On the Initiation Mechanism of One-Dimensional Piston Supported Detonations

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1 Introduction

Ballistic range experiments[1-3] in 1960s and 1970s revealed that the shock-induced combustion around the spherical projectile flying into the combustible gases has unsteady and periodic shock-reaction system. Those experiments show two oscillation modes[2,3] of reaction fronts: low amplitude and high frequency oscillations, "regular regime," and high amplitude and low frequency ones, "large-disturbance regime." Toong and co-authors[2,3] first proposed periodic instability mechanisms based on the experimental observation and one-dimensional wave interaction theory. Recently, computational fluid dynamics has been utilized to simulate the flow features of ballistic range experiments, and the mechanisms of the regular regime and the large-disturbance regime have been clarified by the CFD researches.[4-6] Matsuo and Fujii[4,5] have indicated that not the projectile velocity but the intensity of the concentration of the heat release is the essential factor to determine the unsteadiness, and they newly proposed the wave interaction model of the large-disturbance regime.

One-dimensional piston supported flows have been also investigated employing numerous theoretical and computational analyses to understand the unsteady detonation phenomena. These studies have provided us the insight into the unsteady structure of the ballistic range experiments. Fickett et al.[7] found these two oscillation modes in one-dimensional piston driven flows with a one-step irreversible reaction model. In the works of Sussman[6] the hydrogen-oxygen full chemistry is used for simulation, and the computed results show two modes by changing the degree of overdrive. Matsuo and Fujii[8] have indicated that the oscillation type did not depend on the intensity of the concentration of the heat release in contrast to the unsteadiness of the shock-induced combustion.

In almost all the previous studies of the one-dimensional piston supported detonation, a steady solution was used as initial conditions, and various waves reflected by the piston surface were neglected. In ballistic range experiments, the reflected waves play important roles in the periodic mechanism. From that point of view, the present investigation will be carried out to clarify an initiation process of piston supported detonation waves, taking into account of the reflected waves at the piston surface.

2 Computational Setup

The simulations are conducted using the one-dimensional Euler equations with the two-step chemistry model proposed by Korobeinikov.[9] Yee's non-MUSCL TVD upwind explicit scheme[10] is used as the numerical scheme. Coordinate frame moves at the same speed as a piston speed. For the high-resolution grid system, 8,001 points are provided in the whole computational domain. The computational condition is presented the same condition as in Lehr's experiments[1]: gas mixture $2H_2+O_2+3.76N_2$, pressure 0.421 atm, and temperature 293 K. The C-J detonation velocity, D_{CJ}, is 1938.3 m/s. The degree of overdrive, $f = (D/D_{CJ})^2$, was changed between 1.1 and 2.0 at intervals of 0.1 in the case of employing steady solutions as initial conditions (Steady Detonation, SD), and in the case of overdriving quiescent combustible gases by the piston, the degree of overdrive was fixed to 1.2 (Piston Initiation, PI).

3 Results and Discussion

3.1 Oscillations developed from steady detonations; SD

Figures 1(a) and 1(b) show the histories of the shock pressure for the degree of overdrive 2.0 and 1.4, respectively. Figure 1(a) shows the low amplitude and high frequency oscillations; the high frequency mode. The oscillation amplitude normalized by the shock pressure of the steady solution is about 0.25, and the oscillation period normalized by the induction time was approximately 1.5 for degree of overdrive between 1.6 and 2.0. For degree of overdrive between 1.1 and 1.5, the oscillations are high amplitude and low frequency, the low frequency mode, shown in Fig. 1(b). The normalized amplitude of the oscillations is 1.0-4.0, and the frequency of the oscillations is 7.0-25.0. These numerical results show that the oscillation mode depends on the degree of overdrive as well as the previous investigations[6-8].

3.2 Oscillation developed from piston initiation; PI

Figure 2 is the x-t diagram of the density gradient, and clearly shows the wave pattern in the whole computational domain for degree of overdrive 1.2. In Fig. 2, the shock is initiated by the piston at time 0.0 sec, and the reaction occurs at time 9.1μsec after induction time. The reaction front follows and overtakes the shock front at time 11.3μsec. After the overtaking point, the oscillations of the shock front gradually appear, and the period of the oscillations becomes longer and longer. A series of compression waves and contact discontinuities, which are released from the shock front, can be also seen in Fig. 2. Between time 14.0 and 27.5μsec, two kinds of oscillation modes are observed. Figures 3(a) and 3(b) are the close-up view of Fig. 2 and exhibit the density contour plots around the shock front. Figure 3(a) shows the typical wave interaction mechanism of the high frequency mode[4,5], and the period of the oscillations agrees with the values in Fig. 1(a). Shown in Fig. 3(b), the oscillations exhibit similar behavior to Fig. 1(b); the low frequency mode[4,5]. The mode-transition from the high frequency to the low frequency occurs under the constant degree of overdrive, although the unique oscillation mode is observed for a degree of overdrive in “SD.”

The history of the shock pressure is seen in Fig. 4 and explains the mode-transition from the high frequency mode to the low frequency mode. First, the pressure level is constant. After that, the shock pressure suddenly shows the peak, and it indicates that the reaction front overtakes the shock front. In domain (A) the high frequency mode is observed, and in domains (B-D) the low frequency mode is observed. In domains (A) and (C) the average pressure decreases, and in domains (B) and (D) the average pressure is constant; in domain (D) extremely unsteady oscillations are observed. Figure 5, the x-t diagram of the pressure gradient, indicates that in domains (A) and (C) rarefaction waves attenuate the leading shock, and the shock strength is gradually weakened. After the second incident rarefaction wave, the average pressure of “PI” (1.39 MPa) in domain (D) nearly corresponds to the post-shock pressure of “SD” (1.37 MPa, Pss) for degree of overdrive 1.2. The flow field of domain (D) resembles that of “SD,” too. Though the average pressure in “SD” is constant for each case, the local average pressure in “PI” decreases as a function of time in Fig. 4. This suggests that the mode-transition in “PI” is due to the decrease of the average pressure. Accordingly, the periods and the amplitudes of the oscillations are derived from the shock pressure history in Fig. 4 and are plotted in Fig 6(a) and 6(b) with those in “SD.” Here the plots of “SD” are computed values for degree of overdrive between 1.2 and 1.8, and are clearly divided into two oscillation modes around 1.75 MPa. The relations between the period and amplitude and the shock pressure in “PI” are well agreement with those in “SD”, except for the transitional zone between 1.6 to 1.8 MPa.

4 Summary

The initiation process of the piston supported detonation was successfully simulated, and two kinds of unsteady features were confirmed. The calculation started from the steady detonation indicated one oscillation mode against one degree of overdrive. The calculation started from overdriving quiescent combustible gases by the piston exhibited two oscillation modes responding to the shock pressure. That calculation also indicated that the relations between the local average pressure and the period and amplitude were well agreement with those of the oscillation developed from the steady detonation, except for the transitional zone.

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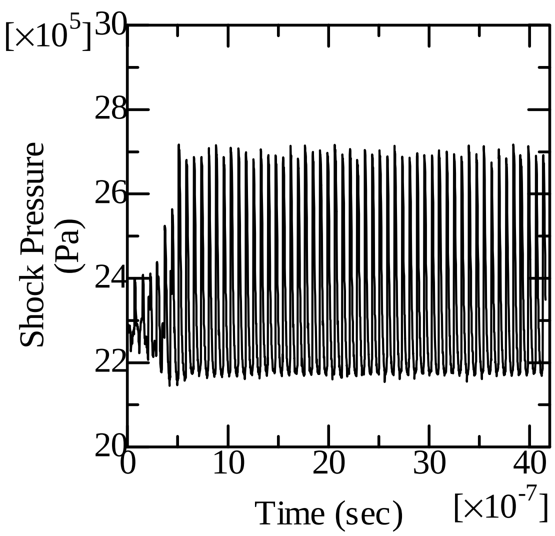
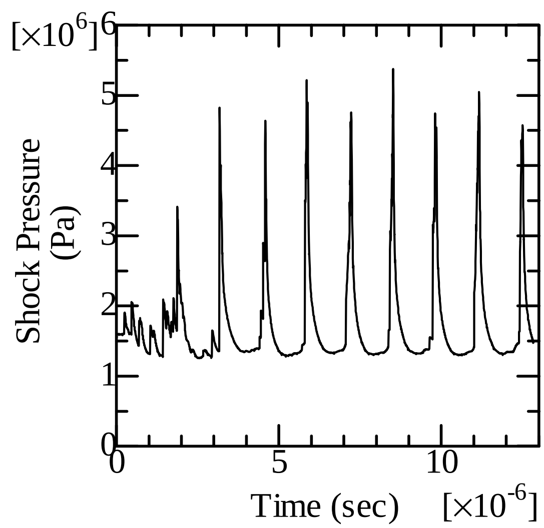


[×10^5]
Shock Pressure (Pa)
30
28
26
24
22
20
0
10
20
30
40
Time (sec)
[×10^-7]



[×10^6]
Shock Pressure (Pa)
6
5
4
3
2
1
0
0
5
10
Time (sec)
[×10^-6]

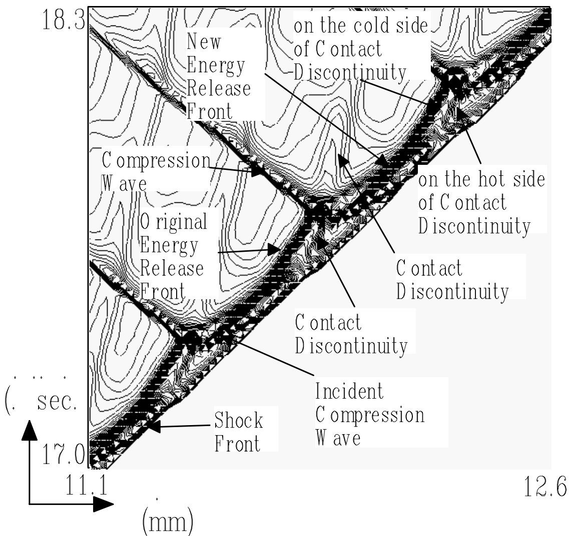


Fig. 3(a) X-t plot of density contour for high frequency mode.

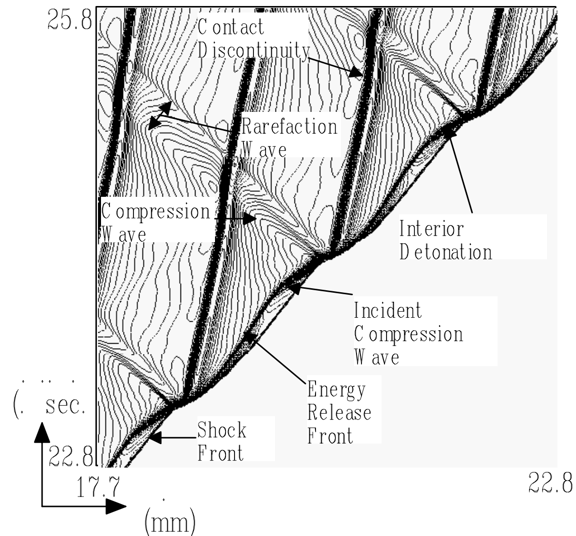


Fig. 3(b) X-t plot of density contour for low frequency mode.

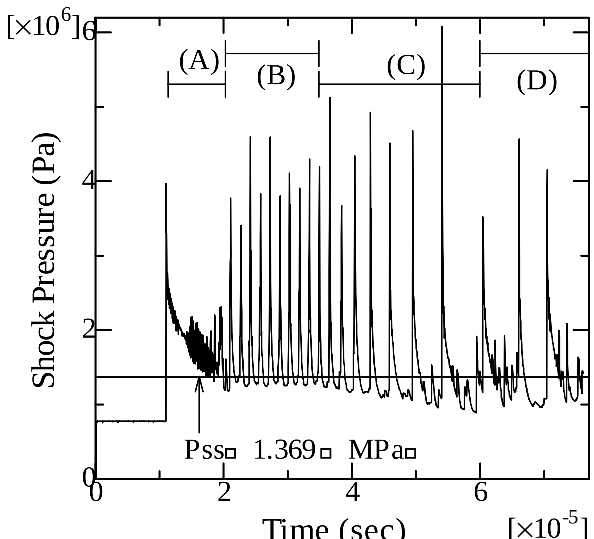


Fig. 4 Shock pressure history for degree of overdrive 1.2.

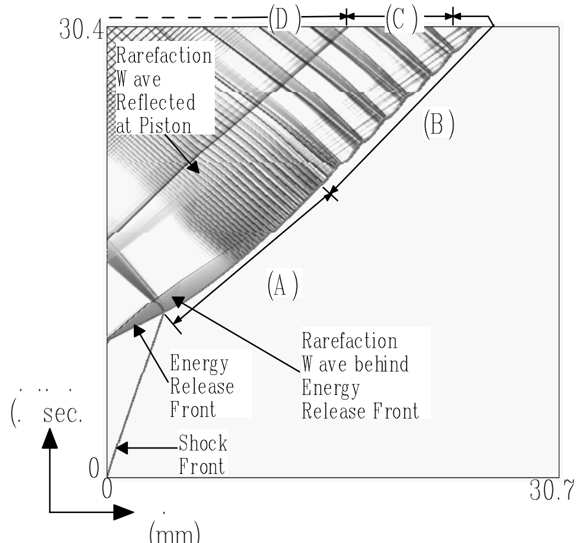


Fig. 5 X-t plot of pressure gradient for degree of overdrive 1.2.

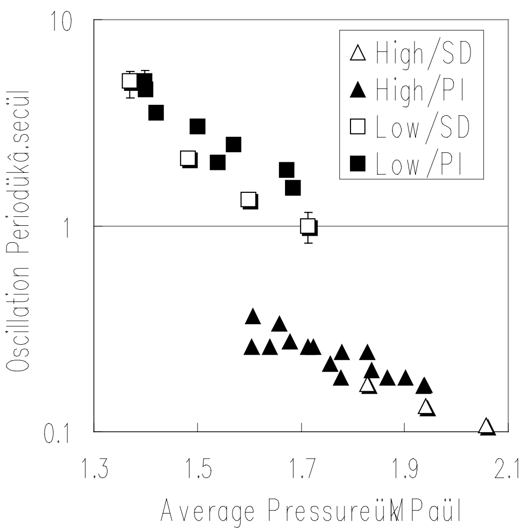


Fig. 6(a) Relation between oscillation period and shock average pressure.

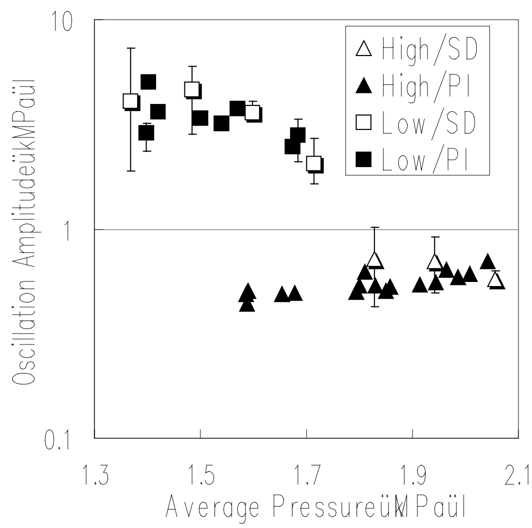


Fig. 6(b) Relation between oscillation amplitude and shock average pressure.