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Knock probability estimation through an in-cylinder temperature model with exogenous noise

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ABSTRACT

This paper presents a new knock model which combines a deterministic knock model based on the in-cylinder temperature and an exogenous noise disturbing this temperature. The autoignition of the end-gas is modelled by an Arrhenius-like function and the knock probability is estimated by propagating a virtual error probability distribution. Results show that the random nature of knock can be explained by uncertainties at the in-cylinder temperature estimation. The model only has one parameter for calibration and thus can be easily adapted online.

In order to reduce the measurement uncertainties associated with the air mass flow sensor, the trapped mass is derived from the in-cylinder pressure resonance, which improves the knock probability estimation and reduces the number of sensors needed for the model.

A four stroke SI engine was used for model validation. By varying the intake temperature, the engine speed, the injected fuel mass, and the spark advance, specific tests were conducted, which furnished data with various knock intensities and probabilities. The new model is able to predict the knock probability within a sufficient range at various operating conditions. The trapped mass obtained by the acoustical model was compared in steady conditions by using a fuel balance and a lambda sensor and differences below 1% were found.

1. Introduction

In spark-ignited (SI) engines the combustion is initiated by the energy released by the spark. This combustion generates a flame front which moves along all the cylinder volume in a uniform manner [1]. During the flame propagation the temperature of the unburned gas increases due to the rise of the in-cylinder pressure. In normal combustion events, the flame front reaches all of the cylinder volume in a controlled scheme; however, high unburned gas temperatures can cause the autoignition of the end-gas.

The autoignition of the end-gas (knock) is an undesirable phenomenon and is one of the main limitations in SI engines. The rapid combustion of the end-gas heavily excites cylinder head resonance, and its vibration reduces the combustion efficiency and can damage the engine [2–4].

Current approaches for knock control use the spark advance (SA) timing for modifying the combustion phasing and thus, the likelihood of knock. The control strategies can be divided into two groups: stochastic and model-based. Stochastic

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methods aim to directly control the knock probability by varying the SA [5–7], while model-based methodologies use the spark advance for keeping in-cylinder conditions, e.g. un-burned gas temperature, within a desired range [8–10].

Regarding the physics behind the knock phenomenon, several studies state that knock cannot be predicted in a deterministic manner [11,12]. On one hand, when operating in steady-state conditions, the flame propagation in SI combustion has a significant cycle-to-cycle variability [13,14], which directly influences the cycle-to-cycle knock probability. On the other hand, some research suggest that the autoignition of the end-gas could be initiated at hot spots, influenced by inhomogeneities of the mixture [15–17]. Furthermore, the autoignition of the end-gas is driven by an Arrhenius-like function [18,19], and small errors in the gas temperature are propagated in knock models by an exponential function resulting in important errors in the prediction of knock.

The present paper proposes estimating the knock probability by adding an exogenous noise over the in-cylinder temperature model. This noise represents uncertainties such as temperature hot spots, in-cylinder pressure pegging, wall heat transfer, residual mass variations, and sensor errors. Hence, the model is developed with the assumption that the random nature of knock is due only to in-cylinder temperature uncertainties. It is beyond the scope of this paper to prove this assumption; however, the experimental results show that it improves the prediction capabilities of a control-oriented knock model.

The model presented aims to reduce the unburned gas uncertainties estimating the trapped mass by identifying the resonant frequencies of the in-cylinder pressure waves. The method was recently applied to compression ignited (CI) and homogeneous charge compression ignited (HCCI) engines [20–22], and some applications, i.e. NOx and residual gas fraction estimation, have been already explored [23,24]. One of the most important sources of error is the estimation of the trapped mass, which is a crucial parameter for the estimation of the unburned gas temperature. Measurement errors of hot-film air mass flow sensors, which are widely employed in automotive applications, can attain up to 20% because of ageing and other non-calibrated effects [25,26]. Furthermore, there are no sensors for estimating the residual gases, which in SI engines without negative valve overlap represent between 3% and 5% of the total mass trapped, and they exhibit important cycle-by-cycle variations [27,28].

In addition, past works on the method, as tested in cylinders with an in-piston bowl, do include the engine speed fluctuations with the bowl effect by a crank angle dependent parameter [29]. In this paper, a spark-ignited engine was used and the instantaneous engine speed was measured and modelled by the camshaft model given by Li and Stone in [30], which estimates the engine speed fluctuations from the in-cylinder pressure evolution and the break mean effective pressure (BMEP). Herein, the frequency is demonstrated to follow Draper's equation [31] with no need for any calibration effort. A fuel balance, a lambda sensor, and a residual mass model were used for validation in steady conditions.

The resonance methodology is specially suitable for the knock modelling of SI engines for three reasons:

(1) SI engines normally do not have a bowl. Theory based on a cylindrical combustion chamber thus fits the physics better.
(2) Knocking conditions are produced at high loads, where combustion heavily excites the resonant frequencies, even in the absence of knock.
(3) SI combustion is performed in stoichiometric conditions and the resulting end-gas properties can be easily identified [32].

In order to evaluate the improvement associated with the methodology based on in-cylinder pressure for estimating the trapped mass, the knock model was run by using the trapped mass from the resonance method and by using the air mass flow sensor.

The paper is organized as follows: The next section describes the procedure for estimating the knock probability. Section 3 introduces the experimental set-up and the tests performed. Section 4 shows the performance of the knock model and illustrates the effect of sensor errors by comparing the air mass flow sensor and the trapped mass obtained from resonance. Finally, the last section highlights the main contributions of the method and points out the future work required for using the model in a control scheme.

2. Model description

The complete model uses the in-cylinder pressure and the geometrical parameters of the engine to estimate the probability of knock. The model can be summarized by the following steps:

(1) The content of the in-cylinder pressure compressed on the frequency band of resonance (between 4 kHz and 20 kHz) is used for characterizing the acoustical waves and estimating the in-cylinder trapped mass.
(2) The low-frequency band of the pressure signal is used to analyse the combustion, compute the temperature of the unburned gases, and estimate the autoignition delay.
(3) An exogenous noise is added to the unburned gas temperature and it is propagated along the model. This yields a probability distribution of the autoignition delay (not a single value).
(4) The knock probability is obtained by integrating the autoignition delay probability distribution which predicts an autoignition of the end-gas before the combustion ends.