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Full Length Article

Correlation between cycle-by-cycle variation, burning rate, and knock: A statistical study from PFI and DISI engines

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HIGHLIGHTS

- The correlation between CBC variation, burning rate, and knock have been studied experimentally.
- CBC variation is linearly correlated with burning rate and relative air-fuel ratio.
- Knock tendency increases with increasing CBC variation, which is attributed to the nonlinear relationship between the peak pressure and NIMEP.

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ABSTRACT

There has been a substantial increase of the number of direct injection spark-ignition (DISI) engines in the last decade as they can achieve much better efficiency than port fuel injection (PFI) engines. With direct injection (DI) system, engines tend to shift from the larger one to the smaller one coupled with turbocharger, namely engine downsizing. Because of the downsizing, the modern DISI engines are more sensitive to knock. Since knock is correlated to the burning rate of a combustion cycle and the burning rate can be varied significantly due to cycle-by-cycle (CBC) variation, one of the recent study on DISI engines is focused on the correlation between CBC variation and knock. Furthermore, as burning rate, CBC variation, and knock are all the functions of in-cylinder pressure, there should be a correlation among them. In this work, such correlation is studied experimentally by using a PFI and two DISI engines. From the statistical analysis, it has been found that CBC variation and burning rate are linearly correlated. It also has been found there is a linear relationship between knock and burning rate. By connecting the relationship between CBC variation and burning rate to the relationship between knock and burning rate, the relationship between knock and CBC variation is developed. Knock tendency increases with increasing CBC variation, which is attributed to the nonlinear relationship between the maximum in-cylinder pressure (p_{max}) and net indicated mean effective pressure (NIMEP). By using the model of limited-pressure cycle with isentropic compression and expansion, it has been demonstrated that p_{max} increases exponentially with increasing NIMEP.

1. Introduction

In spark-ignition (SI) engines, cycle-by-cycle (CBC) variation in the combustion process exists due to the cyclic uneven charge motion inside of combustion chamber [1]. CBC variation is important for several reasons. Firstly, spark timing of an engine is normally set to the point that provides maximum brake torque (MBT). At MBT spark timing, the combustion process gives the best efficiency, and the cycle that burns at a slower rate will be less efficient. Secondly, CBC variation affects the drivability of a vehicle [2]. The fast burning cycle produces more power than the slow burning cycle, and this difference can be large when the CBC variation is high. Therefore, the overall power output can be rough. For instance, for an engine that is idling with high CBC variation, the slow burn that occurs in a cycle may lead to incomplete combustion or even misfire. To prevent such event, a higher engine load/speed is required, which will increase the fuel consumption. For idle operations, this is a waste of energy. Thirdly, because the fast burning cycles are likely to knock [3], higher CBC variation will increase the tendency of knock. To avoid knock, spark timing and/or compression ratio (r_c) of the engine have to be limited,

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Nomenclature

ABDC	degree after top dead center
BTDC	degree before top dead center
CAD	crank angle degree
CA50	combustion phasing
$CA_{10-90\%}$	duration of 10–90% mass fraction burnt
CBC	cycle-by-cycle
COV	coefficient of variation
COV_{CA50}	coefficient of variation of combustion phasing
COV_{NIMEP}	coefficient of variation of net indicated mean effective pressure
DI	direct injection
DISI	direct injection spark-ignition
$[dp/dCA]_{max}$	maximum rate of pressure rise
HKST	high knock spark timing
H_2	hydrogen
KI	knock index
KLST	knock limited spark timing
LKST	low knock spark timing
MBT	maximum brake torque
MFB	mass fraction burnt
MLR	multiple linear regression
NIMEP	net indicated mean effective pressure
NIMEPmax	maximum NIMEP of a sample
NIMEPmedian	median NIMEP of a sample
NIMEPmin	minimum NIMEP of a sample
PFI	port fuel injection
p_{max}	peak pressure
r_c	compression ratio
SI	spark-ignition
s_i	sample standard deviation of parameter i
s_{NIMEP}	standard deviation of net indicated mean effective pressure
$\bar{x}_{CA50}$	sample mean of combustion phasing
$\bar{x}_{CA_{10-90\%}}$	maximum brake torque
$\bar{x}_{[dp/dCA]_{max}}$	sample mean of maximum rate of pressure rise
$\bar{x}_i$	sample mean of parameter i
$\bar{x}_{NIMEP}$	sample mean of net indicated mean effective pressure
$\bar{x}_{p_{max}}$	sample mean of peak pressure
γ	specific heat ratio
$\eta_{f,i}$	indicated fuel conversion efficiency
λ	relative air-fuel ratio

which will reduce the efficiency and hence the power output. This is particularly a concern of modern direct injection spark-ignition (DISI) engines, as they are typically downsized.

Previous research suggested that CBC variation in SI engines is dependent on the location of the kernel and the flame growth rate at the early stage of combustion [4]. This is not only true for the SI engines coupled with port fuel injection (PFI) systems [5,6], but also is true for DISI engines [7,8]. The flame growth at the early stage of combustion is strongly influenced by the mixture composition and the flow in the vicinity of the spark plug gap. Soltau has shown that the engine with several ignition points has less CBC variation than the engine with single ignition point [9]. This is because the time period between the spark discharge and the formation of stable flame front are more constant with multiple ignition points. By measuring the velocity in the combustion chamber, Patterson found that the CBC variation is dependent on the variations of mixture velocity near the spark plug at the time of ignition [10]. Recently, Zeng et al. applied high-speed particle image velocimetry and flame imaging techniques on a fired DISI engine to study the effects of swirl on the variation of ignition and subsequent combustion phases [11]. They demonstrated that the spark-plasma motion is strongly correlated to the direction of the charge motion in the vicinity of the spark plug gap. Without swirl, the plasma moves randomly toward either side of the spark plug; with swirl, the plasma moves consistently toward one direction, and therefore reducing the CBC variation.

In the past, research on CBC variation in SI engines was mainly driven by the motivation of improving combustion stability in order to achieve greater efficiency and drivability. Since the net indicated mean effective pressure (NIMEP) is directly correlated with the drivability, the most commonly used parameter to represent CBC variation in an SI engine is coefficient of variation of NIMEP (COV_{NIMEP}).

Recent years, DISI engines become popular as they can achieve much better efficiency than PFI engines. With direct injection (DI) system, engines tend to shift from the larger one to the smaller one coupled with turbocharger, namely engine downsizing. Because of the compact design of the modern DISI engines, to provide sufficient power output, the engine operating parameters such as spark timing and r_c are all optimized. Any reductions from the optimum will affect the engine performance significantly. For this reason, the performance of DISI engines is more sensitive to knock. It has been demonstrated that the knock is likely to occur in a fast burning cycle [3], and due to the intrinsic nature of the CBC variation, it is likely for an engine with a large CBC variation to have some fast burning cycles. Therefore, CBC variation may have a significant impact on the design and operation of modern DISI engines. From this perspective, it is important to study the relationships between CBC variation and engine knock.

Zervas analysed coefficient of variation (COV) of in-cylinder pressure trace of a PFI engine [12]. He found that there is a consistency in the COV of the pressure trace. The location of the maximum COV in the pressure trace is closely around the location of the combustion phasing (CA50). Such trend also has been observed by Jo in a turbocharged DISI engine [13]. Based on this finding, Samuel et al. studied the relationship between CBC variation and burning rate [14]. They found there is a connection between COV_{NIMEP} and mass fraction burnt (MFB). Furthermore, Reyes et al. also found there is a correlation between COV_{NIMEP} and MFB, as well as COV of maximum combustion pressure [15]. Nevertheless, the relationships among these parameters are vague.

It is commonly agreed that knock is caused by the autoignition of end-gas [16–21], which is strongly dependent on the end-gas temperature and pressure [22,23]. End-gas temperature and pressure are dependent on the burning rate. In a fast burning cycle, there is a greater compression of the end-gas within the time frame, which results a greater end-gas temperature and pressure. Consequently, knock is more likely to occur [3,24]. Recent study also shows that both knock tendency and intensity are correlated to the burning rate [25].

As burning rate is correlated with COV_{NIMEP} and knock, and all these parameters are the function of in-cylinder pressure, there should be a correlation between CBC variation and knock. In this work, a such correlation is studied comprehensively via statistical analysis.