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Investigation on nonlinear dynamic characteristics of combustion instability in the lean-burn premixed natural gas engine

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ABSTRACT

In this paper, the nonlinear dynamic characteristics of combustion instability in the natural gas engine were investigated. The experiments covered the whole excess air ratio (λ) in range from 1 to 1.6 and spark advance angle (SAA) in range from 10°CA to 50°CA before top dead center (TDC). And the real-time series of in-cylinder pressure in combustion process were acquired through a piezoelectric transducer. A couple of new coordinates were proposed for the 0–1 test method. Then the characteristics of the experimentally obtained real-time series of in-cylinder pressure in combustion process were analyzed by using the 0–1 test, the largest Lyapunov exponent (LLE) and the phase space reconstruction methods. The effects of SAA and λ on the complexity of combustion instability of the natural gas engine were tested qualitatively and quantitatively. The results show that all the average asymptotic growth rate K_c are approximately equal to 1 and all the LLE are positive. This indicates the combustion process involves some chaotic characteristics. All the attractors are limited to the finite range of phase space and all the attractors have twist and folded geometry structure. This indicates the combustion process has some irregular deterministic components. Both K_c and LLE have higher values, also the attractor is more complex and looser under higher λ and too large or too small SAA conditions. One can conclude that the chaotic behavior is stronger and the combustion process is more complex and sensitive to small variations of initial condition under higher λ and too large or too small SAA conditions.

1. Introduction

In recent years, the worldwide environmental pollution and energy crisis have become two inescapable challenges that human face. Developing natural gas engine has become an effective and pragmatic way to realize energy saving and emission reduction [1–5]. The combustion process of natural gas engine, which is composed of four strokes namely intake, compression, expansion and finally exhaust, is a strong nonlinear process. The combustion process is influenced by many factors such as mixture constituents related factors, air intake related factors, spark ignition related factors, in-cylinder mixing process related factors and so forth so that it is complex. The SAA and λ are the most important and directly controllable two factors. Combustion instability occurs as cycle-to-cycle variations of in-cylinder pressure time series because of fluctuations of these factors. As a result, the engine will be made difficult to control, the power output will be caused harmful fluctuations and emissions will be increased.

Understanding the cycle-to-cycle instability in a combustion process has been an interesting topic for many years [6–47]. The main source of the cycle-to-cycle combustion fluctuations was based on a nonlinear mixing of fresh fuel, air and exhaust gasses before each combustion event [1,6–15]. Researchers studied the nonlinear dynamic characteristics of cycle-to-cycle instability in a combustion process [16–47]. Litak et al. [16–18] studied the instability of heat release and indicated mean effective pressure (IMEP) of a spark ignition engine by using the methods such as recurrence plots (RP) and recurrence quantification analysis (RQA). They found various structures of RP in IMEP time series and heat release time series with the change of equivalence ratio (φ) or SAA. And they also quantitatively analyzed the structures of RP by RQA. Wendeker et al. [19,20] adopted the phase space reconstruction and RP methods to analyze the in-cylinder pressure cyclic oscillations of a spark ignition engine. They found that the reconstructed attractor of combustion process has characteristics of a butterfly shape, which is similar to a chaotic attractor of classical Lorentz

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system. They also presented the nonlinear dynamics of combustion process which may have relationships with the level of noise in spark ignition. Kamiński et al. [21] observed additional oscillations with longer time interval ranges from one to several hundred engine cycles. And they also estimated the noise level of the heat release by calculating the entropy. Based on the statistics and continuous wavelet transform theories, Sen et al. [22–26] investigated the combustion dynamic characteristics of heat release time series and IMEP time series. They considered single impact factor such as SAA, φ, exhaust gas recirculation or compression ratio. Curto-Risso et al. [27] exploited surrogates and correlation integral methods to examine the dimensionality of heat release time series. They found that the unburned eddies have a great influence on the cycle-to-cycle variations of heat release. The cycle-resolved dynamic model and physically oriented model were proposed by Daw et al. [28–32] to study the chaotic characteristics of combustion instability in a spark ignition engine. These two models could do thousands simulation rapidly on heat release cycles of engine. And also they can analyze the interaction between small-scale fluctuations in engine parameters and nonlinear deterministic coupling in successive engine cycles. Then Daw et al. used the symbolic approach to analyze the simulated heat release time series. Using symbolic time-series analysis and return maps methods, Green et al. [33,34] observed time irreversibility in cycle-resolved combustion process and they concluded that the combustion instability is inherently nonlinear chaotic. Wagner et al. [35–38] employed symbol data analysis technique based on chaos theory and they observed a transition from noisy nonlinear determinism to stochastic behavior as with the φ increasing. Finney et al. [39,40] presented technique of symbolic time-series analysis with which they analyzed the chaotic characteristics of heat release and IMEP time series. Davis et al. [41] exploited a recognition system with the aim of reducing cyclic variations of combustion process in a lean-burn spark ignition engine. Kaul et al. [42] adopted the Shannon entropy analysis approach to estimate the effects of external EGR on cycle-to-cycle combustion dynamics. Glewen et al. [43] built a Wiebe function model to observe inside the unstable combustion processes between thousands of individual cycles. Hellstrom et al. [44] created a model to study the cyclic variability and dynamical instability under different levels of residual gases in an auto ignition engine. Li and Yao [45] studied the nonlinear dynamic characteristics of combustion process in a lean-burn natural gas engine by using the methods of Poincare sections, phase space reconstruction and return maps. And they found a transition from noisy nonlinear determinism to stochastic behavior with the φ increasing from very lean conditions to near stoichiometric conditions. Yang and Ding et al. [46,47] analyzed the nonlinear dynamic properties in the internal combustion engine. They studied the combustion instability with the methods of phase space reconstruction, RP, RQA, correlation integral and LLE.

From the literature survey above, we can conclude that in the field of combustion process in natural gas engine, there are few corresponding studies about the nonlinear dynamic estimation using the 0–1 test method, the corresponding studies using the LLE method are still occasional, and the corresponding studies analyzing the interrelationship of two or more impact factors on the nonlinear dynamic characteristics in one paper are also still scare. Also we have considered the advantages of the 0–1 test and the traditional methods. Therefore, purpose of this paper is designed to contribute some analysis for the lack of literature in these areas and also designed to study the interrelationship of the most important and directly controllable two impact factors, SAA and λ, on the complexity of combustion process in the natural gas engine. At first, in our research, we proposed a couple of new coordinates for the 0–1 test method. Then we comparatively studied the characteristics of the 0–1 test method by applying to the Logistic system and combustion process of natural gas engine. Next, we analyzed the nonlinear dynamic characteristics of the combustion process in a natural gas engine under different SAA and different λ with the 0–1 test method. At last, we compared the results of the 0–1 test method with that of the classical qualitative analysis method phase space reconstruction and quantitative analysis method LLE, which aims to improve the reliability of the 0–1 test method in analyzing the nonlinear dynamic characteristics of combustion process of natural gas engine.

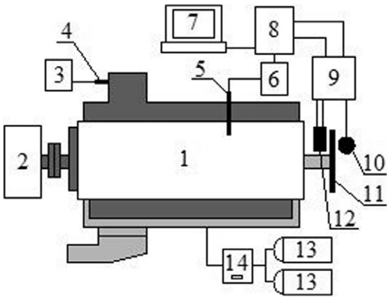

Fig. 1. Schematic diagram of the experimental platform.

2. Experiments setup and data acquisition

1-natural gas engine; 2-electric eddy current dynamometer; 3-lambda meter; 4-oxygen sensor; 5-piezoelectric transducer; 6-charge amplifier; 7-computer; 8-combustion analyzer; 9-terminal box; 10-light source; 11-grating disc; 12-encoder; 13-natural gas bottle set; 14-natural gas flow meter.

The schematic of the experimental platform is shown in Fig. 1. Experiments were performed on an in-line, two-cylinder and water-cooled natural gas engine. The engine was adopted speed feedback system only with the aim of minimizing the effects of other control systems on combustion instability. And also it was adopted multi-point gas injection mode in order to avoid natural gas loss during valve overlapping. The engine was coupled to an eddy current dynamometer through a flexible coupler and speed was measured by using a magnetic transducer. Gas fuel was supplied from the natural gas bottle set and its flow was measured by the natural gas flow meter. Measurement of in-cylinder pressure time series of combustion process was accomplished by using a piezoelectric pressure transducer which installed in the cylinder head of the first cylinder. The direct interaction between the pressure transducer and in-cylinder gas allowed us to gain combustion information effectively without additional signal interference. The pressure transducer was connected to a charge amplifier with the intention that the combustion analyzer can capture the amplified charge signals. Measurement of crank angle was accomplished using a free end mounted crank shaft encoder which was mounted to the front of the engine rigidly. Signals from the piezoelectric pressure transducer and the crank shaft encoder were acquired by the combustion analyzer and then transferred to the computer.

In Fig. 2, the black dots cover the operating conditions of natural gas engine that we chose. Experiments were performed under whole ranges of SAA and λ. The SAA was changed from 10°CA to 50°CA before top dead center (TDC) and also the λ was changed from 1 to 1.6. The interval of SAA and λ is respectively 5°CA and 0.1. The 1800 consecutive in-cylinder pressure cycles of each operating condition were recorded.

Fig. 3 shows 10 of the 1800 working cycles. In our experiment, we acquired the whole pressure signals of each engine cycle. Because the whole pressure signals directly derive from the natural gas engine combustion process and they give whole information of the combustion process. Consequently, the whole pressure