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Nonlinear dynamics of cycle-to-cycle combustion variations in a lean-burn natural gas engine

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Abstract

Temporal dynamics of the combustion process in a lean-burn natural gas engine was studied by the analysis of time series of consecutive experimental in-cylinder pressure data in this work. Methods borrowed to the nonlinear dynamical system theory were applied to analyze the in-cylinder pressure time series under operating conditions with different equivalence ratio. Phase spaces were reconstructed from the in-cylinder pressure time series and Poincaré section calculated from each phase space. Poincaré sections show that the in-cylinder combustion process involves chaotic behavior. Furthermore, return maps plotted from time series of indicated mean effective pressure show that both nonlinear deterministic components and stochastic components are involved in the dynamics of cycle-to-cycle combustion variations in the lean burn natural gas engine. There is a transition from stochastic behavior to noisy nonlinear determinism as equivalence ratio decreases from near stoichiometric to very lean conditions.

Keywords: Natural gas engine; Combustion; Cycle-to-cycle variations; Nonlinear dynamics

1. Introduction

In last two decades, increased attention has been focused on the lean burn option of natural gas engines because of their potential to improvement in energy consumption. However, utilization of very lean mixture of natural gas and air can give rise to instabilities of the combustion process in spark ignition engines, which can cause not only harmful fluctuations of the power out-put but also higher emissions. So, sources of the cycle-to-cycle combustion variations (CCV) have been intensively studied [1–5]. However, to draw a definite conclusion on the nature of dynamics of CCV is sometimes a problematic task, because CCV is caused by coupled effects of a few factors and the influence mechanisms of some factors have not been clear so far [6].

Traditional approach to characterizing dynamical nature of CCV is to use a few simple statistics of a small set of "characteristic" point values which vary randomly from cycle to cycle [7,8]. After 1990, many observed time series suffered by noise were widely analyzed using the nonlinear dynamical system theory. Advantage of applying it to the engineering field is that the input–output relation and the mathematical modeling of the system are not necessary. As the combustion process in cylinder may be considered as a nonlinear dynamical process, it may be studied by tools borrowed to the nonlinear dynamical system theory. In last decade, there appeared a few works on dynamical pattern identification and prediction of in-cylinder combustion behavior. Daily [9] used a simple nonlinear engine cycle model, and illustrated CCV may possibly be connected to a chaotic process. In the work by Chew et al. [10], Phase portraits and Poincaré sections were obtained and the result showed that the in-cylinder pressure response was indeed chaotic. Several nonlinear approaches indicated that CCV might originate in nonlinear dependence of the peak cycle temperature and pressures on the initial conditions at the beginning of compression due to exhaust recirculation and a mixture preparation process [11–13]. Letellier et al. [14] suggested that CCV were not

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Nomenclature

IMEP	indicated mean effective pressure	MBT	maximum break torque
CCV	cycle-to-cycle combustion variations	p	in-cylinder pressure
COV_{IMEP}	coefficient of variations of IMEP	p_{max}	maximal in-cylinder pressure
TDC	top-dead-center	φ	crankshaft angle
ATDC	after TDC	°CA	degree crankshaft angle
BTDC	before TDC	Φ	equivalence ratio

governed by chaotic process because of the exhibition of a stochastic component. In the study by Scholl and Russ [15] concluded that deterministic patterns of CCV are the consequence of incomplete combustion. Nonlinear methods based on the deterministic chaos theory were also used to investigate the chaotic combustion in diesel engines [16]. Recently, some works showed that parameters, such as overall equivalence ratio, in-cylinder mixture homogeneity, turbulence intensity, spark timing and fuel injection timing, have strong effects on the dynamical pattern of CCV [17–21].

To date, contradictory reports about the characterization of the dynamics of in-cylinder pressure time series can be found in the literatures. CCV have been alternatively described as featuring and not featuring deterministic or chaotic behavior.

The present work also used tools belonging to the nonlinear dynamical system theory to study the dynamics of cycle-to-cycle combustion variations, however all experiments was conducted with a lean burn natural gas engine. In this way, the possibility of onset conditions of lean burn instability was intended to confirm and nonlinear determinism of the combustion process was detected in conditions relatively different.

2. Experimental apparatus and test plan

A six-cylinder, four-stroke Diesel engine, adapted for natural gas engine fed by adding a multi-point port fuel injected system and spark plugs, was selected for the study and was mounted on a test-bed (shown in Fig. 1(a)). The engine was turbocharged and after-cooled and its geometric details are listed in Table 1.

Fig. 1(b) shows the test bed set up for the experimental study. The engine was coupled to a 260 kW eddy current dynamometer and speed was measured using a 60 tooth sprocket and magnetic pickup. Engine torque and speed were controlled with the dynamometer controller in conjunction with a throttle controller. In-cylinder pressure measurement was accomplished using a Kistler 6125B quartz pressure transducer connected to a Kistler 5015A mode charge amplifier. The pressure transducer was mounted in the head of cylinder No. 6. Though relatively robust to thermal shock, the transducer was mounted through the engine water jacket, providing additional cooling and protection from such effects. Crank angle was measured using a free end mounted crank shaft encoder that was rigidly mounted to the front of the engine and connected to the crank shaft with a flexible coupler. The optical encoder outputs three channels of signals including "A", "B" and "C" channel. "A" channel outputs a pulse every 0.36 °CA and these pulses offer the ability to continuously trigger the in-cylinder data acquisition. "C" channel used to detect TDC outputs one pulse, which has a fixed interval of crank shaft phase, per crank shaft round. The location of TDC is determined by in-cylinder pressure diagram under the motored engine condition. Signals from the pressure transducer and the crank shaft encoder were acquired by a PC-based in-cylinder pressure measurement and analysis system based on a high-speed data acquisition board.

The scheme of experimental operating conditions is shown in Table 2. Time series of 800–2000 consecutive cycles of in-cylinder pressure data were recorded under each operating condition. Equivalence ratio was varied by adjusting the injected fuel pulse width, and throttle position was maintained constant for each group in the experiment to minimize effects on intake air dynamics and volumetric efficiency.

In order to minimize effects of control algorithms on cycle-to-cycle dynamics of the combustion process, an engine speed control system was the only feedback control used in the experiment. Engine speed was maintained constant even under very lean operating conditions by the eddy-current dynamometer.

3. The nonlinear dynamical system theory

Nonlinear behaviors are so ubiquitous in our world that nonlinear dynamical system theory has been a popular research area for more than 40 years. A dynamical system, which can be described by continuous differential equations or discrete equations, consists of an abstract phase space or state space. But, in most practical systems, their dynamical principles are not clear or parameters in them are even unknown, except that a time series of a parameter associated with the system may only be obtained. So, in order to investigate characteristics of a complicated system, nonlinear dynamical system theory is convenient and useful to deal with observed nonlinear data. By methods of nonlin-