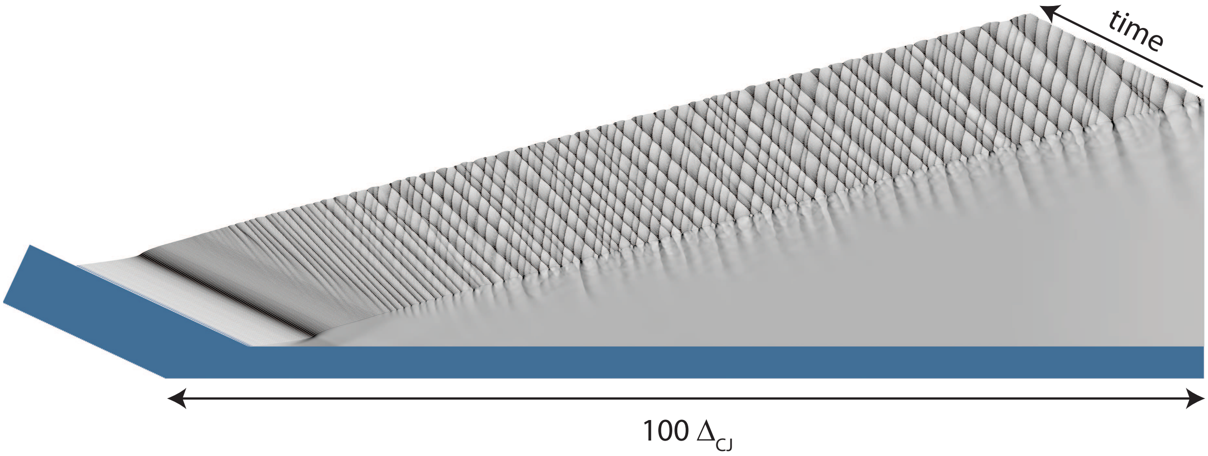

Figure 4: Numerical smoke foil of an ODW attached to a 25° wedge

ized by imposing ZND profiles near the left boundary. The unburnt gas is at rest and the detonation propagates from left to right with a degree of overdrive of 1.62. The height of the channel is 17.1 Δ_{CJ}. The finest grid level is in this case 16 grid points per Δ_{OD}.

3 Cellular structure of oblique and normal detonation waves

An example of an ODW initiated by a 25° wedge is shown in Fig. 3 with pressure contours. An oblique shock wave is attached at the tip of the wedge. Along the wedge surface, a reaction front is initiated a certain distance downstream of the tip. The reaction front eventually couples with the shock, sharply increasing the shock angle which triggers the onset of the ODW. The region between the tip of the wedge and the onset of the ODW is the induction zone. Instabilities along the ODW front, in the form of high-pressure spots, can be clearly observed to arise a certain distance from the end of the induction zone.

In order to visualize the evolution of the instabilities in time, a series of figures, corresponding to a known time sequence, can be superimposed and translated in a specific manner. The translation direction is opposite to that of the freestream, and the distance is given by the velocity of the freestream multiplied by the time interval between two figures. Such a representation is given in Fig. 4 where 100 frames were used between the times $t = 20.57$ and $t = 22.73$. By observation of the triple point trajectories, one can recognize two sets of pressure (or transverse) waves, thus forming a cellular structure. Near the induction zone, only the left-propagating waves are observed, while the right-propagating waves are initiated further downstream along the front. Both sets of transverse waves are swept away from the tip of the wedge. It can be observed that the cell size varies along the front. The smallest and largest cell sizes are respectively 0.62 and 2.1 Δ_{CJ}.

Figure 5 shows a numerical smoke foil of a normal detonation wave with a degree of overdrive of 1.62. The propagation is from left to right. At the early stage (near the left boundary), the cell size is irregular

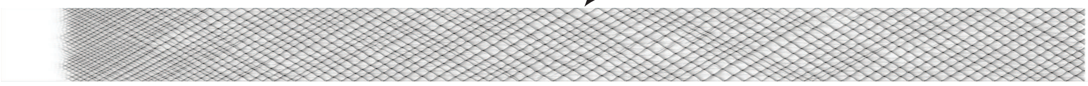

Figure 5: Numerical smoke foil of a normal detonation with a degree of overdrive of 1.62

and merging of transverse waves of the same family can be observed. The smallest cell size at the early stage is 0.55 Δ_{CJ}. Once the detonation has traveled more than 150 Δ_{CJ}, the cell size is more regular and 8 cells can be counted across the channel height, corresponding to a cell size of 2.1 Δ_{CJ}. The range of cell size for both cases (oblique and normal detonation waves) thus agrees very well, suggesting that the cellular structure of the ODW would become regular provided a wider numerical domain. Despite this agreement, a number of questions still need to be answered:

- Are the simulations sufficiently resolved to provide grid-independent cell size measurements?
- Is the velocity of the left- and right-propagating waves the same? In other words, are the cells symmetric or altered by the freestream tangential velocity?
- What is the mechanism that produces the observed instabilities? What is the cause for the left-propagating waves to be initiated earlier than the right-propagating waves?
- Are there flow conditions for which the left-propagating waves propagate towards the tip of the wedge and alter the general structure of the ODW?

4 Conclusion

Numerical simulations of an ODW attached on a wedge showed pressure instabilities along the detonation front. The evolution of the instabilities revealed a cellular pattern similar to that of a normal detonation wave. The cell size comparison between the two cases shows a good agreement at the early stage of the evolution. More simulations are required to obtain a regular ODW cellular structure.

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