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Spectral analysis and self-adjusting mechanism for oscillation phenomenon in hydrogen-oxygen continuously rotating detonation engine

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Abstract The continuously rotating detonation engine (CRDE) is a new concept of engines for aircraft and spacecraft. Quasi-stable continuously rotating detonation (CRD) can be observed in an annular combustion chamber, but the sustaining, stabilizing and adjusting mechanisms are not yet clear. To learn more deeply into the CRDE, experimental studies have been carried out to investigate hydrogen-oxygen CRDE. Pressure histories are obtained during each shot, which show that stable CRD waves are generated in the combustor, when feeding pressures are higher than 0.5 MPa for fuel and oxidizer, respectively. Each shot can keep running as long as fresh gas feeding maintains. Close-up of the pressure history shows the repeatability of pressure peaks and indicates the detonation velocity in hydrogen–oxygen CRD, which proves the success of forming a stable CRD in the annular chamber. Spectrum of the pressure history matches the close-up analysis and confirms the CRD. It also shows multi-wave phenomenon and affirms the fact that in this case a single detonation wave is rotating in the annulus. Moreover, oscillation phenomenon is found in pressure peaks and a self-adjusting mechanism is proposed to explain the phenomenon.
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1. Introduction

The heat releasing process in detonation is nearly isochoric. The isochoric Humphrey cycle has inherently higher thermodynamic efficiency than the isobaric Brayton cycle of deflagration, which is now widely used in engine combustion. When the compression ratio is 12, the thermal efficiency of Humphrey cycle is 18% to 37% higher than Brayton cycle in the combustion of hydrogen–oxygen mixture,[1] and 20% to

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40% higher in the combustion of hydrocarbon–air mixture.[2] In addition, according to Wolański,[3] Fickett-Jacobs cycle for heat addition in detonation mode can reach even higher thermal efficiency than Humphrey cycle. Therefore, it is believed that engines based on detonation have a bright future, and pulse detonation engines (PDEs) have been studied for decades. On the other hand, in recent years, continuously rotating detonation engines (CRDEs) have become a new hot point in detonative propulsion.

The basic concept of CRDEs was first proposed by Voitsekhoviskii,[4] and he experimentally achieved short-lived continuous detonation fuelled by acetylene. In recent years, CRDE has been extensively studied both numerically and experimentally. Kindracki et al.[5] have experimentally obtained promising thrust performances. During the past few years, Innovative Scientific Solutions Inc.,[6] Air Force Research Laboratory,[7] and several other organizations have been making effort to visualize CRDEs. Multi-waves mode in a continuously rotating detonation wave (CRDW) is found and studied by Bykovskii et al.[8] and Liu et al.,[9] individually. Wang et al.[10] found that when there are both axial flow from the head end of the combustor and tangential flow from the pre-detonator after deflagration to detonation transition (DDT), CRDW will split into a main detonation wave and several detonation wavelets, and lead to much lower velocity of the CRDW.

Besides of experimental research, many numerical simulations of the CRDWs are carried out. Shao et al.[11–13] performed comprehensive three-dimensional numerical simulations in CRDWs. They obtained multi-cycles of CRDWs and discussed several key issues, including the fuel injection limit, self-ignition, thrust performance and nozzle effects. Yamada et al.[14] numerically analyzed the propagation limit in hydrogen-oxygen rotating detonation and obtained its lower and upper threshold pressure. Schwer and Kailasanath[15] numerically studied the role of inlet stagnation pressure and back pressure on the rotating detonation characteristics and engine performance, and found that the detonation wave height and mass flow rate are determined primarily by the stagnation pressure, whereas overall performance is closely tied to pressure ratio.

Zhou and Wang[16] numerically studied the thermodynamic performance, showing that in a two-dimensional CRDE without a nozzle, inside of which 23.6% fuel is burned by deflagration and the thermal efficiency is around 39.7%. As the proportion of detonation combustion increases and a nozzle is attached at the exit, the thermal efficiency will be close to the ideal ZND (Zeldovich-von Neumann-Döring) model, which is 52.9%, theoretically. Frolov et al.[17] did the numerical simulation with effects of finite rates of turbulent and molecular mixing among combustible mixture components with each other and with reaction and detonation products. Liu et al.[18] firstly found multi-wave mode in numerical simulation with different injection patterns.

The previous experimental studies on continuously rotating detonations (CRDs) mostly concentrate on generating a stable CRD under various conditions and with different fuel-oxidizer combinations, or even to generate thrust for applications. Only a few studies have been done to investigate the mechanism and stability of the CRD. In the present study, we find the pressure oscillation phenomenon and try to give a reasonable explanation. Therefore, this study takes a further step into the mechanism of how a CRD keeps stable.

2. Experimental setup

2.1. Basic model

The combustion chamber of a CRDE is an annular chamber. A brief model is shown in Fig. 1. As fresh reactants are fed in at the head end, and the products exhaust out from the exit, a detonation wave keeps propagating circumferentially right against the head end. In front of the detonation wave, there is an area filled with fresh reactants, while behind the detonation wave are the products. Downstream inside the chamber, there are contact surfaces, oblique shock wave, and expansion waves, which enhance the ejection of the detonation products.

It is known from numerical simulations[12] that there is a region right behind the detonation wave, where the pressure reaches very high values. Since the fresh reactants-feeding is driven by pressure difference, the high pressure inside the chamber stops the feeding in that region. It is instinct that a stronger detonation wave ends up with higher pressure behind wave front, and would lead to a larger non-feeding region. And this may have a significant effect on the rotating detonation.

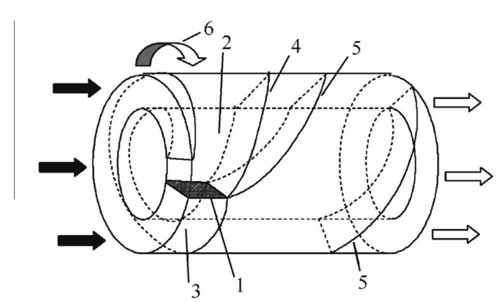
2.2. Experimental facilities

The entire experimental setup is shown in Figs. 2–4, including gas supplying system, combustion chamber, igniting system, exhausting system, and data collecting system.

It is designed to use hydrogen as fuel and oxygen as oxidizer. The fuel-oxidizer combination is chosen for its simple chemical model in combustion, easy-operating, and safe guarantee. Hydrogen is more active than most hydrocarbon fuels, and less reactive than ethylene, which provides a good balance between safety and easiness to generate a detonation wave. Designed as a rocket type engine rather than an air-breathing one makes the oxygen a direct choice.

The CRDE combustion chamber used in this study is an annular chamber with outer diameter 79 mm, inner diameter 59 mm, and length 100 mm. Pre-mixed fuel and oxidizer are fed into the combustor at the head end. A detonation wave propagates circumferentially in the annulus at the head end, while the burnt gas exhausts out of the chamber at the downstream exit.

The pre-mixed detonable gas in the main combustor is ignited by a pre-detonator connected to the combustor cylinder tangentially. The pre-detonator is also filled with hydrogen



1—Detonation wave; 2—Products ; 3—Fresh detonable mixture;
4—Contact surface; 5—Oblique shock;
6—Propagating direction of the detonation wave

Fig. 1 Model of a CRDE.

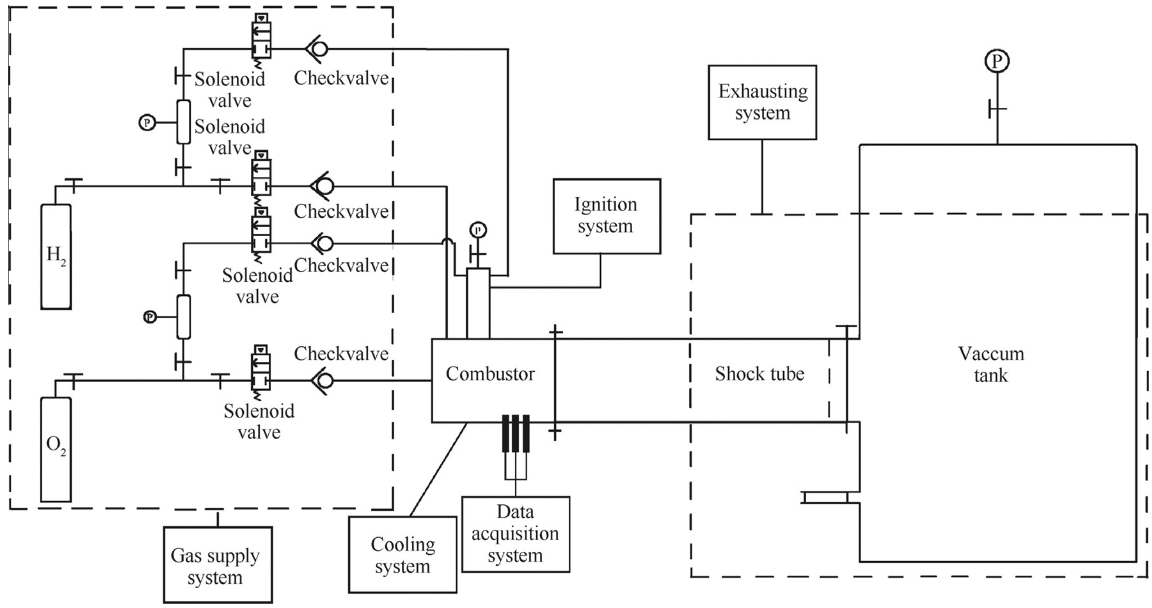


Fig. 2 Schematic of experimental setup.

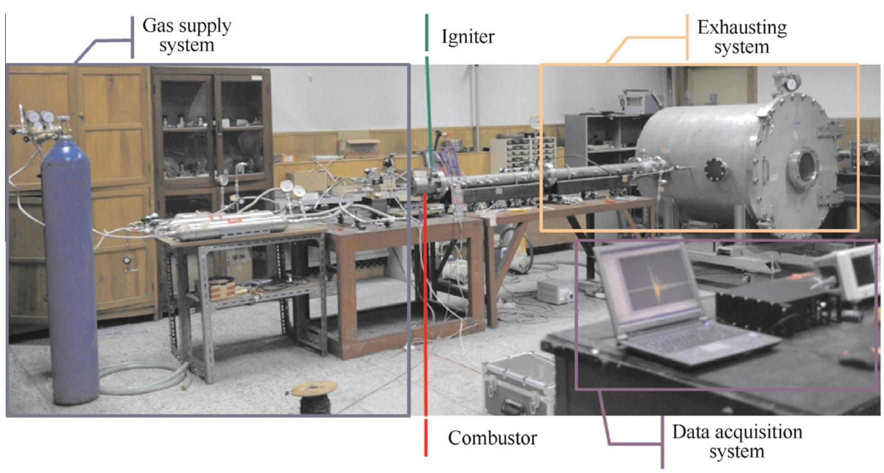


Fig. 3 Photo of experimental setup.

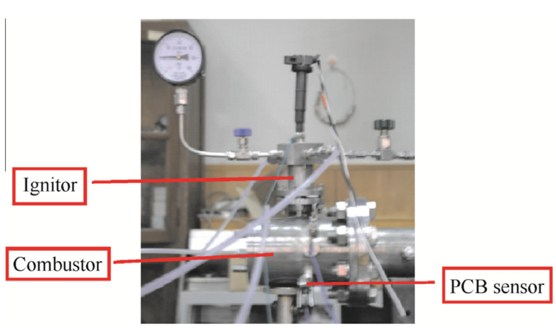


Fig. 4 Photo of combustor and igniter.

and oxygen, and a spark plug ignites the detonable gas at the end. Deflagration to detonation transition completes inside the pre-detonator with the help of Shchelkin spiral. During each run, the pre-detonator only works once at the beginning.

Gas feeding is controlled by an electromagnet-valve on each single pipeline. A computer program controls the electromagnet-valves and the spark plug separately, and its time accuracy reaches 0.1 s. The time sequence is shown in Fig. 5.

The exit of the combustion chamber is connected to a vacuum tank without any nozzle. The burnt gas is exhausted to the tank directly. On the one hand, the tank can guarantee safety as the experiment is executed indoors. On the other hand, the initial pressure in the tank can be controlled to simulate the changing atmosphere at different altitudes. In current experiments, the pressure inside the tank is set at 20 kPa.

A PCB Piezotronics ICP® dynamic pressure sensor is used to detect the pressure variation in the combustor during experiments. According to the instruction of the sensor, its working environmental temperature should be between −200 °C to 315 °C. In detonation experiments, the transient temperature behind the detonation front may be over 2000 °C. Besides, the frequency of a CRDW is higher than 5 kHz, which means

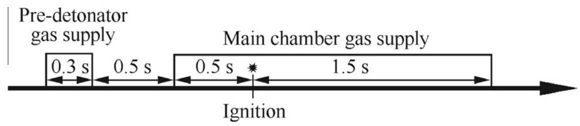


Fig. 5 Time sequence of experiments.

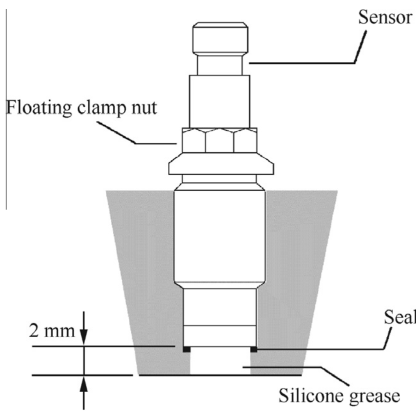


Fig. 6 Mounting of PCB sensor.

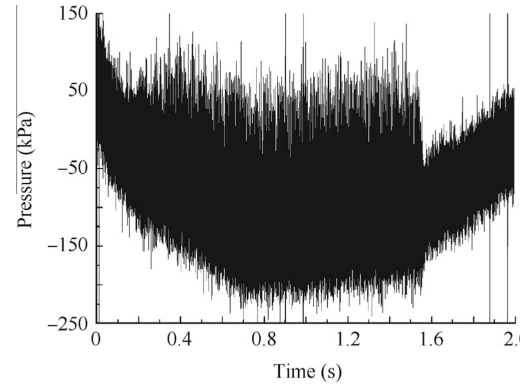


Fig. 7 A typical result of pressure history of an entire run.

the sensor is under extremely high temperature environment throughout every experiment shot. This would seriously curtail the sensor life as well as result in unreliable measurement. To protect the sensor from damage and achieve relative reliable results, the sensor is mounted to the outer wall of the combustor behind a 2 mm-deep hole. And the hole is filled with silicon grease to insulate from thermal flash, as shown in Fig. 6. With these protections, the measured pressure is significantly lower than the real value in the combustor, and the pulse rise time is increased. But still each single detonation wave can be detected and captured when it sweeps over. In experiments, when the first time a detonation wave reaches the measuring point, the high pressure triggers on the recording system to write down the pressure change at the sensing point.

3. Results and discussion

3.1. Pressure history of CRD

A typical result of the pressure history obtained in experiment is shown in Fig. 7. It is the history of an entire run. In this run, the total pressure of O_2 and H_2 feeding is 0.8 MPa and 0.7 MPa, respectively, while the average mass flow rate into the main combustor during the entire 2 s is 5.9 g/s and 0.8 g/s, for O_2 and H_2 respectively.

Ignition takes place at time point 0 ms and it takes around 250 ms to form a stable rotating detonation wave. After that, it comes to the stable stage when the detonation wave propagates circumferentially in the annulus. During the stable stage, the pressure ranges within 300 kPa. Considering that the low background pressure is 20 kPa and the static pressure inside the combustor without detonation is close to that, the pressure range with CRDW is reasonable. The gas feeding is shut down at 1.5 s. And then the detonation wave dies out because of lacking fresh reactants. However, the figure shows that the die-out is not right at 1.5 s, which is mainly because of the delay of electromagnet-valves and some fresh gas remaining in the feeding pipes downstream the electromagnet-valves.

As the detonation wave leads to an obvious rise in temperature, it causes significant baseline drifting for the piezoelectric pressure sensor. That is why the figure seems somehow distorted. Even though, the full trace clearly shows the igniting section and the dying out section.

Close-up of pressure history in stable section is shown in Fig. 8. Each time the detonation wave sweeps over the sensor, a peak appears in the pressure history. The peak values are determined by the strength of the detonation waves, and they are not exactly the same, which means the strength of the detonation wave is not perfectly constant. This phenomenon and its reasons will be discussed later.

A series of much smaller perks is found between the adjacent high peaks, which implies that the CRDW may have split into a main detonation wave and smaller wavelets. The same phenomenon had also been found in the work by Wang et al.[10] with both axial and tangential flow of fresh gas feeding. And such splitting would lead to much lower velocity of the main detonation wave.

Concentrating on the reproducibility of pressure peak, it is seen that the duration between two neighboring peaks is 175 μs. Ahead of each exact peak, there is always obvious fluctuation, which is mainly caused by the installation of the sensor. Assume that there is only one detonation wave rotating in the combustion chamber, the detonation wave takes 175 μs to

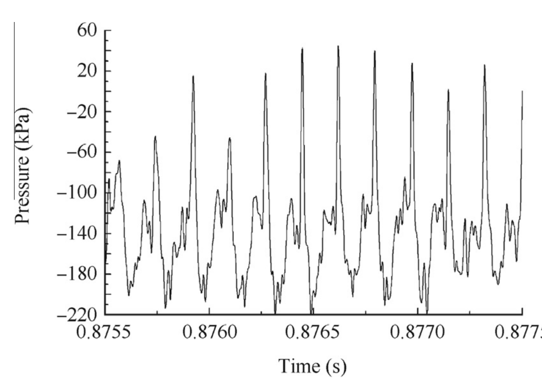


Fig. 8 Close-up of pressure history in stable section.

propagate one cycle in the annulus. As the outer diameter of the annular chamber is $D = 79$ mm, the wave propagating velocity can be calculated as

$(\pi D)/t = 1417$ m/s.

As mentioned above, the CRDW splitting results in that the velocity of the main detonation reduces to about 60% of the normal single wave mode. This is the main reason for the velocity decrease.

Besides, in CRDW experiments, the narrow space between outer and inner walls may enhance the effect of viscosity and boundary layer, and three-dimensional expansion costs more energy than one-dimensional theory. At the same time, fuel and oxidizer are fed into the cylinder with only one pipe, respectively. And they are fed from almost the opposite position of the ring, which can be seen in Fig. 3 in the revision. Thus, the mixing condition can be extremely bad. Even though the total mass flow rate is close to a stoichiometric state, the distribution around the circle is quite poor.

All of the above factors results in the detonation velocity measured in experiment turn out to be smaller than the Chapman–Jouguet (C–J) velocity of the stoichiometric hydrogen–oxygen mixture in standard state. However, it is still evidently higher than deflagration velocity and the sound speed of the fresh mixture, therefore, it proves that it is a detonation wave rotating circumferentially in the annulus.

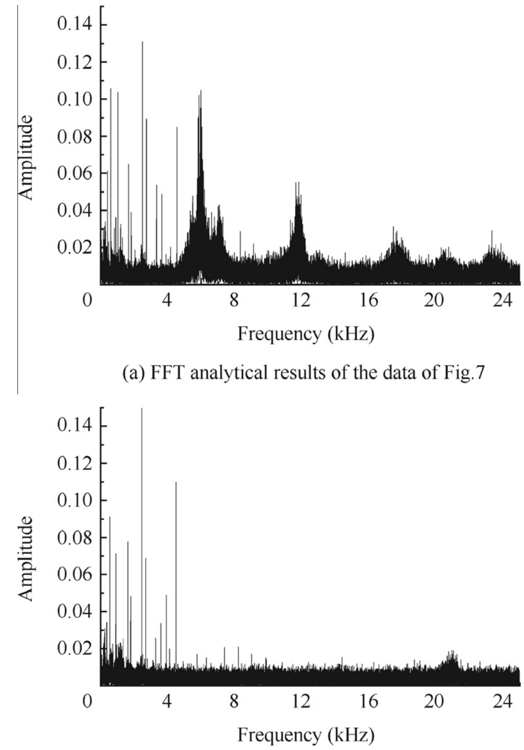
3.2. Spectrum of the pressure history

Close-up of the pressure history only gives partial features of CRDs, while the spectrum of the pressure history can show some overall characteristics. Fig. 9 shows the comparison between the FFT analytical results of the pressure data of Fig. 7, and a blank control. Data of the blank control is collected in an experiment with the same gas feeding, but without ignition, which shows the environmental noise. The differences between them can be easily figured out. Meanwhile, it is obvious that the resonant frequency of the sensor is around 20.5 kHz.

The highest pressure amplitude occurs at about 6 kHz, and some others are around 12 kHz, 18 kHz, and 24 kHz. The basic frequency is not exactly 6 kHz, but a little lower, around 5.9 kHz. This frequency means a periodic time of 170 μs. It implies that if there is only one detonation wave rotating in the annular chamber, it takes 170 μs to propagate one cycle in the annulus. This result matches the analysis of the close-up of the pressure history.

As for the other three frequencies, 12 kHz, 18 kHz, and 24 kHz, they are just twice, three times, and four times of the basic frequency 6 kHz. This implies that in this experiment, sometimes there exist two, three, or even four detonation waves, and they propagate in the annulus in the same direction.

The original data is divided into quarters by time, 0–0.5 s, 0.5–1.0 s, 1.0–1.5 s, and 1.5–2.0 s. FFT is applied to each quarter individually, as shown in Fig. 10. The starting section Fig. 10(a) mainly contains the base frequency. The stable section Fig. 10(b) and Fig. 10(c) has almost the same spectrum with the overall data. While the die-out section Fig. 10(d) is more likely to be the same as the environmental noise. These indicate that the detonation wave splits during the stable section. According to Wang et al.[10] CRDWs may split into a



(a) FFT analytical results of the data of Fig.7

(b) FFT analytical results of the data of a blank control

Fig. 9 FFT analytical results of the pressure transducer data.

main detonation wave and weaker detonation wavelets. And under the splitting circumstance, the main detonation wave speed will drop down to nearly 60%. This further explains the courses for the propagating velocity of the CRDW is lower than C–J velocity.

3.3. Oscillation phenomenon and self-adjusting mechanism in CRD

As mentioned before, the peak values of the stable state in the pressure history are not exactly the same. This phenomenon has been found in Refs. [3,19,20] but they all focus on the time between pressure peaks and the velocity change of the detonation wave, rather than the peak value variations. In order to investigate the mechanism of the CRD stability, it is necessary to take a further look at the peak value variations.

Fig. 11 displays a quasi-steady part of the signal shown in Fig. 7. It clearly shows that the peak values are changing periodically rather than keeping the same. Wu et al.[21] also found the oscillation phenomenon in numerical simulation and annualized the mechanism. And Wolański[3] has also found and discussed the "galloping rotational detonation". It is known that the peak value is based on the strength of detonation wave. The more the fresh gas accumulating in front of the detonation wave, the stronger the detonation wave would become. For a given gas feeding condition, there is a certain level of intensity of the detonation wave to balance the system.

Since the disturbance always exists, for example, the unavoidably strong disturbance brought in by igniting process,

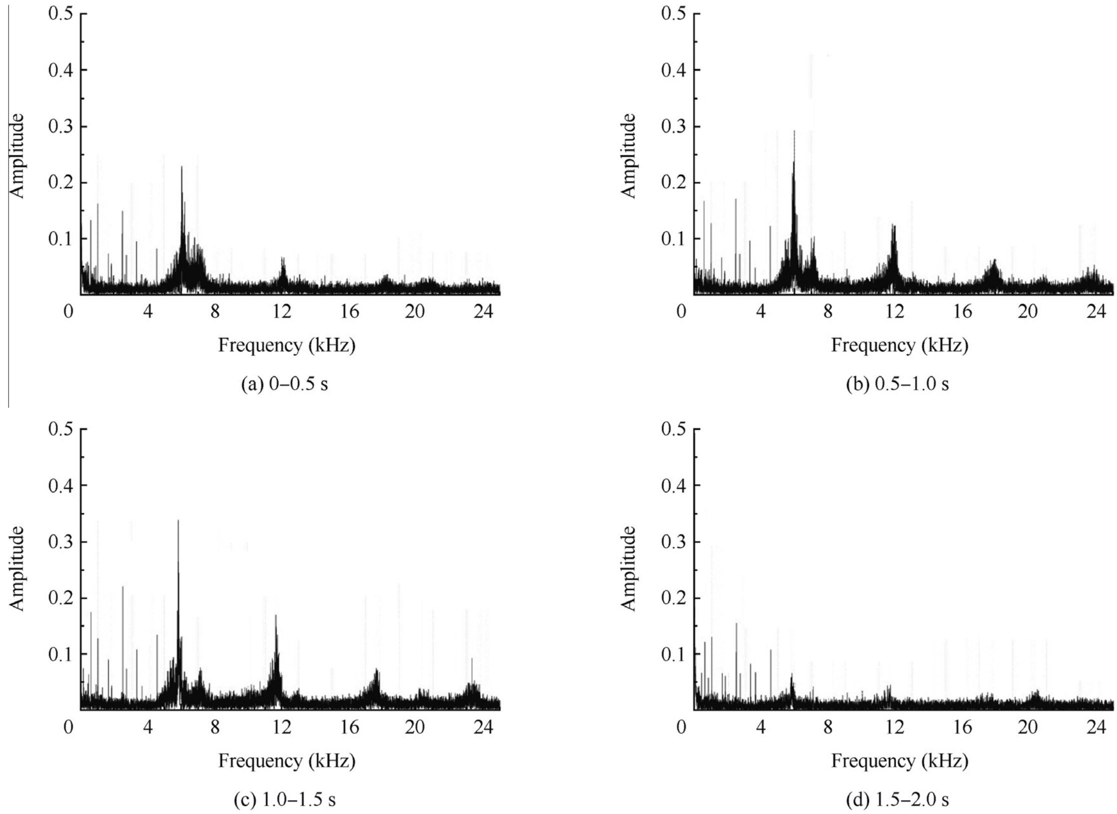


Fig. 10 Spectrum of quarters of pressure transducer data of Fig. 7.

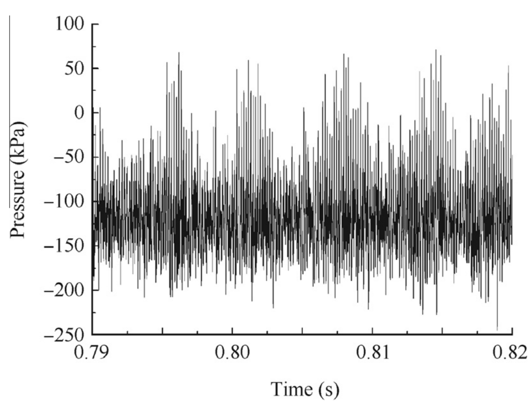


Fig. 11 Part of the pressure history in Fig. 7.

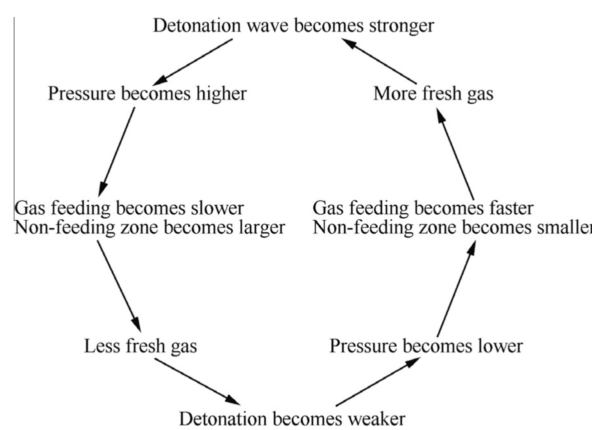


Fig. 12 Self-adjusting mechanism of CRD.

the exact balancing-level cannot maintain. If the detonation wave becomes stronger, the pressure behind the detonation front becomes higher. Higher pressure slows down the gas feeding so that less fresh gas can be injected into the combustor during the next cycle. When the wave front rounds back, there is less fresh gas ahead. Then the detonation wave becomes weaker. And as the detonation wave becomes weaker than the balancing level, it goes the other way round. The whole procedure is shown in Fig. 12, and it is the self-adjusting mechanism in the CRD system.

This process may maintain for more than one cycle, sometimes tens of cycles, represented by the pressure history that their peaks become gradually weaker and then stronger.

4. Conclusions

An experimental study is carried out to investigate the continuously rotating detonation (CRD). An annular chamber combustor is designed for testing, and pressure history is obtained during each shot. According to the analysis of the experimental data, several conclusions are obtained.

(1) The overall pressure history shows that stable CRDs can be obtained in the combustor when hydrogen–oxygen is used for combustible gas. The experiments are successful with feeding pressure higher than 0.5 MPa for fuel and

oxidizer respectively. And each run can keep going as long as fresh gas feeding maintains.

(2) Close-up of the pressure history shows the repeatability of pressure peaks and splitting of the CRDW. An estimation of the detonation velocity of a hydrogen–oxygen CRD is done, proving the success of forming a stable CRD in the annular chamber.

(3) Spectrum of the pressure history matches the close-up analysis and confirms the CRD. It also shows multi-wave phenomena and verifies that there is only one quasi-steady CRDW in this case, and the CRDW splits into a main detonation and two, three or four detonation waves.

(4) Oscillation phenomenon is found in the pressure peaks, and a self-adjusting mechanism is proposed to explain this phenomenon.

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