Applied Energy 195 (2017) 52–66

Contents lists available at ScienceDirect

Applied Energy

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

Characteristics and effect factors of pressure oscillation in multi-injection DI diesel engine at high-load conditions

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HIGHLIGHTS

- The energy and TFD of pressure oscillation in MI diesel engine are analyzed.
- Detailed characteristics of pressure oscillation in MI diesel engine are revealed.
- Pilot injection is important to pressure oscillation in each combustion stage.
- Effects of operating conditions on pressure oscillation performance are discussed.
- Potential methods for pressure oscillation reduction are discussed.

ARTICLE INFO

Article history:
Received 16 October 2016
Received in revised form 8 February 2017
Accepted 10 March 2017

Keywords:
High-frequency pressure oscillation
DI diesel engine
Multi-injection
Time-frequency analysis

ABSTRACT

The in-cylinder pressure oscillation during combustion process in multi-injection (MI) DI diesel engine is researched in this paper. The in-cylinder pressure testing is conducted under different operating conditions and different injection parameters. The high-frequency pressure oscillation signal and the oscillation energy are extracted from the in-cylinder pressure signal. The time-frequency characteristics of the pressure oscillation in each combustion stage are analyzed using AGST. The effects of engine speed, load and injection parameters on pressure oscillation are investigated. Results show that for DI diesel engine with pilot-main injection strategy, the amplitude of pressure oscillation in pilot injection combustion (PIC) is the maximum and the oscillation energy in PIC is pretty high. Moreover, the pilot injection also shows important influences on pressure oscillation in main injection combustion. Generally, high engine speed and high load lead to drastic pressure oscillation. However, the pressure oscillation decreases when the engine speed rises above 2200 r/min due to the influence of injection parameters. Under the same engine speed and load, the main injection advance angle and the pilot injection interval time show great influences on the amplitude, oscillation energy and time-frequency characteristics of pressure oscillation in each combustion stage, while the pilot injection quantity has less effects on the pressure oscillation when it varies in a narrow range. Based on the conclusions above, the potential methods to reduce the pressure oscillation are also discussed.

1. Introduction

The diesel engine has been widely used in automotive vehicles in China [1] and Europe [2] due to its lower fuel consumptions and CO_2 emissions, compared with gasoline engine [3–5]. However, pollutant emissions and NVH (Noise, Vibration and Harshness) performance are still the most concerning issues in the R&D process of diesel engine [6–8]. Previous studies have shown that the emissions and noise of diesel engine are conspicuously related to the high-frequency pressure oscillation in combustion process [9,10], however the detailed characteristics have not been revealed yet.

The pressure oscillation (knock) is very easily occurred in spark ignition (SI) gasoline engine with high compression ratio. The combustion process of gasoline engine is the typical homogeneous premixed combustion. When the mixture between gasoline and air is ignited at the spark plug center and the flames begin to diffuse, the local unburned mixture self-ignites because of enough temperature or is ignited by the “hot pots” [11]. This causes a sharp rise of local temperature and pressure. The pressure waves diffuse and reflect back and forth [12]. And then, the knock in gasoline engine happens. The knock has negative impact on power performance, fuel economy and reliability of gasoline engine. The most

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http://dx.doi.org/10.1016/j.apenergy.2017.03.048
0306-2619/

expected combustion condition is the edge of knock occurrence and free-knock. Thus, a lot of research works have been done on gasoline engine knock [11–15].

The combustion mode of the compression ignition diesel engine is mostly the diffusion combustion. However, premixed combustion dominates the reactions in the preliminary stage of diesel combustion. So the pressure oscillation is still an important part of combustion process in diesel engine and should be detailedly studied. In the preliminary stage of combustion, several regions of mixture self-ignite and the flames spread along with the diffusion of pressure waves. When the pressure waves run into the chamber walls, they will reflect back and forth in the chamber. Then the high-frequency pressure oscillation of the gas takes place. The resonance frequency is dependent on the chamber geometry and the sound speed of the mixture, and thus on the gas physical properties such as temperature, pressure, and density [16]. In addition, the intensity of the oscillation is closely related to the pressure gradient in the early stages of combustion. Therefore, it is also related to the combustion process such as the quantity of premixed combustion and ignition delay (ID) [17].

The pressure oscillation has been shown to have important impacts on the NVH performance, power performance and emissions of diesel engine. When the pressure oscillation occurs, it stimulates the cylinder wall to vibrate. These vibrations then transmit to the engine surfaces through the engine structures, radiating much combustion noise [18]. Payri et al. decomposed the in-cylinder pressure signal to pseudo-motored pressure, combustion pressure and resonance pressure to enhance the understanding of the function of pressure oscillation for combustion noise [19]. Zhang et al. also emphasized the importance of the high-frequency pressure oscillation in the combustion noise optimization [10]. Furthermore, in the research on the pressure oscillation and cycle-to-cycle variations in diesel engine, Kyrtatos et al. found the limitation of the pressure oscillation on engine power and the effects on emissions performance (soot and NOx) [9,17]. Moreover, Broatch et al. [20] and Kyrtatos et al. [16] both developed the trapped mass prediction method from the in-cylinder pressure oscillation signal. All these researches above illustrate the significance of the study on pressure oscillation and of the reduction of it.

An available way to weaken the pressure oscillation for diesel engine is to adjust the reasonable injection strategy [21]. Modern diesel engine is generally equipped with high pressure common rail system, which can not only precisely control the timing and quantity of fuel injection but also supply multi-injection (MI) pulse that benefits the noise reduction and emissions performance [10,21–23]. Compared with the single-injection diesel engine, the combustion process of multi-injection engine is extremely different [22]. Thus the pressure oscillation is also different. On the one hand, the combustion process is divided into several stages in an engine cycle (depending on the number of injections). On the other hand, due to the pilot injection, the combustion of main injection is much gentler than the single-injection engine. Thus, the study of pressure oscillation in multi-injection diesel engine should be divided into different stages and the differences between the oscillations in different stages should be studied.

The A Broatch group did lots of experimental works on pressure oscillation when they studied the in-cylinder pressure and combustion noise. Firstly, they decomposed the in-cylinder pressure and got the resonance pressure evolution and its spectrum [19]. Then, the chamber resonance indicator was built using the decomposed resonance pressure [24]. The sensitive of resonance indicator to pilot injection was also investigated [21]. However, the time-frequency characteristics of pressure resonance and different injection stages were not considered. Badawy et al. investigated the combustion resonance using an ion current sensor and researched the effect of injection pressure and EGR on the combustion resonance [25]. Rusly et al. investigated the effects of pilot injection timing and duration on the diesel knock using the high-speed visualization and in-cylinder pressure test [26]. They found that the pilot injection helps reduce the in-cylinder pressure ringing. Besides, Hou et al. and Shi et al. pay their attention on the combustion resonance in HCCI engine [27,28]. The characteristics of combustion pressure oscillation for soybean bio diesel oil was also experimentally studied by Peng et al. [29]. They found that the pressure oscillations with 0% and 30% EGR were the most significant under some specific conditions. However, there were no detailed time-frequency characteristics of pressure oscillation being revealed and injection stages were also not mentioned in these previous work above.

Except experimental research works on pressure oscillation, some efforts were also made to calculate or simulate the oscillation pressure. Torregrosa et al. and *Broatch* et al. calculated the frequency and energy of the pressure oscillation using the acoustic model and CFD method and studied the influence of the chamber geometry on the pressure oscillation [18,30]. However, only the characteristic spectrum of oscillation pressure was considered and the timing of the oscillation occurrence was unclear. Besides, Wei et al. predicted the pressure fluctuation during combustion process in diesel engine coupling the wave equation with KIVA program [31]. Bodisco et al. presented the combustion resonance frequency models based on the Bayesian models [32,33].

Throughout these previous pressure oscillation researches above, they either based on the single-injection diesel engine, or focused on the variations of pressure oscillation in the main injection stage after introducing the pilot injection. The pressure oscillation in the pilot injection stage is neglected, which according to the findings in our present work is much more significant than other injections in multi-injection diesel engine. Therefore, the pressure oscillation in the pilot injection stage should be studied systematically to reveal the detailed characteristics of pressure oscillation in different stages based on the multiple injections in diesel engine.

This paper aims to investigate the detailed time-frequency characteristics of the pressure oscillation in multi-injection diesel engine and the effects of operating conditions on them. The main goal of this investigation is to highlight the differences between the pressure oscillations occurring in different combustion stages and the importance of pilot injection for pressure oscillation, rather than considering the multiple combustion stages as a whole combustion process simply.

For this purpose, a four-cylinder DI diesel engine with pilot-main injection strategy is adopted to study the pressure oscillation characteristics and the influences of engine speed, loads and fuel injection parameters in both pilot and main injection stages systematically. The experimental setup and testing conditions including different engine speeds, loads and fuel injection parameters are presented in Section 2. In Section 3, results analysis and discussion are elaborated, with significant focus being placed on the pressure oscillation and its effect factors in both pilot and main injection stages. The advanced time-frequency analysis method (Adaptive Generalized S Transform) for pressure oscillation, the combustion stage discrimination principle and calculation method of the pressure oscillation energy in each combustion stage are also proposed in this section. Finally, the main conclusions and contributions of this work are highlighted in Section 4.

2. Experimental setup

2.1. Test equipment and setup

In this work, the experiment is conducted on a four-cylinder DI diesel engine, which has a ω-type of bowl geometry (as shown in