Analogy between Wedge-induced Oblique Detonation and One-dimensional Piston-supported Detonation

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Introduction

Aerospace propulsion systems utilizing the characteristics of detonation waves are being watched with interest as the next generation systems [1-5]. The fundamental physics on the detonation has not been fully elucidated to design an optimized engine of the aerospace propulsion systems. Suppose that the detonation wave holder is inserted in the supersonic combustible flow, the characteristics of the ignition and stabilization of detonation wave are totally different from the self-sustained detonation waves usually observed in the experiments. One of the concepts on the detonation-based aerospace propulsion system is the utilization of the stabilized oblique detonation wave [2-5]. The combustion behind the leading shock wave could be sustained by the holders such as the wedge, and the oblique detonation wave is settled at the supersonic combustor.

The elucidation of an onset of the wedge-induced oblique detonation must be necessary for the development of the detonation-based aerospace propulsion system. In fact, the onset is strongly related with the wave structure of the wedge-induced oblique detonation [6, 7]. In the present study, the two-dimensional wave structures of oblique detonation are tried to understand by the one-dimensional piston-supported detonation wave structures, analogically. All consideration on the analogy is numerically carried out. Finding the analogy must be the great help for the understanding of the fundamental physics on the wedge-induced oblique detonation, and makes the cost less to predict the two-dimensional physics.

Computational Setup

The computational setup in the present study is the same procedure as that used in a previous study [8]. For the simulations of wedge-induced detonations, the grid around the wedge is clustered to wedge nose and a part that the reaction is stiff. The grid spacing of 10 or more points is maintained in the half-reaction length: $L_{1/2}$. For the simulations of piston-supported detonations, the grid spacing of uniform 100 points is prepared in $L_{1/2}$ in the whole grid.

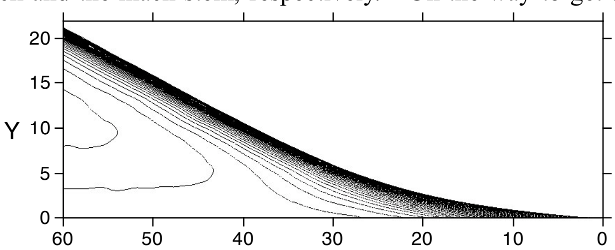
Table 1 denotes the parameter of main flow conditions of wedge-induced oblique detonation; the main flow speed U, the angle of the wedge θ, the activation energy E, and the heat release parameter Q. The frozen shock strength initiated by the piston is set to be the same as the frozen oblique shock strength by the wedge, because the growth of the detonation wave front at the early stage is focused for the analogy. The degree of normal overdrive, f_n, which is calculated by U, θ, E, and Q is shown in same table. Additionally, the degree of overdrive for the piston-supported detonation is indicated by f_p.

Table 1. Computational conditions: Main flow speed U, angle of wedge θ, activation energy E, heat release parameter Q.

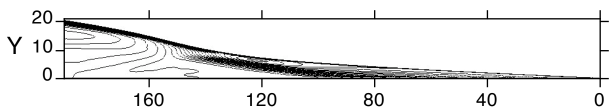
Case	U	θ(°)	E	Q	f_n	f_p
1	9.255	27	10	50	1.200	1.111
2	20.580	20	50	50	2.000	1.865
3	11.509	35	50	50	1.830	1.722
4	12.171	20	40	50	1.132	1.103

Result and Discussion

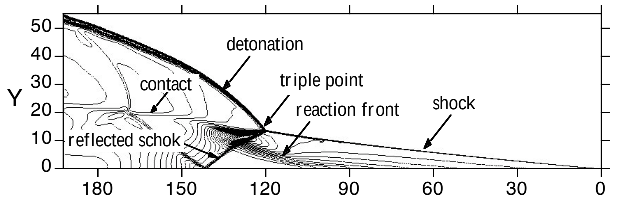
In a wedge-induced oblique detonation, a tip of the wedge initiates an oblique shock, and a reaction occurs behind the oblique shock. Subsequently, the reaction front interacts with the shock and finally develops into the oblique detonation. On the other hand, a piston, which moves at supersonic speed, generates a shock wave, and a reaction occurs behind the shock wave in a piston-supported detonation. The reaction wave soon catches up with the shock wave, and these waves develop into the detonation. As mentioned above, the basic wave components of a steady wedge-induced detonation are the same as those of an unsteady piston-supported detonation. A series of simulation results of the wedge-induced oblique detonation demonstrates four types (Type A-D) of wave structure in Figs. 1. Figures 2 show the *t-x* diagrams of the density distributions of the one-dimensional piston-supported detonation corresponding to the conditions in Figs. 1, as shown in Table 1. The *x* in Figs. 2 is the distance from the piston surface. The wave structure of each case in Figs. 1 is the same as the growing feature of the wave front in Figs. 2, except for Fig. 1c and Fig. 2c. In Type A (Figs. 1a and 2a), the shock wave always couples with the reaction front and smoothly develops into the oblique detonation. The wave structure in Type B (Figs. 1b, 2b, and 2c) are slightly different from that in type A, because the shock wave is decoupled with the reaction front at the early stage of the shock initiation. Near the tip of the wedge, the shock is essentially inert. The temperature increase across the oblique shock is small and the detonable gas reacts very slowly in the decoupling region. After the induction region, the reaction becomes rapidly. In Type D (Figs. 1d and 2d), the shock waves generate from the tip of the wedge and the piston surface. Subsequently, the reaction starts at the wedge and the piston surface, and expands gradually as an interior detonation. Eventually, the interior detonation penetrates the shock wave and becomes the detonation. Type C in Fig. 1c must be the unique feature in the two-dimensional flow, because the triple point is observed on the oblique shock. The oblique shock and the oblique detonation correspond to the incident shock and the mach stem, respectively. On the way to get the converged solution, the triple point and the reflected shock



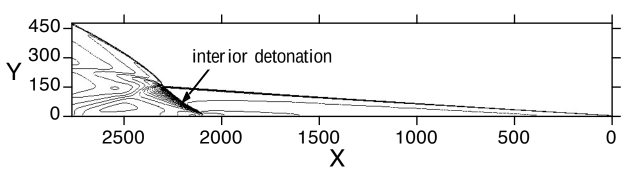
(a) U=9.255, □=27° , E=10, Q=50 (Type A)



(b) U=20.580, □=20° , E=50, Q=50 (Type B)

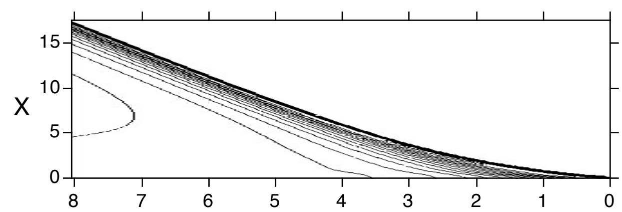


(c) U=11.509, □=35° , E=50, Q=50 (Type C)

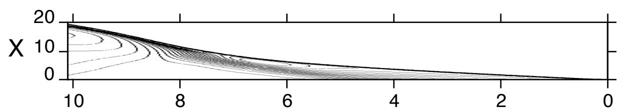


(d) U=12.171, □=20° , E=40, Q=50 (Type D)

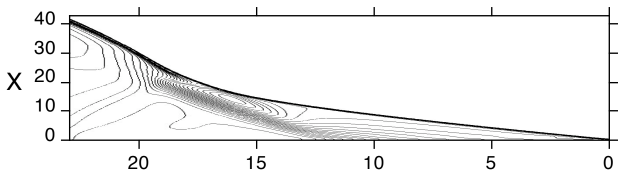
Fig. 1. Density distributions of the wedge-induced detonations. U ; incoming flow speed, □ ; wedge angle, E ; activation energy, Q ; heat release.



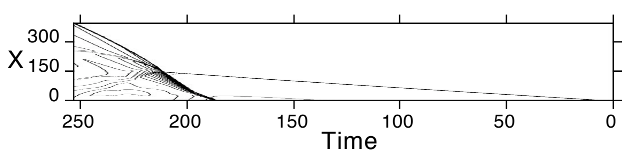
(a) f_p=1.111, E=10, Q=50 (Type A)



(b) f_p=1.865, E=50, Q=50 (Type B)



(c) f_p=1.722, E=50, Q=50 (Type B)



(d) f_p=1.103, E=40, Q=50 (Type D)

Fig. 2. *t-x* diagrams of density distributions of the one-dimensional piston-supported detonations. f_p ; degree of overdrive, E ; activation energy, Q ; heat release.

moves upstream, and finally settles down around x=120. This feature must be affected by the multi-dimensional effect and never happen in the one-dimensional flows. Therefore, Type B observed in one-dimension is supposed to be the necessary condition for the occurrence of Type C in two-dimension. In other words, the results of the piston-supported detonation indicate the possibility of the wave structure with the triple point in the wedge-induced oblique detonation.

In order to reveal the analogy between wedge-induced oblique detonation and one-dimensional piston-supported detonation, the reactant mass fraction history, the pressure history on the wall, and the shock pressure history of each case are shown in Fig 3. The time in the wedge-induced oblique detonation corresponds to the elapsed time of the flow along the wedge surface. In each case, the reactant mass fraction histories are almost the same between the wedge-induced oblique detonation and the one-dimensional piston-supported detonation. Therefore, the reactant mass fraction histories on the wedge surface can be predicted by the results of the piston-supported detonation. Types A and B have been treated as the same smooth structure in previous work [6]. In present study, Types A and B are regard as the different type because the separation of shock wave and the reaction front exists at the early stage in Type B. Furthermore, the reactant mass fraction of Type B does not decreases as smoothly as that of Type A. However, the pressure histories of the wedge-induced detonation qualitatively agree with those of the piston-supported detonation. Both of Type C and D are the abrupt structures having the connected point of the oblique shock wave and detonation. See the specific feature of pressure history of Type C (wedge) in Fig. 3c, the peak of the shock pressure corresponds to the triple point, and the peak of wall pressure does to the incidence of the reflection shock from the triple point. In Case 3, the pressure histories of wedge-induced detonation are quantitatively different from those of piston-supported detonation in Fig. 3c. On the other hand, in Case 4, the shock pressure histories of Type D are quantitatively agree between the wedge-induced detonation and the piston-supported detonation in Fig. 3d. The abrupt structure is caused by the penetration of the interior detonation, which is observed in the both case of the wedge-induced and the piston-supported detonation. The sudden peak of shock pressure histories corresponds to the penetration. The reactant mass fraction histories of Type D have a long induction time and decrease rapidly after the induction time. As mentioned above, the each type has the specific reaction progress. The wave structures of Type A, B, and D are dominated by the reaction progress that is affected by the shock strength.

The detailed investigation on the simulation results clarifies that the wave structure type is dominated by the reaction progress, which is represented by the profile of the reactant mass fraction on the wedge wall and the piston surface. The characteristic reaction time is considered in order to quantitatively indicate the variation of the reactant mass fraction behind the leading shock wave. See Fig. 4 with the following ideas, the time of intersection between the tangent line whose gradient is maximum on the reactant mass fraction history and the line of Z=1 is defined as induction time, t_i. The time of intersection between the tangent line and the line of Z=0 is defined as total reaction time, t_r. The non-dimensional characteristic value is defined by t_i/t_r, which represents the reaction intensity. Table 2 shows the characteristic value t_i/t_r

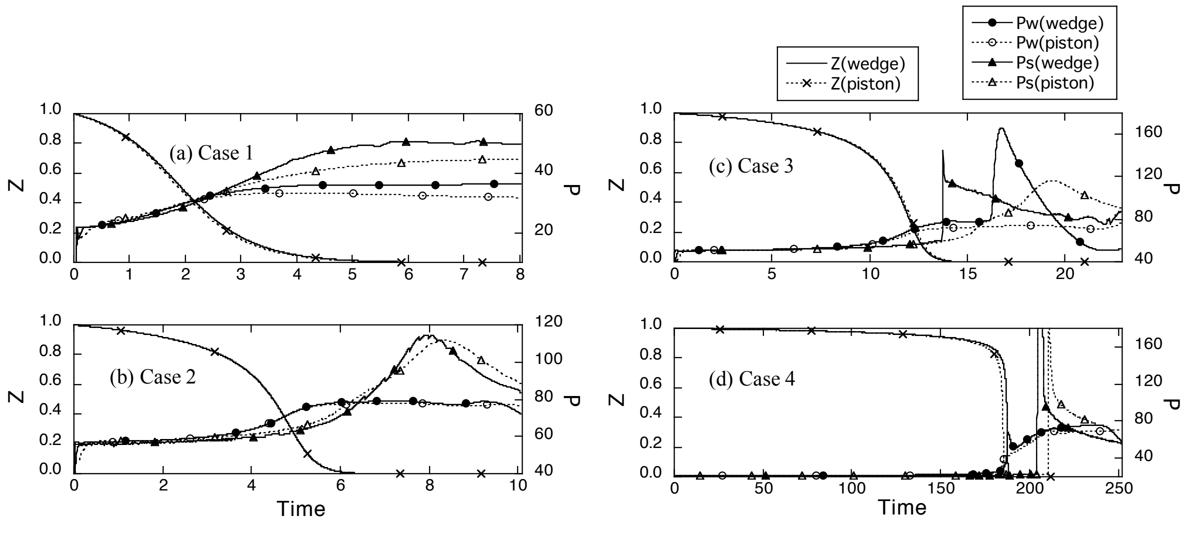


Fig. 3. Histories of the reactant mass fraction, the pressure on the wall, and the shock pressure.

on the wedge wall and the piston surface in all cases corresponding to the condition in Figs. 1 and 2. In each case in Figs. 3, the profiles of the reactant mass fraction on the piston surface are quantitatively the same as that on the wedge wall. A series of simulations of the one-dimensional piston-supported detonations varying an activation energy, a heat release, and a degree of overdrive were carried out in an attempt to understand a dominant parameter determining the wave structure. Figure 5 shows the relation between the degree of overdrive and t_i/t_r and the type of the wave structure of piston-supported detonations. The results clarify that the characteristic value dominates the wave structure in the one-dimensional piston-supported detonation and predicts the wave structure observed in the wedge-induced oblique detonation as follows; $t_i/t_r<0.4$ (Type A), $0.4<t_i/t_r<0.99$ (Type B or C), $0.99<t_i/t_r$ (Type D).

Summary

Analogy between the wedge-induced oblique detonation and the one-dimensional piston-supported detonation was investigated based on the present numerical results. The wave structures of the wedge-induced oblique detonation are basically the same as those of the piston-supported detonation, except for the wave structure having the triple point. Utilizing this analogy, *U* and □, which are the parameters of wedge-induce detonation, can be replaced with the piston speed, and the wave structure except for the wave structure having the triple point can be predicted. The characteristic value representing the reaction intensity dominates the wave structure in the one-dimensional piston-supported detonation. The reactant mass fraction history of the wedge-induced detonation is predicted by the results of the piston-supported detonation, which takes the lower cost than two-dimensional calculation.

Acknowledgements

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Table 2. Characteristic value.

Case	1	2	3	4
Wedge	0.212	0.648	0.758	0.993
Piston	0.210	0.649	0.756	0.992

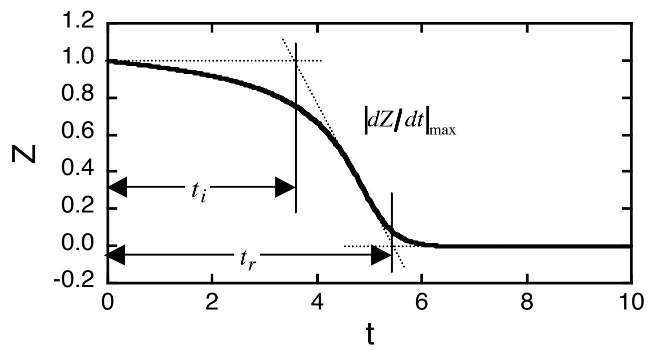

Fig. 4. Definition of the characteristic value.

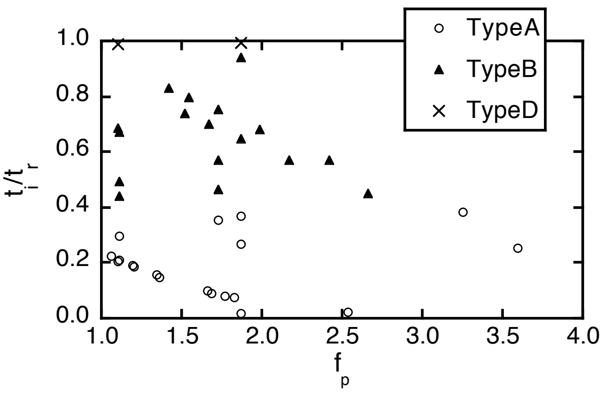

Fig. 5. Degree of overdrive vs the characteristic value.