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Formation mechanisms and characteristics of transition patterns in oblique detonations

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ABSTRACT

The transition structures of wedge-induced oblique detonation waves (ODWs) in high-enthalpy supersonic combustible mixtures are studied with two-dimensional reactive Euler simulations based on the open-source program AMROC (Adaptive Mesh Refinement in Object-oriented C++). The formation mechanisms of different transition patterns are investigated through theoretical analysis and numerical simulations. Results show that transition patterns of ODWs depend on the pressure ratio P_d/P_s, (P_d, P_s are the pressure behind the ODW and the pressure behind the induced shock, respectively). When $P_d/P_s > 1.3$, an abrupt transition occurs, while when $P_d/P_s < 1.3$, a smooth transition appears. A parameter ε is introduced to describe the transition patterns quantitatively. Besides, a criterion based on the velocity ratio $\Phi=U_0/U_{CJ}$ is proposed to predict the transition patterns based on the inflow conditions. It is concluded that an abrupt transition appears when $\Phi < 0.98\Phi^*$, while a smooth transition occurs when $\Phi > 1.02\Phi^*$ (Φ^* is the critical velocity ratio calculated with an empirical formula).

1. Introduction

The oblique detonation wave engine (ODWE) concept offers the potential for greater efficiency at higher Mach numbers [1–4] in comparison with the traditional scramjet. In the combustor of an ODWE, the oblique detonation wave (ODW) is initiated and stabilized by a wedge, and combustion occurs near the detonation wave front, which enables structure simplification and loss minimization of the engine. However, due to the complexity of ODW structure and the difficulty in performing experimental studies, there remain lots of challenges in the development of ODWE. It is still of great interest to conduct research on the basic structure of ODWs.

The ODWs are always classified based on the transition structure, i.e. smooth transition and abrupt transition, which are shown in Fig. 1.

In early studies, the ODW was usually simplified into a strong oblique shock with an instantaneous post-shock heat release. Until 1990s, Li et al. [5,6] investigated the structure of ODW and mentioned that the ODW structure consists of a non-reactive oblique shock, an induction zone, a set of deflagration waves and an oblique detonation wave. The transition from the non-reactive shock to the oblique detonation wave is achieved abruptly, and they are separated by a triple-point. Later, Broda [7] conducted experimental studies on ODWs and observed a smooth transition from oblique shock to oblique detonation. Vlasenko et al. [8] performed a numerical study on the wedge-induced ODW with an algorithm they developed and a smooth transition was also observed in their results. Viguier et al. [9] studied the structure of stable oblique detonations both numerically and experimentally. Their simulation results showed a good agreement with the overall flow structure observed experimentally, which is also consistent with that in Refs. [5,6]. Gui et al. [10] investigated the ODW with a Mach 7 inflow over a wedge of 30° turning angle numerically. According to their results, the ODW front is composed of oblique shock wave and oblique detonation when the wedge length is short. However, when the wedge is long enough, the flow field behind ODW is divided into three regions: ZND-model-like structure; single-sided, triple-point structure; and dual-headed, triple-point structure. Liu et al. [11] investigated the wedge-induced ODWs at low inflow Mach numbers via Rankine-Hugoniot analysis and numerical simulations. Their results showed that the strengthening influence of Chapman-Jouguet (CJ) detonation wave can lead to an upstream propagation of the ODW, and during this process, a Mach reflection wave configuration is always established on the wedge. Lately, Liu et al. [12] have made some further investigations on the structures of wedge-induced ODWs via the same method as Ref. [11]. In their numerical results, four configurations of CJ ODW reflection (overall Mach reflection, Mach reflection, regular reflection, and non-reflection) are observed to take place sequentially as the inflow Mach number increases,

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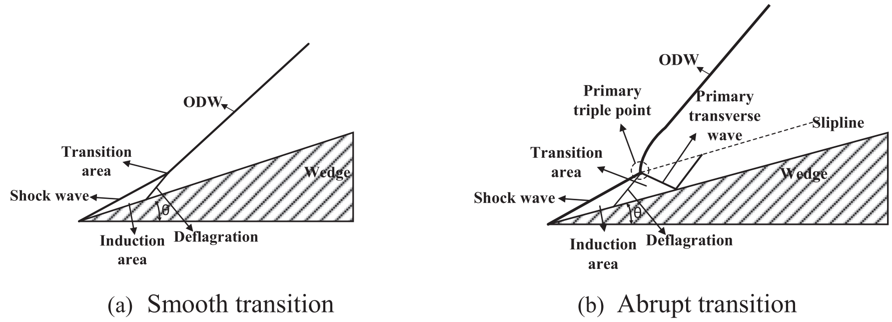

Fig. 1. Schematic diagram of ODWs with different transition structures.

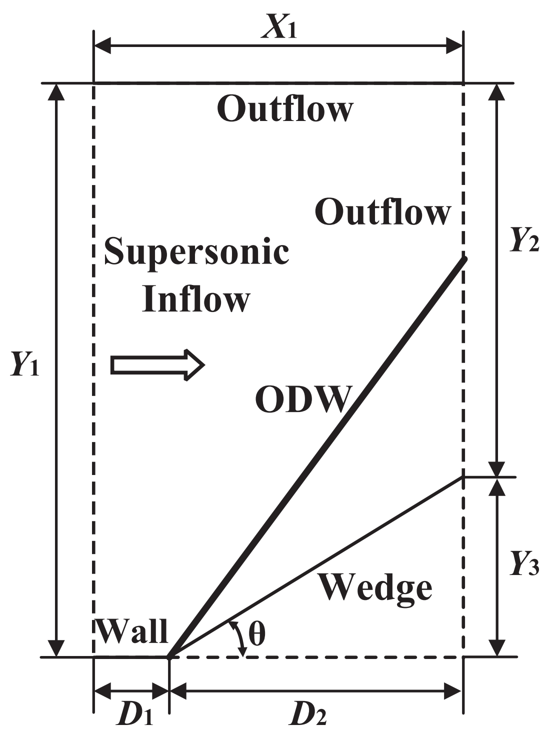

Fig. 2. The schematic of the calculation model.

and the change of the configuration results from the interaction among the ODW, the CJ ODW, and the centered expansion wave.

Recently, studies on transition patterns of ODWs have been specially conducted. Lefebvre and Fujiwara [13] simulated ODWs with different inflow Mach numbers and the effects of blunt body size on detonation structures were investigated. They argued that a smooth transition appears when the blunt body is large, while an abrupt transition forms under a small size of blunt body. Papalexandris et al. [14] observed the transition structures at different wedge angles, and the results showed that for moderate wedge angles the induced shock curves smoothly and for higher wedge angles an explosion occurs at the induced shock, leading to an abrupt transition. Teng et al. [15] studied the induction zone structures with different incident Mach numbers and three kinds of shock configurations, i.e., the λ-shaped shock, X-shaped shock and Y-shaped shock, were observed at the end of the induction zone. In the most recent research of Teng et al. [16], the initiation features of a wedge-induced ODW were investigated via numerical simulations. The effects of inflow pressure and Mach number on the initiation structure and length were studied. And the results demonstrated that the transition patterns strongly depend on the inflow Mach number, while the inflow pressure is found to have little effects on the transition type. Furthermore, a few quantitative investigations on the transition patterns have been conducted. Silva and Dashaies [17] may be the first to explore the criterion to predict the transition structures of ODWs. In their study, ODWs with different wedge angles, temperatures and pressures were investigated and the time ratio t_i/t_r was proposed for the estimation of transition patterns, where t_i and t_r are the induction time and the total reaction time, respectively. When $t_i/t_r \rightarrow 0$, the transition is abrupt and when $t_i/t_r \rightarrow 1$, it is smooth. However, the time ratio is a zero-dimensional scalar, it may not be convincing enough to describe a two-dimensional or three-dimensional phenomenon, and the wedge angle was not included in this criterion. Afterwards, Wang et al. [18] examined the existence or inexistence of the primary transverse wave in wedge-induced ODWs. A criterion associated with the ratio $\varphi = U_2/U_{CJ}$ was chosen to estimate the transition structures, where U_2 is the flow velocity behind the ODW and U_{CJ} is the CJ speed of the ODW. They indicated that when $\varphi < 1$, an abrupt transition occurs, and when $\varphi > 1$, a smooth transition forms. However, the formation mechanisms of different transition patterns were not explained in their paper and the ratio is not so convenient when applied to the prediction of transition patterns. Teng et al. [19] studied the transition structures numerically and a criterion based on the difference in the oblique shock angle and detonation angle was raised to predict the transition patterns. They suggested that a smooth transition appears when the angle difference is small, while an abrupt transition occurs when the angle difference is large. The shift between the two different transition patterns occurs when the angle difference is about $15^\circ - 18^\circ$. This criterion is considered to be more applicative for different cases. However, the formation mechanisms of different transition patterns are still not explained clearly.

In the present study, structures of the wedge-induced ODWs are systematically studied based on AMROC [20], which has been validated in multi-dimensional detonation simulations [21–23]. First, the numerical method is introduced and validated in Sections 2 and 3. And then, theoretical analysis and numerical simulations are conducted in Section 4.2 to explain the formation mechanisms of different transition patterns. In Section 4.3, a quantitative criterion is established to predict the transition patterns based on the inflow conditions.

2. Mathematical model and numerical method

2.1. Computational setup

The two-dimensional numerical simulations are conducted in a channel with a fixed wedge, as depicted in Fig. 2. The length and the height of the channel are $X_1 = 70$ mm and $Y_1 = 110$ mm, respectively. The wedge starts from $D_1 = 5$ mm.

The left boundary models the supersonic inflow, while the upper and right boundaries model the outflow. Reflecting boundaries with slip wall conditions are used on the lower boundary and the wedge. To mimic a realistic working condition, high-enthalpy supersonic combustible mixtures are selected. The premixed mixtures consist of hydrogen, oxygen and nitrogen with a mole ratio of $2 \times ER/1/3.76$, where ER is the equivalence ratio. To make a comparison and validation, a representative