Energy 128 (2017) 813–829

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

# Proper orthogonal decomposition for energy convergence of shock waves under severe knock

Han Xu [a], Anren Yao [b], Chunde Yao [a, *], Jian Gao [a]

[a] State Key Laboratory of Engines, Tianjin University, Tianjin 300072, China
[b] School of Environment Science and Engineering, Tianjin University, Tianjin 300072, China

ARTICLE INFO

*Article history:*
Received 18 July 2016
Received in revised form
2 April 2017
Accepted 5 April 2017
Available online 8 April 2017

*Keywords:*
Proper orthogonal decomposition
Energy convergence
Shock wave focusing
Severe knock
Destruction

ABSTRACT

Under severe knocks of internal combustion engines, parts like pistons and spark plugs are vulnerable to be damaged by energy convergence of shock waves. Furthermore, the damaged positions and failure modes have a significant regularity. In order to reveal the mechanism and avoid such damage, numerical simulations combined with detonation bomb experiments were conducted to explore the energy convergence phenomenon. Proper orthogonal decomposition was developed to extract the main pressure distributions so that the positions where energy converges can be found and the convergence modes can be recognized. Results show that energy convergence could occur in combustion chambers when severe knocks occurred. The spark plug, central region and edge region of a piston are in typical positions where energy converges. In addition, the position and intensity of such convergence are varied with the chamber shapes. The damaged samples further prove that the engine parts failure is caused by the energy convergence of shock waves. It's shown that the proper orthogonal decomposition is a simple and efficient method to identify the convergence modes and find the convergence positions. This research can provide a theoretical basis for the chamber design to avoid energy convergence as well as the destruction under severe knock.



## 1. Introduction

As a widely used power machinery, IC (internal combustion) engines are facing austere requirements of energy conservation and emission reduction. In order to fulfill these requirements, technologies like engine down size, shift to other fuels, HCCI (homogenous charge compression ignition) and other combustion modes are tried to be applied in modern IC engines. However, with the application of these technologies, in-cylinder thermal conditions become more severe and the combustion is hard to be controlled at high load, so that severe knock like super knock in gasoline engines would occur. Once severe knock occurs, fuel is burned so fast that rapidly form high temperature and high pressure gas which may cause shock waves and detonation at last. Wang et al. [1] found that the detonation is caused by hotspot-induced DDT (deflagration to detonation) through a visualization rapid compression machine; Robert et al. [2] revealed the process of detonation formation transferred from deflagration by Large Eddy Simulation. Chen et al. [3] studied end-gas autoignition and detonation development in a closed chamber using one dimensional simulation. Yao et al. [4,5] proved that the severe knock is caused by the detonation formation through the analysis of different auto-ignition modes. As a consequence, the pressure oscillations amplitude can reach up to 30 MPa or even more; the oscillation frequency can far more exceed 10 kHz [6–9]. Moreover, shock waves caused by violent combustion may aggregate the energy released by fuel to damage engine parts like pistons and spark plugs easily [10–14]. Such destruction is different from the conventional destruction which is usually caused by thermal stress, thermal fatigue or mechanical fatigue. The destruction under severe knock has a significant regularity: damaged points always occur in typical positions and behave like suffering strong strikes.

In the research of severe knock, most scholars so far have only focused on the origin of it [1–5] or the methods to avoid it [15,16] while few concerns the phenomenon after severe knock which is related to the engine parts destruction closely. In the research of knock phenomena, acoustic theories like small perturbation acoustic wave equation, acoustic models and cavity resonance were widely used [17–19]. Especially, the acoustic pressure wave

* Corresponding author. Tel./fax: +86 22 2740 6649/2738 3362.
*E-mail address:* arcdyao@tju.edu.cn (C. Yao).

http://dx.doi.org/10.1016/j.energy.2017.04.019
0360-5442/

formula $f_{m,n} = \rho_{m,n}\frac{C}{\pi B}$, originally published by Draper [20], is widely used to analyze the knocking mode [21,22]. Though it can give a good predication for vibration mode in knocking combustion, it's only suitable for cylindrical combustion chamber and it's hard to consider the effect of chamber geometry on pressure wave behavior. On the other hand, it's suitable for light knock with small pressure amplitude but may not be suitable for severe knock, since this theory is derived from the linear acoustic theory while a strong non-linear phenomenon may occur in severe knock. Therefore, traditional methods are hard to be applied to reveal the severe knock phenomenon. Furthermore, engine parts material like the aluminum alloy of piston is so tough that it's hard to be damaged by tens of MPa pressure oscillations, which is also hard to be explained by traditional acoustic theory. In our research, non-linear detonation theory was used to explore the severe knock in IC engines, in which energy convergence of shock waves and its destruction effects were revealed.

A novel DBD (detonation bomb device) experiment was developed to simulate the severe knock of IC engines. Four pressure sensors installed in different positions were used to monitor the in-cylinder pressure wave behavior and the energy convergence phenomenon. Validated by the data from these DBD experiments, numerical simulations were conducted to reveal the detailed process that pressure waves focus in the combustion chamber. Since severe knock may occur at any crank angle corresponding to different chamber clearances and the wave behavior in different clearance is different, the DBD experiments and corresponding simulations were conducted in a series of clearances varied from 0 mm to 32 mm. Considering this, the workload is huge, since the complicated pressure data and contours needs to be processed one by one for each clearance to conduct the parametric analysis [23]. In order to refine the useful information from the numerous data and increase the efficiency of data mining [24], a method called POD (proper orthogonal decomposition) was developed to extract the main pressure distributions from the complicated in-cylinder flow so that the locations where energy converges can be quickly found and the convergence modes can be identified soon for each clearance.

Proper orthogonal decomposition is a widely used method in different research fields. In general, it can be classified into two main applications: model simplification [25] and field analysis [26]. The POD in our research belongs to the field analysis, especially the pressure field analysis. Most POD field analyses are focused on extracting large scale features and coherent structures from velocity field [27–29], while little are focused on the pressure field [30]. However, the POD of pressure field is important in our research since it can recognize the convergence positions and identify convergence modes for severe knock.

At last, the damaged samples were shown to further prove that the failure of engine parts is caused by the energy convergence of shock waves. This research can provide a theoretical basis for the chamber design to avoid energy convergence of shock waves as well as the destruction under severe knock.

## 2. Experimental setup

### 2.1. Detonation bomb

A DBD was developed to simulate the severe knock of IC engines. The schematic and photo of this system can be seen in Fig. 1 (a) and (b) separately. This system is made up of four parts, separately the intake-outlet system, high-energy ignition system, signal acquisition and processing system and detonation bomb. In the intake-outlet system, C2H2 and O2 are introduced into the detonation bomb based on the partial pressures. By adjusting the partial pressures, the equivalence ratio can be controlled. The reason we choose C2H2/O2 mixture is that this kind of mixture is vulnerable to detonate and result in a detonation wave similar to that in severe knock of IC engines. Through the high-energy ignition system, a detonation wave can be directly caused by a high-energy spark ignition in the middle region of such mixture. The high-energy ignition system consists of an ignition control cabinet and a coaxial ignition plug, which can provide an output voltage of 2500 V and ignition energy of 12 J. After the formation of detonation, shock waves would oscillate in the bomb chamber, which are monitored by the signal acquisition and processing system. This system is made up of four PCB 119B11 pressure sensors, four PCB 402A03 in-line amplifiers, a PCB 482C05 signal conditioner and a DLM 2000 signal oscilloscope. The four pressure sensors were installed in different positions to detect pressure oscillations and energy convergence. One of them was installed in the cylinder head of the bomb. Other three were installed in different positions of the piston, separately the middle region, 1/4 region and edge region. The detailed installation position can be seen in Fig. 2. The resonant frequency of the pressure sensor is more than 400 kHz and the rise time is shorter than 2 μs. The sample frequency of the signal oscilloscope is as high as 625 MHz. Such acquisition and processing system is enough to capture the behavior of shock waves. The shape and structure of the detonation bomb is shown in Fig. 2. This bomb chamber has the same inner shape with combustion chambers in real spark-ignition engines. The cylinder bole is 83 mm and the angle of the cylinder head is 140°. Also, the clearance is variable from 0 mm to 32 mm corresponding to different crank angles of IC engines.

Considering that severe knock cannot stably occur in IC engines and it's also impossible to install pressure sensors in the piston as the piston is in a high speed reciprocating motion. Therefore, the DBD can make this research simple and realizable. It should be emphasized that in this work, a detonation wave was forcibly introduced into the combustion chamber from the middle region. The method we used here is called DDI (detonation direct initiation) [31] which is realized by a spark ignition of a high energy plug. This method can produce a stable detonation wave which has a constant intensity as long as the initial condition and the equivalence ratio are the same. Such method can be used to research different wave behaviors comparably in chambers with different shapes. However in IC engines, detonation may be caused by various ways under severe knock. DDT and SWACER (shock wave amplification by coherent energy release) [32] of end gas are both possible ways for detonation formation in IC engines. On the other hand, detonation may also be formed from the end gas instead of the middle region. In any case, the processes of the shock wave reflection and the following convergence are the same.

### 2.2. Test conditions

This DBD experiment is used to mimic severe knock in IC engines, so similar pressure oscillations should be formed in the DBD. The experiments were conducted under ambient temperature 274 K. The intensity of the detonation wave was adjusted through modifying the initial pressure and equivalence ratios. The mixture of C2H2/O2 was used in this study. Ultra-high purity grade oxygen (>99.999%) and acetylene (>99.99%) were introduced into the detonation bomb in a sequence by the method of partial pressure, according to which, the equivalence ratio can be controlled. The reason to use the mixture of acetylene and oxygen is that this kind of mixture is easy to form a stable detonate wave under indoor temperature. Based on a detonation calculation by C-J (Chapman-Jouguet) theory, initial pressure of 0.4 MPa and C2H2/O2 equivalence ratio of 1 were used as the initial condition, which can result