Control of oblique detonation wave in an unsteady inflow

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1 Introduction

Recently, there have been great interests in detonation engines that have promising applications in hypersonic propulsion [1]. Oblique detonation engine (ODE) is suitable for operating at high Mach number and thereby has been widely studied [2-6]. As the core of ODE, the morphological characteristics of the wedge-induced ODW have been widely investigated [2-4]. However, previous studies mainly focused on the steady-state structure of ODW while the flow and thermal states in a hypersonic propulsion system are usually unsteady. It is necessary to understand the evolution of the ODW in unsteady conditions [7] and to maintain stable ODW under unsteady inflows [8, 9].

There are some studies on the ODW structure affected by different disturbance types including inflow, mixture composition and thermal states. Fusina et al. [10] introduced small disturbance into mixture composition and found that the ODW is resilient to such transient disturbance. Yang et al. [11] studied the influence of single-pulse sinusoidal density/temperature disturbances on ODW structures and found that the ODW front can quickly returns to the original state when the single-pulse disturbance is over, which indicates the ODWs are relatively robustness to external, transient disturbances. Furthermore, using the dynamic mesh technique, Sun et al. [6] studied the ODW evolution under the changing wedge angles and results indicate the ODW position and structure can be effectively affected by adjusting the geometry configuration of combustion chamber.

To control the ODW in unsteady conditions, the magnetohydrodynamic technology with an ionized mixture and the novel wedge with a step or cavity have been proposed to stabilize the ODW locating in a certain region for different inflow Mach numbers [8, 9]. Their results indicate the ODW ignition position can be controlled to the designed location for a steady incoming flow, but the proposed regulation methods are invalid for the unsteady circumstances. It is necessary to develop more effective methods to ensure the ODW's optimum structure and position in unsteady conditions and broaden the ODE's operating boundary. Motivated by this point, a proportional-integral-differential (PID) control system [12] is proposed to regulate the ODW in this work. The two-dimensional simulations with detailed chemistry are conducted for wedge-induced ODW for a stoichiometric hydrogen/air mixture.

2 Numerical model and specifications

The compressible reactive flow solver, *detonationFoam* [6], is used to solve the governing equations. The finite volume method is used in the solver, in which the second-order MUSCL scheme [13] is

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adopted to reconstruct the face centered values from the body centered data and the modified Riemann solver, HLLC-P [14], is used to calculate the convection fluxes. The first-order implicit Euler scheme is used for time advance. Planar/cellular detonations have been simulated to prove the reliability of the solver in previous work [6].

The computational domain is chosen by referring to previous studies [6] and schematically described as the dotted rectangle in Fig. 1. The size of rectangle domain is -0.3 ⩽ x ⩽ 3 cm and 0 ⩽ x ⩽ 2 cm. Supersonic inflow condition is employed on the left boundary and the top boundary, and the flow parameters are fixed. The right boundary is model as the supersonic outflow. On the bottom boundary, the outflow condition is used in -0.3 ⩽ x ⩽ 0 cm to avoid the singularity at the wedge tip and the wedge surface (i.e., 0 ⩽ x ⩽ 3 cm) is simulated as the slip wall. In the simulations, the inflow parameters are specified according to the flight altitude (H_0 = 20 km) and flight Mach number (Ma_0 = 9). The airstream has been compressed the inlet and thus the inflow states are specified as P_0 = 196.3 kPa, T_0 = 814.4 K [4]. The inflow velocity, V_0, is set as 2660.8 m/s, which is slightly higher than the velocity (2481.9 m/s) given by Teng et al. [4] to move the auto-ignition position to the middle of the computational domain in Fig. 1. The ignition position, x_i, is defined as the maximum heat-release point on the wedge surface. The attack angle, θ_0, is set as 17º. The inflow is the stoichiometric H_2/air mixture and the detailed hydrogen reaction mechanism published by Burke et al. [15], including 13 species and 27 reactions, is used to describe the combustion process.

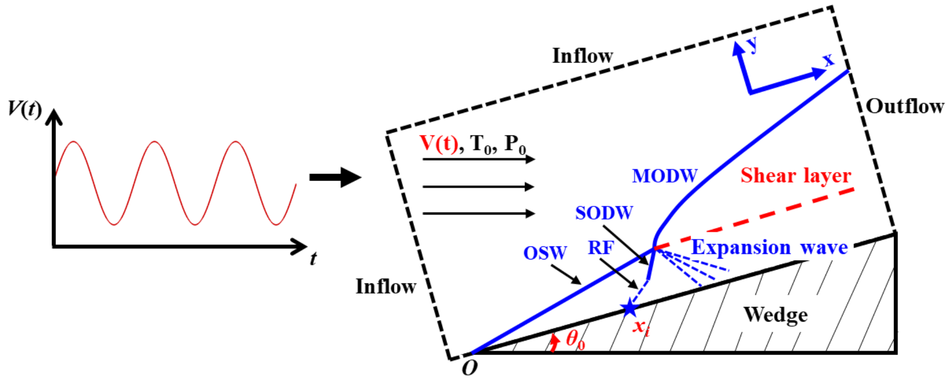

Figure 1. Schematic of wedge-induced ODW and simulation settings. OSW: oblique shock wave, RF: reaction front, SODW: secondary oblique detonation wave, MODW: main oblique detonation wave.

3 Results and discussion

3.1 The wedge-induced ODW regulation system

The schematic of wedge-induced ODW regulation system based on PID controller is described in Fig. 1. First, a target ignition position (x_t) can be preset as the regulation objective. The temperature sensors are arranged on the wedge surface to identify the actual ignition position (x_i). Then x_t and x_i are as the input parameters of the PID controller to calculate the wedge rotation angular velocity (ω). For approaching the target ignition position, the wedge will be rotated at the angular velocity, ω, to adjust the actual ignition position. It is supposed that the ODW structure can be stabilized in a relatively narrow area in unsteady inflows through this real-time regulation system. As Fig. 1 shows, the PID controller consists of the proportional controller, the integral controller and the derivative controller. The wedge rotation angular velocity ω is calculated by PID controller as:

$$\omega(t) = K_P\left(x_t - x_i\right) + K_I\int\left(x_t - x_i\right)dt + K_D\frac{d\left(x_t - x_i\right)}{dt} \tag{1}$$

where K_P, K_I, and K_D are the PID controller coefficients. In this work, $K_P = 10^7$, $K_I = 0$ and $K_D = 0$. ω is the input parameter of the combustion chamber which is the actuator in the regulation system. In this work, the dynamic mesh library provided by Jasak [16] is used to simulate the wedge rotation and the *movingWallVelocity* boundary condition is applied for the rotating wedge front. To reproduce more realistic inflow disturbances, the Perlin Noise [17] is used to generate the pseudorandom noise of the inflow velocity, and then the noise signal is fitted using eight sin functions. Hence, the results in this work are repeatable and the fitted disturbance is calculated as:

$$f(t) = \sum_{n=1}^{8} a_n \cdot \sin\left[\left(b_n \frac{t}{T_C} + c_n\right) + d_n\right] \quad (2)$$

where T_C is an adjustable parameter to adjust the disturbance frequency. a_n, b_n, c_n and d_n are the fitting coefficients and their values are in Tab. 1 in Appendix. The inflow velocity, $V(t)$, is calculated as:

$$V(t) = \left[1 + A \cdot f(t)\right] \cdot V_0 \quad (3)$$

where A is the adjustable parameter to adjust the disturbance amplitude is set as 10%.

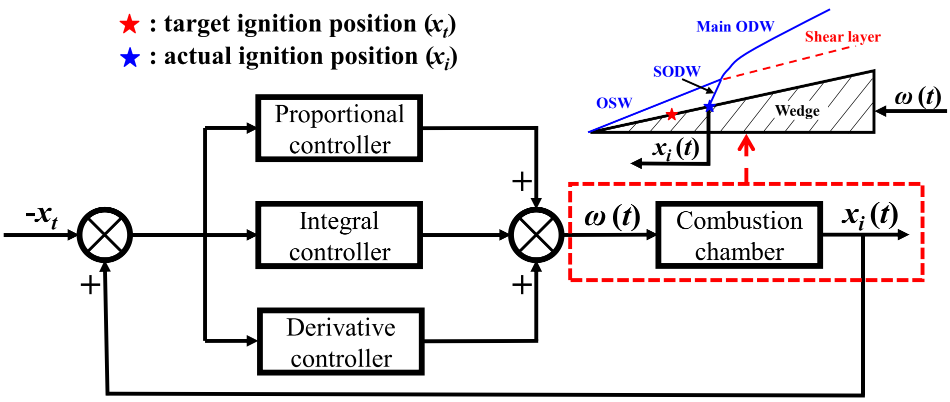

Figure 2. Schematic of wedge-induced ODW regulation system based on PID controller.

3.2 Regulation effects in unsteady flows

The pseudorandom noise frequency in the simulations is set to $T_C = 20$ μs and the steady-state ignition position corresponding to $V = V_0$ is chosen as the target ignition position and $x_t = 1.34$ cm. The inflow velocity varies with time is recorded in Fig. 3(a) and it oscillates randomly around V_0. Then the transient ODW structures under pseudorandom inflow with/without PID controller are numerically simulated and the actual ignition positions are recorded in Fig. 3(b). The blue line denotes the result of the case without PID controller and it oscillates sharply and the maximum error between x_t and x_i in the transient process is 0.77 cm. When the PID controller is applied (see the red line), the large-displacement oscillation of ignition position is almost inhibited. The maximum error between x_t and x_i is only 0.07 cm and the error is reduced by 90.9% compared with the result without PID controller. The probability density function (PDF) of x_i with/without PID controller are shown in Fig. 3(c) and the actual ignition position is mainly centered in the target position ($x_t = 1.34$ cm) when the PID controller is applied. The angle between the inflow and the wedge during the PID regulation process is recorded in Fig. 3(d) and it oscillates within 2°. Hence, a slight variation in wedge angle has an efficient control effect on ODW ignition position and this control method shall have a good practicability in applications.

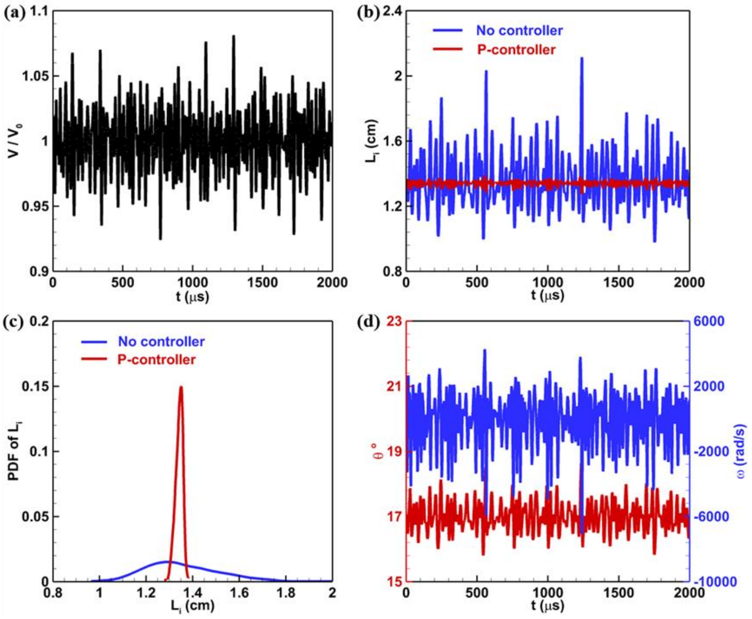

Fig. 3. (a) The temporal velocity variation in pseudorandom unsteady inflow with T_C = 20 μs; (b) the actual ignition position variation with/without PID-controller; (c) the probability density function of actual ignition positions with/without PID-controller and (d) the relative angle between the inflow and the wedge and the wedge rotational angular velocity during the regulation process.

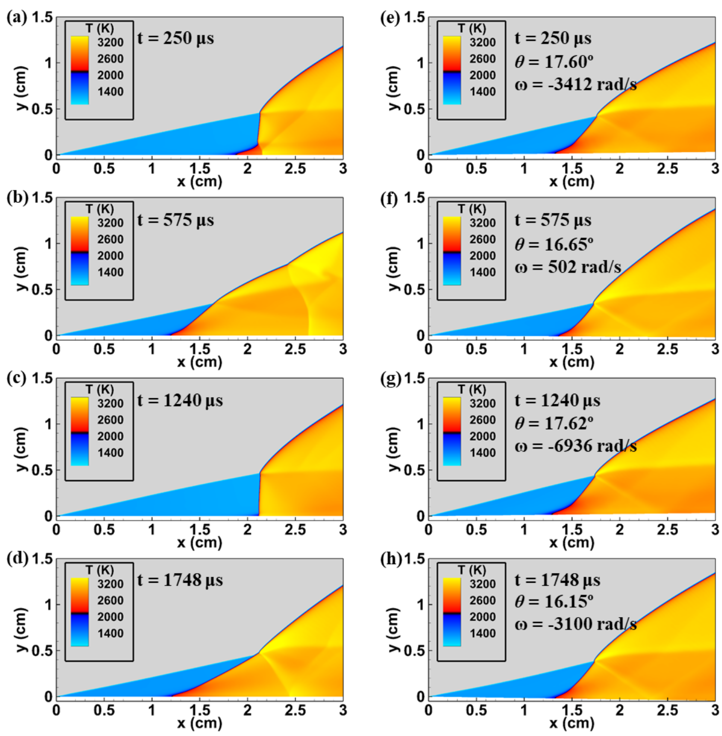

Figure 4. The temporal evolution of temperature contour in the pseudorandom unsteady inflow with T_C = 20 μs: (a)-(d) without controller and (e)-(h) with PID controller.

To further display the effects of PID controller on ODWs in the inflow with pseudorandom noise, the comparisons of temperature contours without (see Figs. 4a-d) and with controller (see Figs. 4e-h) are shown in Fig. 4. The ODW structures without controller changes drastically while the relatively stable ODW structures are acquired with the regulation effects of PID controller. From the results in Fig. 3 and Fig. 4, we can conclude that the great regulation effects of PID controller have been achieved for ODWs. This method can help to acquire a more stable ODW flow field and make the ODW ignition position always stay in the target region even for the unsteady inflows.

3.3 Discussion

The PID regulation system aims to reduce the error between the target ignition position and the actual ignition position and it is indeed independent of the origins of the error. Hence, the PID regulation system still can work on other unsteady operating situations and it is not limited to the case of unsteady velocity. With a fixed inflow velocity equaling to V_0, the inflow temperature and attack angle with an unsteady form can be expressed as:

$$T(t) = \left[1 + A \cdot f(t)\right] \cdot T_0 \tag{4}$$

$$\theta(t) = \left[1 + A \cdot f(t)\right] \cdot \theta_0 \tag{5}$$

where A is fixed to 10% and T_C is set as 20 μs. Figure 5 (a) shows the curves of ignition position x_i varies with time for temperature disturbance. The blue and red lines denote the results with and without PID controller, respectively. The maximum error between x_t and x_i is reduced from 0.94 cm (without controller) to 0.07 cm (with PID controller) and 92.6% reduction is achieved. Correspondingly, the evolutions of x_i for the attack angle disturbance are recorded in Fig. 5(b), the maximum error is reduced from 0.72 cm to 0.04 cm and decreased by 94.4% with the help of PID regulation system.

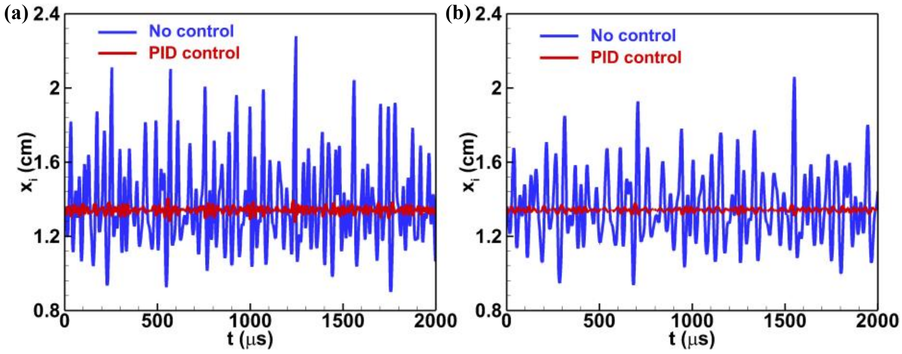

Fig. 5. The actual ignition position changes with time with/without PID controller in pseudorandom unsteady inflow for disturbance in (a) temperature and (b) attack angle.

4 Conclusions

In this work, two-dimensional simulations are conducted for wedge-induced ODW in a stoichiometric hydrogen/air mixture. The detailed chemistry for hydrogen is considered in all simulations. A regulation method based on PID controller is proposed to adjust the ODW so that the auto-ignition point is at fixed position in unsteady flow conditions. The pseudorandom disturbance is introduced using Perlin Noise function to mimic the unsteady inflow. The response characteristics of the regulation system for the inflow with velocity disturbance are examined. The results indicate that the auto-ignition position can be successfully adjusted to the target region. Meanwhile, the PID controller makes the ODW structure to remain relatively stable in the unsteady inflow. Furthermore, it is demonstrated that the regulation method based on PID controller works well in inflows with different types of disturbance including the temperature and attack angle perturbations.

Acknowledgements

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Appendix

Table 1: The coefficients in the fitting Eq. (2) used in this work.

n	1	2	3	4	5	6	7	8
a_n	0.01875	0.01608	0.009065	0.01057	0.01034	0.006862	0.009161	0.01189
b_n	2.796	3.539	4.688	5.188	1.571	5.752	2.038	3.201
c_n	0.2945	0.2945	0.2945	0.2945	0.2945	0.2945	0.2945	0.2945
d_n	0.6174	-1.138	-2.074	3.605	2.299	0.4858	-1.72	-3.844

References

[1] P. Wolański, Detonative propulsion, Proceedings of the Combustion Institute 34 (1) (2013) 125-158.
[2] Y. Liu, D. Wu, S. Yao, J. Wang, Analytical and numerical investigations of wedge-induced oblique detonation waves at low inflow Mach number, Combustion Science and Technology 187 (6) (2014) 843-856.
[3] Y. Liu, Y. S. Liu, D. Wu, J. P. Wang, Structure of an oblique detonation wave induced by a wedge, Shock Waves 26 (2) (2015) 161-168.
[4] H. Teng, C. Tian, Y. Zhang, L. Zhou, H. D. Ng, Morphology of oblique detonation waves in a stoichiometric hydrogen–air mixture, Journal of Fluid Mechanics 913 (2021).
[5] Z. Zhang, C. Wen, W. Zhang, Y. Liu, Z. Jiang, Formation of stabilized oblique detonation waves in a combustor, Combustion and Flame 223 (2021) 423-436.
[6] J. Sun, P. Yang, B. Tian, Z. Chen, Effects of wedge-angle change on the evolution of oblique detonation wave structure, Physics of Fluids 34 (9) (2022).
[7] Y. Liu, B. Xiao, L. Wang, C. Wang, Z. Ren, Numerical study of disturbance resistance of oblique detonation waves, International Journal of Aerospace Engineering 2020 (2020) 1-9.
[8] X.-H. Sun, Z.-H. Chen, H.-H. Zhang, MHD control of oblique detonation waves, Chinese Physics Letters 28 (1) (2011).
[9] Q. Qin, X. Zhang, A novel method for trigger location control of the oblique detonation wave by a modified wedge, Combustion and Flame 197 (2018) 65-77.
[10] G. Fusina, J. P. Sislian, B. Parent, Formation and stability of near Chapman-Jouguet standing oblique detonation waves, AIAA Journal 43 (7) (2005) 1591-1604.
[11] P. Yang, H. D. Ng, H. Teng, Numerical study of wedge-induced oblique detonations in unsteady flow, Journal of Fluid Mechanics 876 (2019) 264-287.
[12] A. Visioli, Practical PID control, Springer Science & Business Media 2006.
[13] B. v. L. M. Y. Hussaini, J. V. Rosendale, Upwind and high-resolution schemes, Springer 1997.
[14] W. Xie, R. Zhang, J. Lai, H. Li, An accurate and robust HLLC-type Riemann solver for the compressible Euler system at various Mach numbers, International Journal for Numerical Methods in Fluids 89 (10) (2018) 430-463.
[15] M. P. Burke, M. Chaos, Y. Ju, F. L. Dryer, S. J. Klippenstein, Comprehensive H_2/O_2 kinetic model for high-pressure combustion, International Journal of Chemical Kinetics 44 (7) (2012) 444-474.
[16] H. Jasak, Dynamic mesh handling in OpenFOAM, 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition, 2009.
[17] K. Perlin, An image synthesizer, ACM SIGGRAPH Computer Graphics 19 (3) (1985) 287-296.