

# Experimental Investigation on H<sub>2</sub>/O<sub>2</sub> Continuously Rotating Detonation Engine

Yusi Liu, Jianping Wang, Tianyi Shi, Yuhui Wang, Yongsheng Li, Yang Li  
Center for Combustion Propulsion and Power, State Key Laboratory of Turbulence and Complex System, Department of Mechanics and Aerospace Engineering, College of Engineering, Peking University  
Beijing, 100871, China

## 1 Background

Approximate to constant volume combustion, detonation has inherently higher thermodynamic efficiency than constant pressure combustion, like deflagration. Engines based on detonation are believed having bright future. And in recent years, continuously rotating detonation engine (RDE) has been extensively studied.

The basic concept of RDE was first proposed by Voitsekhoviskii[1], and he experimentally achieved short-lived continuous detonation fuelled by acetylene. In the recent years, RDE has been extensively studied both theoretically and experimentally, by Bykovskii et al.[2]. Kindracki et al.[3] have experimentally obtained very promising thrust performances from a rocket-type RDE. Wang et al.[4] obtained multi-cycle of steady continuously rotating detonation in the experiment. Shao et al.[5,6,7] comprehensively studied three-dimensional (3D) numerical simulations in continuously rotating detonations. They obtained multi-cycles of continuously rotating detonations and discussed several key issues, including the fuel injection limit, self-ignition, thrust performance, and nozzle effects. Zhou et al.[8] numerically studied the thermodynamic performance, showing that in a 2D RDE without a nozzle, inside of which 23.6% fuel is burned by deflagration, 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 model, which goes up to 52.9%.

## 2 Experimental Setup

The RDE combustion chamber used in this study is an annular chamber with outer diameter 79mm, inner diameter 59mm, and length 100mm. 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 then exhausts out of the chamber at the downstream exit.

The system was designed to use H<sub>2</sub> as fuel and O<sub>2</sub> as oxidizer. The fuel-oxidizer combination was chosen for its simple chemical model in combustion, easy-operating, and safe guarantee. Hydrogen is more active than most hydrocarbon fuels, and more inert 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 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 and oxygen, and a spark plug starts the reaction at the end. Deflagration to detonation transition completes inside the pre-detonator with the help of solenoids. During each run, the pre-detonator only works once at the start. Gas feeding is controlled by a magnet-valve each single pipeline. A computer program controls the magnet-valves and the spark plug separately, and its timing accuracy reaches 0.1 second.

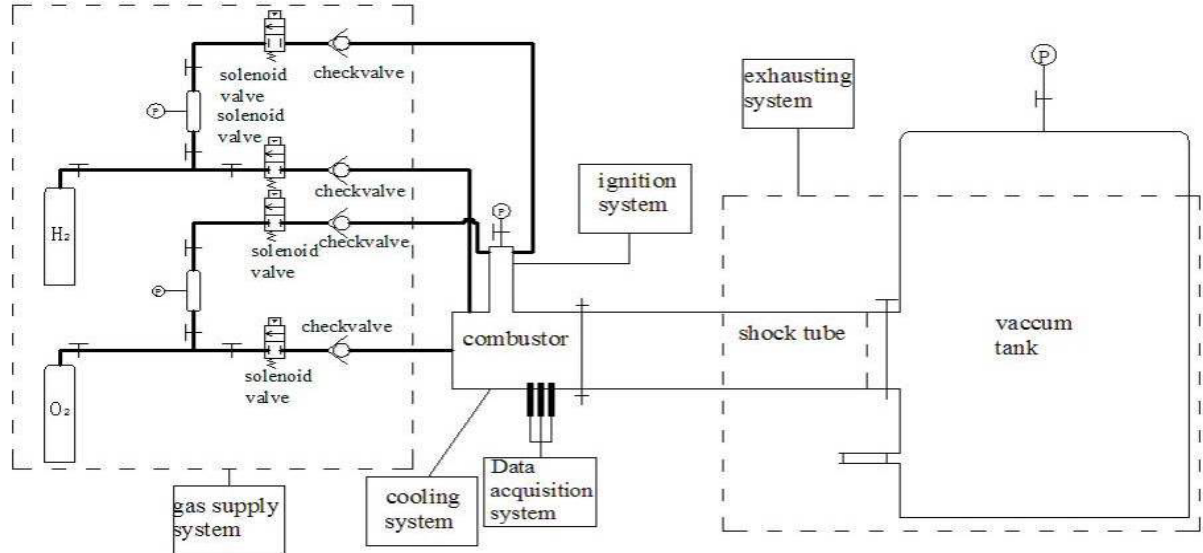


Figure 1. The experimental system

The exit of the combustion chamber is connected to a vacuum tank without any nozzle. Burnt gas is exhausted to the tank directly. On 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 altitude.

As for measuring, a PCB piezoelectric ICP dynamic pressure sensor is recess-mounted to the outer wall of the combustor, right at the head-end. So that the change of pressure at the sensing point can be detected while a detonation wave sweeps past periodically. The first time a high pressure reaches the measuring surface of the sensor, it triggers on the recording system to write down the pressure changing at the sensing point.

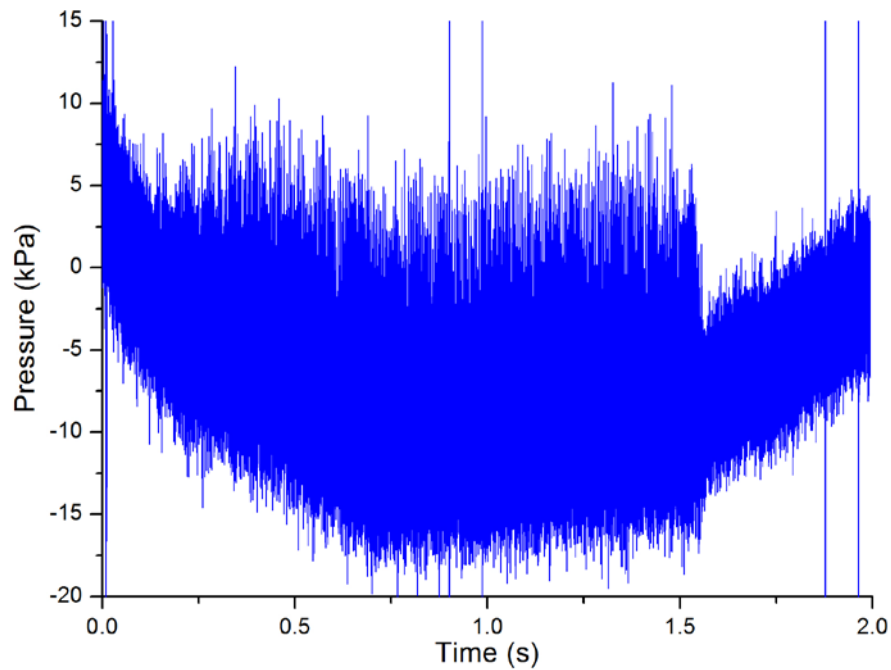
### 3 Results and Discussions

One typical result of the pressure trace taken in experiment is shown in Figure 2. It is the history of an entire run. In this run, ignition takes place at time point 0, and it takes around 250ms to form a stable rotating detonation wave. After that, comes the steady stage when the detonation wave propagates circumferentially in the annulus. The gas feeding is shut down at 1.5s and then the detonation wave dies out because of lacking fresh reactants. However, the graph shows the die-out is not right at 1.5s, and it is mainly because of the delay of magnet-valves and some fresh gas remaining in the feeding pipes.

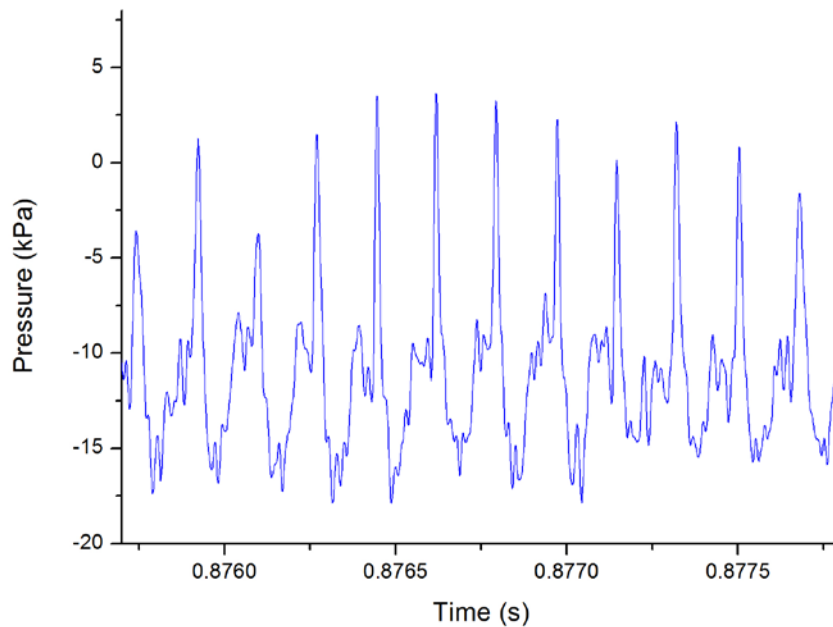
As the detonation wave leads to an obvious raise in temperature, it causes obvious baseline drifting for the piezoelectric sensor, and that is why the graph seems somehow distorted. Still, the full trace clearly shows the igniting and dying out section.

A close-up of the steady section is shown in Figure 3. Every time the detonation wave sweeps over the sensor, a peak appears in the pressure trace. Through, the peak values of each pressure peak which are determined by the strength of the detonation wave are not exactly the same; we can see them repeat around every other 175 $\mu$ s. Before every exact peak, there is always distinct disturbance on pressure; these are mainly caused by the installation method of the sensor. Assume that there is only one

detonation wave rotating in the combustion chamber, it takes the detonation wave  $175\mu\text{s}$  to propagate one cycle in the annulus.



a



b

Figure 3 Pressure trace for an entire run (a) and a close-up of the pressure trace in the steady section (b)

Comparing the FFT result of the pressure data of Figure 1 and a blank control, as shown in Figure 4, the difference is obvious. The rotating detonation wave results in two peaks at  $5750\text{Hz}$  and  $6770\text{Hz}$  in the amplitude-frequency graph, indicating periodic time of the detonation wave are around  $174\mu\text{s}$  and  $148\mu\text{s}$ .  $174\mu\text{s}$  matches the result from Figure 2(b), while  $148\mu\text{s}$  is not clearly identified yet.

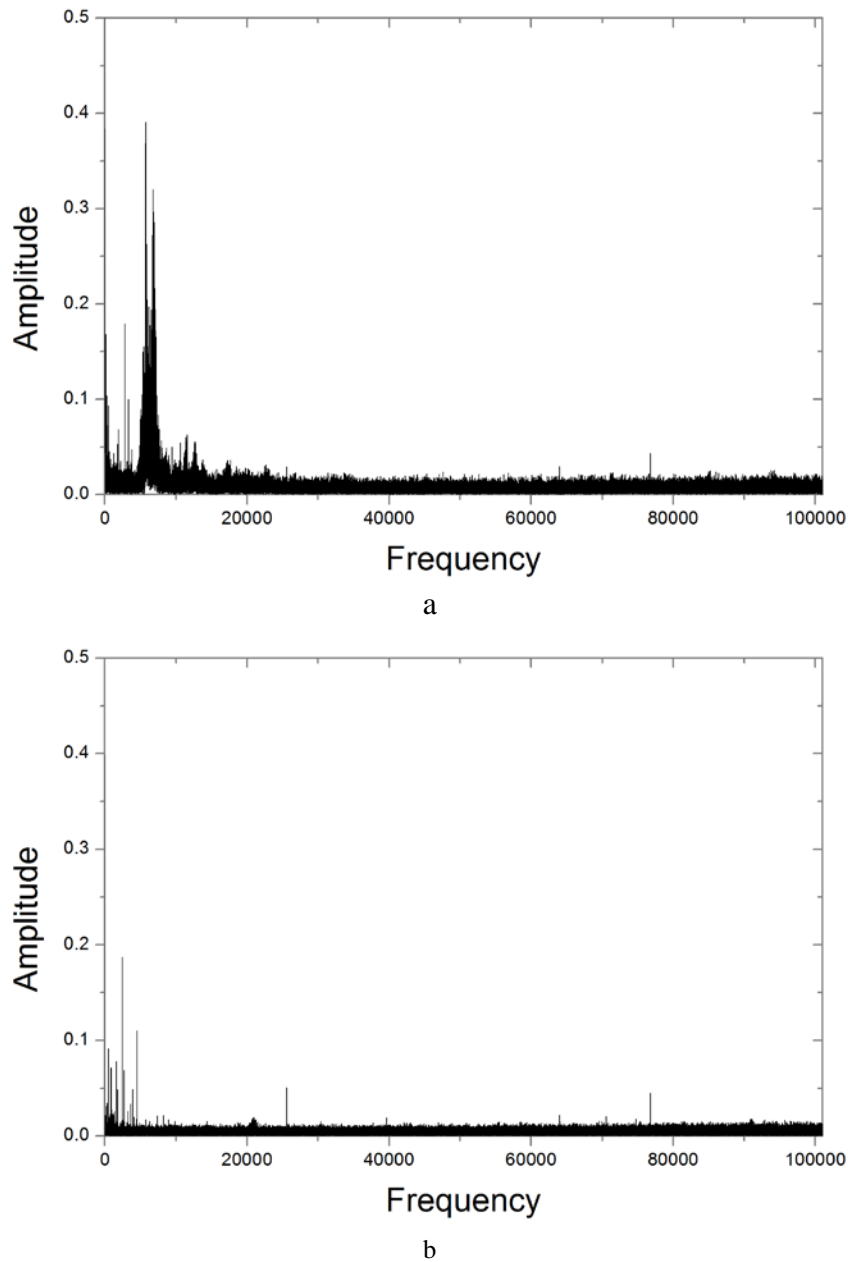


Figure 4 Fourier transforms of Figure 1 (a) and a blank control (b)

As it takes  $175\mu\text{s}$  for the detonation wave to propagate 314mm around the annulus once, the speed of the detonation wave is 1780m/s. This proves that it is a detonation wave rotating azimuthally in the annulus of the combustor, which results in such a pressure trace. As the speed is smaller than the CJ velocity of hydrogen-oxygen mixture in standard state, it is mainly because of the equivalence ratio or the initial state of the mixed gas is not the same.

It is mentioned before that the peak values of each pressure peak are not exactly the same. And now, take a further look at the peak value changing. The pressure trace as shown in Figure 4 is also part from Figure 1. It clearly shows the peak values are not completely stable. In fact, they change periodically based on the intensity of the detonation wave. The more fresh gas accumulates in front of the detonation wave, the stronger the detonation wave would get. For a given gas feeding condition, there is a certain level of intensity of the detonation wave to balance the system.

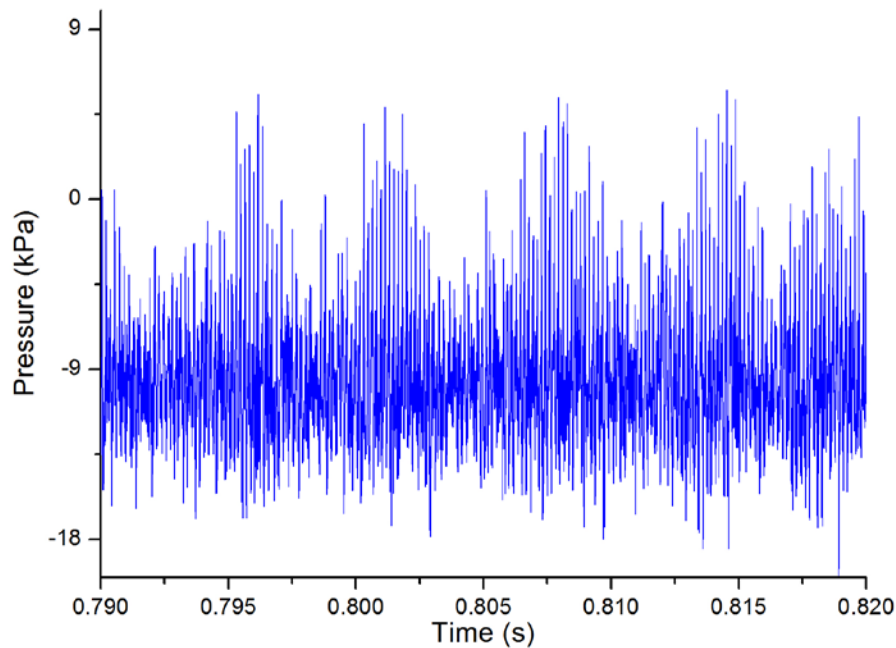


Figure 5 Part of the pressure trace from Figure 1

Since the disturbance always exists, the exact balancing-level cannot maintain. If the detonation wave get stronger, the pressure gets higher, both in the wave front area and the area following. The 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 gets weaker than the balancing level, it goes the other way round. This is the self-adjusting mechanism in the continuously rotating detonation system. And it explains the periodically changing peak values in the pressure trace.

## 4 Summary

The Continuously Rotating Detonation Engine combustion chamber and prototyping kit are tested by experiments. Results show that steady rotating detonation waves can be gained in the combustor, when hydrogen-oxygen is used for combustible gas. The experiments are successful with a certain range of feeding conditions, and each run can keep going as long as the gas feeding maintains. The self-adjusting mechanism holds the dynamic balance in the combustion chamber.

## References

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