



Cyclic variations and prior-cycle effects of ion current sensing in an HCCI engine: A time-series analysis



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HIGHLIGHTS

- Nonlinear characteristics are identified to cause strong cyclic variations in ion current signals.
- Time series, return maps and CoV are applied to analyze cyclic variations of ion current signals.
- Due to the low ionization energy, the stability of ion signals can be largely improved by adding CsOAc.
- Pattern structures in prior cycles are determined by a symbol-sequence statistics method.
- By stronger deterministic features, ion current signals are more reliable to be predicted than pressure signals.

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ABSTRACT

As an approach to replace pressure transducers, ion current sensing is a promising candidate for overcoming the difficult task of controlling the start of combustion in Homogeneous Charge Compression Ignition (HCCI) engines which require feedback from previous cycles. In this study, cyclic variations and prior-cycle effects of ion current signals are analyzed by comparing against pressure transducer signals using time-series methods in an HCCI engine. Additionally, the effects of various calibrated ion signal intensities are tested by adding cesium acetate (CsOAc) to the base fuel. Nonlinear characteristics of ion current signals are identified to cause strong cyclic variations through a single-zone model analysis with different equivalence ratios. By analyzing the time series, return maps, and coefficient of variations (CoV), the study finds that the stability of the ion signals can be largely improved by adding CsOAc due to the low ionization energy. After reconstructing a complex, nonlinear dynamical system model with symbol-sequence statistics, the measured cycle-resolved data of the ion current signal is analyzed to determine the pattern structures within prior cycles of fixed length, which is optimized by a modified Shannon entropy calculation. The results suggest that long, consecutive symbols of the ion current signal can be reliably predicted through the application of designed deterministic patterns especially when a small amount of CsOAc is added, although the ion current signal is normally considered a localized information provider and affected by many dynamical factors. Consequently, ion current signals are very promising for model-based control systems in HCCI engines with tolerable amounts of signal enhancing additives.

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1. Introduction

Homogenous Charge Compression Ignition (HCCI) is an ideal candidate for a next generation combustion mode because of its high efficiencies, low NO_x emissions, low Particulate Matter (PM) emissions, and the potential to operate on various fuels [1,2].

However, difficulties in directly controlling combustion timing and limits in operating ranges are two key issues constraining HCCI engine industrialization [3]. HCCI operating ranges are limited by the knock propensity at high loads [4] and unstable combustion processes caused by the strong cyclic variations at low loads [5,6]. The characteristics of cyclic variations can be defined to be linear random or deterministic coupling between consecutive cycles through a time-series method analysis [7,8]. The deterministic feature means the future states of the system follow explicit cause and effect laws, which can be predicted by the past values

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Nomenclature

Definitions, Acronyms, Abbreviations

aBDC	after bottom dead center
aTDC	after top dead center
bBDC	before bottom dead center
CA50	crank angle where 50% heat release occurs
CAD	crank angle degree
CoV	coefficient of variations
CsOAc	cesium acetate
EtOH	ethanol
HCCI	homogeneous charge compression ignition
H_s	modified Shannon entropy
IVC	intake valve closed

L	symbol sequence length
N	total possible number of symbol sequence
n	symbol set size
RPM	revolution per minute
SI	spark ignition
TDI	turbocharged direct injection
WMR	Well-Mixed Reactor
θ_{imax}	crank angle where maximum ion current occurs
θ_{pmax}	crank angle where maximum in-cylinder pressure occurs
φ	equivalence ratio

[9]. This structure can be applied in a model-based cycle-resolved control system to consider prior-cycle effects and effectively stabilize HCCI ignition timing [10]. Therefore, understanding dynamic features of HCCI under high cyclic variation conditions can potentially expand the operating ranges if there is a deterministic structure between consecutive cycles.

In the past, research analyzing cyclic variations using time-series methods were mainly performed on the characteristic combustion parameters measured by in-cylinder pressure transducers [10–13], which are prohibitively expensive outside of research environments. Using ion current sensing, usually employing a sparkplug as the sensor, to obtain feedback signals from different types of combustion is a promising replacement for piezoelectric pressure transducers [14,15]. Many researchers have proven that the ion current signal has a close phase relation with heat release parameters [16–19]. In SI engines, ion sensors have been widely studied to be the deduced feedback variable for the controller to estimate air/fuel ratio [20], pressure peak location [21,22] and IMEP [23] by neural networks, fuzzy controls, and other methods. In HCCI engines, apart from the feedback for CA50 [24], the crank angle where 50% heat release occurs, recent research indicates that a strong relationship exists between chemical ionization and NO_x generation, thus providing a real time ion current based NO_x detection feedback control for selective catalytic reduction (SCR) systems [25]. Thus the ion current signal is very promising for model-based HCCI combustion control systems as a low cost method with rich in-cylinder combustion information. However, the detected ion current signal is localized around the ion sensing probe [26]. The signal can be affected by dynamical noise in temperature, airflow, and local species concentration [26]. Therefore, cyclic signal variations are crucial issues in the ion current sensing methodology [14], especially at lean conditions where the ion signal becomes increasingly indistinguishable from the background measurement noise [15].

As mentioned earlier, most previous research has only considered the correlation between the ion current and the variable to be estimated. Since HCCI cycle-resolved feedback control also needs to consider the prior-cycle effects, dynamical noise can obscure the underlying deterministic patterns in previous cycles, which are deteriorated by errors in measurements. Symbol-sequence statistics [9,12] offer a simple and effective approach to minimizing the dynamic noises and measurement inaccuracies so that the prior-cycle effects can be quantified. The pattern structure found in the consecutive cycles can then be applied to predict future cycles and embedded within the control algorithm to stabilize ignition timing of HCCI combustion [6,10]. Additionally, the symbolization can be used during data acquisition so that it

becomes a means of data compression, which can strongly accelerate data processing.

This paper first analyzes the causes of ion current signal cyclic variation using a single-zone model. Cyclic variations are then investigated and compared between the ion current and pressure transducer signals in time series, return map, and coefficient of variations (CoV). An approach that reconstructs a complex, nonlinear dynamical system model with symbol-sequence statistics is applied to analyze pattern structures in the time-series data within prior cycles of fixed length, which is determined by the modified Shannon entropy calculation. Due to the low ionization energy, small amounts of cesium acetates (CsOAc) are added to show how deterministic features are affected by various ion signal intensities.

2. Experimental methods

2.1. Engine specifications

The HCCI engine used in this research is modified from a 1.9L 4-cylinder Volkswagen TDI engine. Engine specifications are shown in Table 1. More details can be found in [27,28]. The fourth cylinder was chosen as the single cylinder mode by deactivating fuel injection into the other three cylinders. Major modifications to realize HCCI mode in this engine include:

1. The original deep bowled piston is replaced with a flat top piston.
2. Holes of the glow plug are re-machined for the standard 10 mm sparkplugs which are used as the ion sensing probe.

Table 1
Engine specifications.

Configuration	4-cylinder
Displacement	1.9 L
Compression ratio	17:1
Bore diameter	79.5 mm
Stroke	95.5 mm
Connecting rod length	144.0 mm
Firing order	1-3-4-2
Valves (intake, exhaust)	1, 1
Intake valve open (IVO)	16 CAD aTDC
Intake valve close (IVC)	25 CAD aBDC
Exhaust valve open (EVO)	28 CAD bBDC
Exhaust valve close (EVC)	19 CAD aTDC
Valve overlap	1 CAD
Valve lift (intake, exhaust)	1.0 cm
Engine speed	1800 ± 5 rpm

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