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Exploring the stochastic and deterministic aspects of cyclic emission variability on a high speed spark-ignition engine

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ABSTRACT

This study contributes to the understanding of cycle-to-cycle emissions variability (CEV) in premixed spark-ignition combustion engines. A number of experimental investigations of cycle-to-cycle combustion variability (CCV) exist in published literature; however only a handful of studies deal with CEV. This study experimentally investigates the impact of CCV on CEV of NO and CO, utilizing experimental results from a high-speed spark-ignition engine. Both CEV and CCV are shown to comprise a deterministic and a stochastic component. Results show that at maximum break torque (MBT) operation, the indicated mean effective pressure (IMEP) maximizes and its coefficient of variation (COV_{IMEP}) minimizes, leading to minimum variation of NO. NO variability and hence mean NO levels can be reduced by more than 50% and 30%, respectively, at advanced ignition timing, by controlling the deterministic CCV using cycle resolved combustion control. The deterministic component of CEV increases at lean combustion ($lambda = 1.12$) and this overall increases NO variability. CEV was also found to decrease with engine load. At steady speed, increasing throttle position from 20% to 80%, decreased COV_{IMEP}, COV_{NO} and COV_{CO} by 59%, 46%, and 6% respectively. Highly resolved engine control, by means of cycle-to-cycle combustion control, appears as key to limit the deterministic feature of cyclic variability and by that to overall reduce emission levels.

1. Introduction

Spark-ignition (SI) internal combustion engines (ICEs) constitute the most widespread power source for light duty vehicles [1]. SI engine technology has to fulfill increasingly stringent air pollutants and greenhouse gas emissions standards. Leaner and more diluted air-fuel mixtures generally increase thermal efficiency and reduce pollutants resulting from incomplete combustion, but also increase combustion variability from cycle to cycle (CCV) [2]. Hence, CCV is one of the combustion limits that have to be considered when designing efficient lean-burn combustion engines. Moreover, as pollutants formation is linked to the combustion process and mixture conditions, CCV appears as the main origin of cyclic emissions variability (CEV) [3–5]. Understanding and controlling CCV is therefore required to design both more efficient and cleaner engines.

CCV mostly originates from variations in the in-cylinder gas motion, perturbations in the air/fuel ratio from cycle to cycle and mixture non-uniformities, including variance in the residual gas mass from the previous combustion cycle [6]. The exact magnitude of all these variables, especially close to the spark plug, is very important due to their impact on the early flame kernel development. Early flame development is recognized as the most crucial stage of combustion evolution [7,8] and greatly affects the subsequent build-up of cylinder pressure during flame propagation [9,10]. Slow rate of early flame kernel leads to slow flame propagation rate and subsequently to lower peak pressures [11]. The variation of in-cylinder turbulence and the local mixture composition were found in the study of Sjerić et al. [12] to be the dominant factor that affects the cyclic variability. Experimental studies on a lean-burn SI engine showed that slightly rich conditions close to the spark plug give fast burn cycles, while too lean mixtures may not even ignite [2,13]. It is also well known that at very lean and highly diluted mixtures, the spark ignition energy has a significant impact on the combustion process [14].

CCV consists of both stochastic and deterministic phenomena. On one hand, SI engine operation at stoichiometric, homogeneous-charged and low-dilution conditions exhibits CCV that can be approached as a random phenomenon with no short-term

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predictability. Fluctuations of the gas mixture motion and turbulence as well as perturbation of the quantity and spatial distribution of the fuel are related with the stochastic aspect of cyclic dispersion. On the other hand, at leaner and more dilute mixture conditions, a more visible deterministic aspect of cyclic variability implies some degree of predictability and potential for real-time control [15]. Grünefeld et al. [16] showed that high combustion pressure of the preceding cycle results to a higher quantity of residual gas and a lower combustion pressure in the following cycle. The "memory" effect from cycle to cycle has been also revealed in another study [17]. The deterministic aspect of CCV is interesting because it can be limited through high-frequency real-time control of the combustion process. Therefore, it becomes extremely useful for future SI engines design [18] to explore the potential of combustion efficiency improvement and pollutants formation reduction by limiting the deterministic feature of CCV, under various engine operating conditions.

Although the nature of CCV has been explored in a great number of studies, only a few deal with the experimental investigation of CEV. Still, the effect of combustion variation on emissions variability cannot be satisfactorily interpreted. Milkins et al. [19] found that the mean combustion cycle corresponds to relatively low CO and HC emissions while faster and slower burning cycles always lead to higher emissions. It is known from mean cycle studies that CO emissions are mainly controlled by the overall mixture equivalence ratio [20]. However the impact of air/fuel ratio on the actual scatter of CO levels has been investigated in the literature only from the stochastic point of view [21]. On the other hand, NO formation is linked to oxygen availability, burn rate, and maximum cylinder pressure [5,22–24]. Cyclic variations of combustion and pressure development [25], cyclic fluctuations of mixture air/fuel ratio [26], and heterogeneities of cylinder charge [27] are the main sources of NO variation. One study [25] showed that NO formation exhibits a non-linear correlation with indicated mean effective pressure (IMEP), while a more recent study investigated the impact of various engine parameters such as equivalence, load, and ignition timing on NO CEV [21]. However, a detailed experimental study that explains the origins of NO variability into deterministic, which can be controlled, and stochastic, which cannot be controlled, has not yet been conducted.

This work experimentally studies the nature of cyclic emissions variability, primarily of NO and CO, under various engine loads and speeds by varying the equivalence ratio and the ignition timing. The aim is to identify the extent by which phenomena leading to emissions variability can be determined and controlled and to separate these from neatly stochastic variability. To the best knowledge of the authors, this is the first study of its kind.

2. Experimental setup

2.1. Engine

The experiments were conducted on an in-line four cylinder port fuel injection SI engine, modified from an original HONDA CBR600RR motorcycle (Table 1). The engine was controlled by a programmable open-access engine control unit (ECU), which enabled alteration and recording of the entire set of engine parameters (e.g., spark timing, equivalence ratio, fuel injection timing and duration, etc.) and was connected to a Schenk steady-state hydraulic brake. The fuel used was a market petrol with a nominal octane number of 98 RON.

2.2. Experimental configuration and measurements

The experimental setup is schematically illustrated in Fig. 1 and Table 2 provides the main specifications of the relevant instruments. The measurements involved recording of two sets of parameters, one at high and the other one at low sampling frequency. High frequency sampling was conducted for cylinder pressure, exhaust gas temperature, crankshaft and camshaft position and emissions of CO, CO_2, NO and NO_x. Pollutants measurement was conducted in the exhaust manifold directly downstream of the exhaust valve. A National Instruments 6341 USB data acquisition card was used for high frequency sampling, capable of sampling rates up to 500 kHz. In this experimental study, a set of 150 consecutive cycles was sampled at each engine operating point, while the sampling rate was adjusted to correspond to 0.5° of crank angle.

Table 1
Engine characteristics.

Main specifications		
Bore	67.0	[mm]
Stroke	42.5	[mm]
Con. Rod length	91.8	[mm]
Compression ratio	12.2	[–]
Displacement	599	[cm^3]
Maximum power	95HP@10800 rpm	
Cam timing		
IVO	26	BTDC
IVC	23	ABDC
EVO	40	BBDC
EVC	5	ATDC
Valvetrain	Chain driven, DOHC	
Cylinder head		
Type	Honda CBR-600	
Inlet valve diameter	26.0	[mm]
Exhaust valve diameter	22.5	[mm]
Number of valves	4	[–]
Fuel system		
Fuel delivery	Port fuel injection	

The low sampling frequency set of parameters comprised ECU derived signals, including the lambda sensor value (λ), ignition timing, throttle position, inlet air pressure and temperature and coolant temperature, all recorded at a frequency of 10 Hz. Average CO, CO_2, and HC emissions were also recorded at low frequency in the exhaust line, upstream of the muffler.

A Kistler 6113B measuring spark plug with an integrated piezoelectric transducer was used to measure cylinder pressure. This is manufactured to fit the particular engine cylinder head and can be used as a direct replacement of the original spark plug. The signal from the transducer was fed to a Kistler 5011B charge amplifier. The error in the cylinder pressure measurement was less than ±1% full scale reading (FSO). The exhaust gas temperature was measured with a K-type thermocouple connected to the relevant transducer, with maximum error of 0.75% of reading.

High frequency pollutants measurement of cycle-resolved emissions was conducted using fast response analyzers. In this study, a Cambustion fNOx400 analyzer was employed for cycle-to-cycle measurement of NO and NO_x concentrations. This fast response NO detector combines standard chemiluminescence detection (CLD) with a rapid sampling method [23,28]. Both sampling heads of this analyzer sampled from the exhaust port, as illustrated in Fig. 1. One channel was used for NO measurement, with response time in the order of 4 ms, while the second one measured total NO_x (by converting NO_2 to NO using the necessary converter). Similarly, a fast response CO/CO_2 analyzer (Cambustion NDIR500) utilizing the standard NDIR measurement was used, with the short response time achieved by miniaturizing the sampling volume [29,30]. This analyzer also comprised two channels, each able of detecting both CO and CO_2 signals. The first channel measured exhaust port concentrations while the second one