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Analysis of the dynamic characteristics of combustion instabilities in a pre-mixed lean-burn natural gas engine

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HIGHLIGHTS

- Combustion instabilities in a pre-mixed lean-burn natural gas engine were studied.
- Effect of gas injection timing on the complexity of combustion system was analysed.
- Analysis is based on return map, recurrence plot, recurrence quantification analysis.
- Source of combustion instabilities is identified based on 3-D CFD simulation.

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ABSTRACT

The cyclic combustion instabilities in a pre-mixed lean-burn natural gas engine have been studied. Using non-linear embedding theory, recurrence plots (RPs) and recurrence qualification analysis (RQA), the hidden rhythms and dynamic complexity of a combustion system in high dimensional phase space for each gas injection timing (GIT) have been examined, and the possible source of combustion instabilities has been identified based on 3-D computational fluid dynamics (CFD) simulation. The results reveal that for lower engine load, with the decrease of mixture concentration, the combustion instability and complexity of combustion system become more sensitive to the variation of GITs. Richer mixture and earlier (GIT < 30°CA ATDC) or delayed (GIT > 90°CA ATDC) gas injection will lead to more stable combustion, regular oscillatory and low complexity of combustion system, while leaner mixture together with the medium GITs (from 30 to 90°CA ATDC) easily leads to increase of combustion fluctuations, time irreversibility and dynamic complexity of combustion system. When GITs are changed, the combustion instabilities of pre-mixed lean-burn natural gas engines are from in-cylinder unreasonable stratification of mixture concentration and turbulent motion.

1. Introduction

Energy saving and environmental protection have become two focus issues right around the world, and the development of clean alternative energies in place of petroleum is an effective measure to alleviate these issues. Natural gas is regarded as one of the most promising alternative fuels due to its abundant reserves and clean combustion properties. Reserves of natural gas are 149.76 trillion cubic metres, much larger than for crude oil [1]. The primary constituent of natural gas is methane (CH_4), and it also contains a small amount of heavier hydrocarbons (ethane, propane and butane) and inert gases (carbon dioxide and nitrogen). The hydrogen to carbon ratio (H/C) of natural gas is close to 3.8 and is the highest of all hydrocarbon fuels. Therefore, the combustion of natural gas produces the least CO_2 per unit of energy released for all hydrocarbon fuels [2,3]. For example, natural gas produces 25–30% less CO_2 emissions per unit of energy than gasoline and diesel [4,5]. At the same time, oxides of nitrogen (NOx), sulphur dioxide (SO_2) and particulate matter (PM) emissions produced in the combustion process are lower than for petroleum-based fuels, so natural gas is widely applied as one of the most ideal fuels of internal combustion engines [6,7].

Currently, pre-mixed natural gas engines using multi-point manifold gas injection are being more widely used in the vehicle, marine and power plant fields. In order to meet the increasingly strict emission restrictions and demands for fuel efficiency, lean-burn and exhaust gas recirculation (EGR) technologies are

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considered to be the most effective measures to further improve fuel efficiency and to minimise NOx emissions on natural gas engines [8–11]. However, a mixture of air and gas that is too lean, or an excessive EGR supplied to a cylinder may cause combustion instability [12,13], and cycle-to-cycle variations (CCV) - which are an inherent consequence of combustion instability - leading to poor thermal efficiency and an increase of CO and UHC emissions [14,15]. If CCV can be eliminated, engine power output will increase by 10% for the same fuel consumption in a spark ignition (SI) engine [16]. The effects of some boundary conditions and structure parameters on combustion characteristics and engine performance were estimated [17–21]. However, during the actual operating process of the lean-burn natural gas engine, the apparently stochastic character of CCV makes it difficult to control. Therefore, it is one of the most important issues in the field of internal combustion engines to further understand the internal nature of CCV, to identify their sources and then develop effective engine control strategies for highly efficient combustion [22–29].

The nature of CCV in internal combustion engines has been widely investigated. However, sometimes researchers have reported apparently conflicting observations. For example, some have described CCV as strictly stochastic, while others have illustrated the determinism which has been typically characterised in strictly linear terms [30–32]. Daily has indicated that CCV are an inherent consequence of non-linear combustion kinetics, and that highly chaotic behaviour will occur when the burn time occupies an excessive fraction of the cycle time [33]. Non-linear dynamic theory has been increasingly applied to analyse the dynamic properties of CCV in internal combustion engines because it is a more sophisticated approach to reveal the complexities of such a dynamic system. Litak et al. analysed the noise level of maximum peak pressure fluctuations in a single-cylinder spark ignition (SI) engine by means of coarse-grained entropy and an autocorrelation function, and indicated that the dynamic of the combustion is a non-linear multidimensional process mediated by noise [34]. Curto-Risso et al. used the correlated integral and surrogate data to investigate the complexity of cycle-to-cycle heat release variations in a spark ignition engine, and found that low dimensionality is related to the presence of determinism in heat release fluctuations [35]. Wagner et al. used return maps, Shannon entropy and symbol sequence statistics to analyse cycle-to-cycle combustion dynamics, and observed a transition from stochastic behaviour to noisy non-linear determinism when the equivalence ratio was decreased from stoichiometric to very lean conditions [36]. Daw proposed a physically oriented model to predict the lean combustion instability in SI engines. The model combined both stochastic and non-linear deterministic elements and can be used to simulate the interaction between stochastic, small-scale fluctuations in engine parameters and non-linear deterministic coupling between thousands of engine cycles. The results showed that lean combustion instability should occur as a dynamic period-doubling bifurcation sequence [37]. Sen et al. investigated the complex dynamics of cyclic combustion heat release variations in a spark ignition (SI) engine by multifractal and statistical analyses. The multifractal complexity is based on the singularity spectrum of the heat release time series in terms of the Hölder exponent. The result indicated that the complexity increases with an increasing spark advance angle. The kurtosis of their probability density functions was calculated to perform a statistical analysis of combustion fluctuations [38]. Wavelet analysis also was used to characterise the dynamics of CCV in SI engines [39–41].

Usually, time series of in-cylinder pressure, indicated mean effective pressure (IMEP) or heat release are used to describe the variation rules of combustion systems in internal combustion engines [34–36,38,42–44]. The dynamic state and its evolution process of combustion system attractor in a high dimensional phase space can only be visualised by projection into two or three dimensional subspace. However, the recurrence plot (RP) makes it possible to investigate the dynamic characteristics of the motion trajectory of combustion system attractors in an m-dimensional phase space by using a two-dimensional representation of its recurrences. As a graphical tool, the RP can be used to visualise the recurrences of dynamic systems and to reveal temporal correlations. It can provide a qualitative picture of the correlations between the different states of the combustion system in a natural gas engine. The information contained in RPs is rich and manifold, and often cannot be easily obtained by other methods [45]. Furthermore, recurrence quantitative analysis (RQA) introduced by Zbilut and Webber (and extended by Marwan et al.), can move beyond the visual impression from RPs and provide the quantitative characteristics of the dynamic system [46,47]. Another advantage of RQA is that it can provide useful information even for non-stationary and short data when other analysis methods fail, such as identifying laminar states or detecting transitions between regular or chaotic regimes in complex systems [48–51].

The natural gas engine is a complex dynamic system, and the combustion instabilities in lean-burn SI natural gas engines are determined by a wide variety of factors [52]. Among these factors, only a few parameters can be directly controlled or flexibly modified by the experimenters based on test purpose during engine operation, such as ignition (ignition timing, duration and energy), gas injection (injection timing and quantity) and throttle opening. Gas injection timing (GIT) has a strong influence on mixture formation and the combustion process in natural gas engines [53–57]. From the above literature, it is obvious that the majority of the research work regarding combustion instabilities and dynamic properties of combustion systems has been done on SI engines. But only a few research works in the relevant literature have focused on the effect of GIT on combustion instabilities of premixed lean- burn natural gas engines. No study has been performed to elucidate the effects of GIT on dynamic complexity of the combustion process in pre-mixed lean-burn natural gas engines.

In this regard, the main objectives of the present research are to (i) to investigate the effect of GIT on the combustion instabilities in pre-mixed lean-burn natural gas engines, (ii) to reveal temporal correlations, and quantitatively and qualitatively analyse the hidden rhythms and the dynamic complexity of the combustion system using chaos theory and more sophisticated non-linear data analysis methods (including return map, RPs and RQA), and (iii) to identify the possible sources of combustion instabilities when GIT is changed, based on 3-D computational fluid dynamics (CFD) calculations. Our research results are useful to understand the complex dynamics of cyclic combustion instabilities and may provide useful information to improve control strategies for gas fuel injection leading to improvements in the performance of premixed lean-burn natural gas engines.

2. Facilities and experiment

Tests were conducted on a modified single cylinder, water-cooled, intake port injection natural gas engine. The test dynamometer used in our study is an eddy current dynamometer with an automatic control function. It can work in constant speed control and constant torque control modes. During the experiment process, all other feedback controls were cancelled except for engine speed. Air-to-fuel ratio and gas mass flow rate were real-time monitored using a Lambda meter and gas flow meter respectively. The in-cylinder pressure data, crank angle and top dead centre (TDC) signals were captured by a high-speed data acquisition system which includes a cylinder pressure sensor, a