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Characterization of cycle-to-cycle variations in a natural gas spark ignition engine

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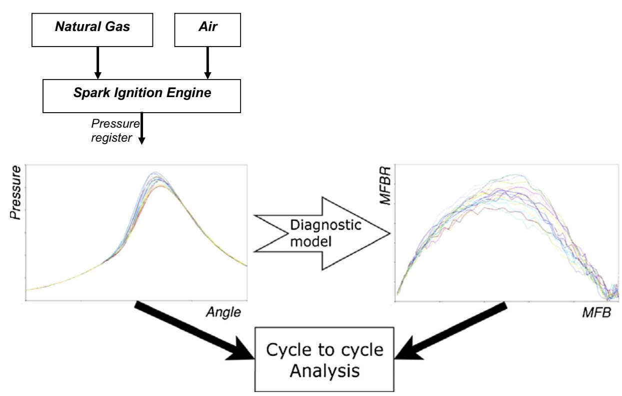
HIGHLIGHTS

- Study the influence of equivalence ratio and engine speed on cyclic variations.
- Diagnostic model with temperature dependant properties.
- Genetic algorithms applied to the analysis of the combustion inside an engine.
- Automatic adjustment of the diagnostic parameters.
- Application of the methodology to the study of the cyclic variability.

GRAPHICAL ABSTRACT



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ABSTRACT

In this work a study of the influence of the fuel/air equivalence ratio and engine rotational speed on the cycle-to-cycle variations in combustion in a natural gas spark ignition engine is presented. The study considers both classic estimators of cyclic dispersion and a new one, based on the burned mass and burning rate. The engine experimental conditions were as follows: Intake pressure 0.5 bar, while fuel/air equivalence ratio was changed from 1.0 to 0.63, and engine rotational speed was varied from 1000 rpm to 2500 rpm. For each equivalence ratio and engine speed, a diagnosis model is used to process the experimentally obtained combustion pressure data in order to provide combustion relevant results such as the mass burning rate at a cycle level. A procedure based on the use of genetic algorithms is used to obtain a very accurate and objective (without human intervention) adjustment of the optimum parameters needed for combustion diagnosis: angular positioning and pressure offset of the pressure register, dynamic compression ratio, and heat transfer coefficients. The model allows making the diagnosis of series of 830 consecutive engine cycles in an automatic way, increasing the objectivity of the combustion diagnosis. The paper focuses on using the values of the mass fraction burned computed from the pressure register and especially on the analysis of the combustion cycle to cycle variation in the natural gas fuelled engine. A new indicator for the study of cycle-to-cycle variations is proposed, i.e. the standard deviation of the mass fraction burning rate. The values of this new indicator are compared with other classic indicators, showing the same general trends. However, a deeper insight is provided on the combustion cyclic variation when the values of the new indicator are plotted as a function of the mass fraction burned, since this allows analyzing the cyclic variation along the combustion development in each cycle from a mass fraction burned of zero to one, with a relevant value at mass fraction burned of 0.5. More important is that the consideration of the dependence of the combustion variables (density, flame front surface,

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combustion speed) on the mass fraction burned allows ensemble averaging of all registered cycles for each value of mass fraction burned. This permits using the ensemble averaged mass fraction burning rate as an estimator of combustion speed.

The analysis of the general trends of cyclic dispersion when engine speed and equivalence ratio are modified (1000, 1750 and 2500 rpm; 0.7, 0.8, 0.9 and 1.0) indicate that cycle-to-cycle variations show, as expected, a strong dependence on the engine rotational speed, increasing the variation with engine rpm. However, when the standard deviation of mass fraction burning rate is plotted as a function of mass fraction burned, there is a linear dependence on engine rpm, but only a very weak dependence on equivalence ratio. This means that the proposed estimator of cyclic dispersion is sensitive to only flow turbulent intensity and not to equivalence ratio.

Nomenclature

A_f	spherical flame front area (m^2)
c_m	mean piston velocity (m/s)
CR	compression ratio (–)
E	error
HCCI	homogeneous charge compression ignition
ICE	internal combustion engine
IMEP	indicated mean pressure (Pa)
m	total mass (kg)
MFB	mass fraction burned (–)
MFBR	mass fraction burning rate (1/° or 1/s)
NG	natural gas
p	pressure (Pa)
p_m	motored engine pressure (Pa)
R_j	universal gas constant
S_c	combustion speed (m/s)
T	temperature (K)
TDC	top dead center
u_j	internal energy (J/m^3)
V	volume (m^3)
$V(\alpha)$	cylinder volume for each crank angle (m^3)
Greek	
α	crank angle (° or rad)
Φ	fuel/air equivalence ratio ($\varphi = \dot{m}_{\text{sto air}}/\dot{m}_{\text{air}}$)
μ	mean value
ρ	density (kg/m^3)
σ	standard deviation
Subscripts	
b	burned
max	maximum
u	unburned, fresh
wos	Woschni's

1. Introduction

Because of concerns for the environment protection and energy shortages, much effort has been concentrated on the utilization of alternative fuels in internal combustion engines (ICE). Alternative fuels are clean when they are compared to conventional ones derived from petroleum in ICE. Natural gas (NG) is considered to be a possible alternative fuel due to its higher octane number and properties. NG is a mixture of different gases where methane is its main component (75–98% of methane, 0.5–13% of ethane and 0–2.6% of propane [1]). NG combustion produces lower emission than that of conventional fuels because the chemical structure of NG is less complex, together with the non-existence of fuel evaporation [2]. The high octane number of NG (between 120 and 130) allows the engine to operate at high compression ratios, because it gives a high anti-knocking potential [3].

In general, combustion in spark-ignition engines varies considerably from cycle to cycle [4]. Many studies have been carried out in order to find the main causes of this effect [5,6]. These variations are associated with considerable variations in flame speed and combustion duration [7]. The effect of cyclic dispersion is also described by Litak et al. [8,9]. These variations produce a reduction in the mean effective torque as much as 20% [10].

Cyclic dispersion has been classically evaluated by statistical processing of the maximum pressure (p_{max}) and the angle in which this maximum pressure is reached ($\alpha_{P\max}$) [11]. It has also been studied with the variation in the heat released during the combustion [12,13]. Recently it also has been studied in homogeneous charge compression ignition (HCCI) engine processes [14], compression ignition engines [15] and also by using CFD simulations [16]. A traditional [17–22] estimator of the cycle-to-cycle variation is the Coefficient of Variation in Indicated Mean Pressure, COV_{IMEP}. In this paper, the authors propose complementary considering the variation of the mass fraction burning rate of each individual cycle to characterize cyclic variation, as explained later (Fig. 1).

Cycle-to-cycle dispersion studies carried out using combustion diagnosis require a lot of effort because each cycle requires adjusting some parameters such as pressure offset, angular positioning and others, before an accurate analysis can be performed. This implies that cyclic dispersion studies conducted by manual or traditional diagnostic techniques include some degree of subjectivity in the results. Moreover, in many studies, the combustion models were simple as the one described by Li and Yao [23].

A complex diagnostic model, with temperature dependent thermodynamic properties and heat loses, is used to evaluate the pressure data obtained experimentally. The model has been

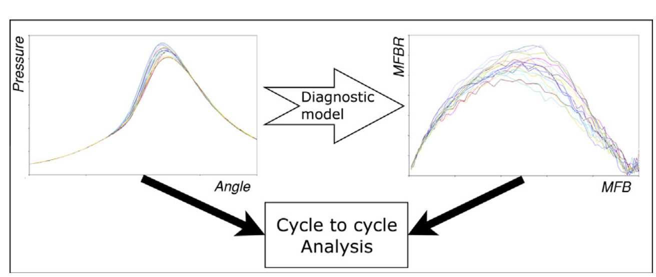

Fig. 1. Classical and proposed ways of analyzing cycle to cycle variation outline.