Applied Energy 171 (2016) 142–152

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Identification of ringing operation for low temperature combustion engines

Bahram Bahri [a,*], Mahdi Shahbakhti [b], Kaushik Kannan [b], Azhar Abdul Aziz [c]

[a] Automotive, Fuel and Emission Research Center (AFERC), Department of Automotive Engineering, Shahreza Branch, Islamic Azad University, Shahreza, Iran
[b] Department of Mechanical Engineering-Engineering Mechanics, Michigan Technological University, 1400 Townsend Drive, Houghton, MI, USA
[c] Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, Automotive Development Centre (ADC), Johor Bahru, Malaysia

HIGHLIGHTS

- Proposes and experimentally validates a model to predict ringing intensity (RI) in HCCI engines.
- The RI model is computationally efficient for realtime identification of high RI engine operation.
- Investigates performance and emissions of an HCCI engine at ringing operation.
- Examines the relation between major engine combustion parameters and RI for over 155 steady-state HCCI operating conditions.

ARTICLE INFO

Article history:
Received 24 December 2015
Accepted 13 March 2016
Available online 22 March 2016

Keywords:
HCCI
LTC
Ringing operation
Ringing intensity
Artificial neural network

ABSTRACT

High-efficiency and low-emission low temperature combustion modes including homogeneous charge compression ignition (HCCI) are limited at high load conditions due to rapid pressure rise rate, short combustion duration and ringing operation. This study uses two different HCCI engines to investigate combustion-generated ringing at a number of HCCI engine operating points between misfire and ringing zones for ethanol and *n*-heptane fuels. Ringing intensity (RI) is investigated along with main HCCI combustion parameters and engine-out emissions. The results show the RI generally increases by advancing crank angle of 50% fuel burnt (CA50) and also decreasing burn duration (BD). It is found that adjusting CA50 can provide a control knob for the RI since all the extreme noisy data points have CA50 < 9 CAD aTDC. In-cylinder pressure at 5, 10, 15 CAD aTDC (P_5, P_{10} and P_{15}) and maximum in-cylinder pressure (P_{max}) show strong correlation with RI. To this end, P_5, P_{10} and P_{15} and P_{max} are used to develop an artificial neural network (ANN) model to predict RI. Experimental data at 155 steady-state points are used to evaluate the ANN model for two totally different HCCI engines running with high and low octane fuels. The validation results indicate that the ANN model can predict RI with less than 4.2% error. The ANN model can be used to identify HCCI ringing operation for combustion control applications.

1. Introduction

The demand for reducing greenhouse gas emissions and stringent governmental emission regulations have motivated engine designers and manufacturers to develop alternative technologies to tackle these challenges [1,2]. Homogenous charge compression ignition (HCCI) is a promising combustion mode among low temperature combustion (LTC) regimes that have the potential of providing high thermal efficiency, while having ultra-low engine-out nitrogen oxides (NOx) and particulate matter (PM) emissions [3]. However, high levels of unburned hydrocarbon (uHC) and carbon monoxide (CO) emissions, low efficiency at low-load engine conditions, control complexity of HCCI combustion, and ringing at upper zone of HCCI operation are some major HCCI limitations [4–6]. This paper aims to analyze HCCI ringing operation and develop a model to identify HCCI ringing.

For upper zone of HCCI operation, extreme noise level is generated due to audible pressure oscillation and also excessive pressure-rise rates (PRRs) are produced due to rapid combustion [7,8] which can cause ringing phenomenon. This event is called HCCI ringing and can cause thermal efficiency loss, damage the engine parts and decrease lifetime of the engine. Thus it is important to identify and avoid ringing operation in HCCI engines [8–10]. The HCCI combustion event is more rapid than that of conventional

* Corresponding author.
E-mail addresses: bahri@iaush.ac.ir (B. Bahri), mahdish@mtu.edu (M. Shahbakhti), kkannan@mtu.edu (K. Kannan), azhar@fkm.utm.my (A.A. Aziz).

http://dx.doi.org/10.1016/j.apenergy.2016.03.033
0306-2619/

Nomenclature

Φ	equivalence ratio	P_{max}	maximum in-cylinder pressure
aBDC	after bottom dead center	PM	particulate matter
aTDC	after top dead center	PPM	parts per million
ANN	artificial neural network	PPRR	peak pressure rise rate
BD	burn duration	R^2	correlation coefficient
CA_x	crank angle for x% of mass fraction burnt fuel (e.g., CA_{50})	RI	ringing intensity
CAD	crank angle degree	RMSE	root mean square error
CI	compression ignition	RPM	revolution per minute
CO	carbon monoxide	SI	spark ignition
EOC	exhaust oxidation catalyst	SOC	start of combustion
HCCI	homogeneous charge compression ignition	T_{ad}	adiabatic flame temperature
ICE	internal combustion engine	T_{exh}	exhaust gas temperature
IMEP	indicated mean effective pressure	T_{in}	intake temperature
LTC	low temperature combustion	uHC	unburned hydrocarbon
NOx	oxides of nitrogen	VFD	variable frequency drive
P_x	in-cylinder pressure at x crank angle degree (e.g., P_{20})		

spark ignition (SI) and compression ignition (CI) engines. Thus, HCCI combustion generally has a relatively high PRR [9] which limits the peak practical load of the engine [11]. Saxena et al. [12] found that HCCI ringing differs from knocking in HCCI and ringing detection is more difficult by external sensors mounted on cylinder wall because the effect of pressure waves are dampened by cylinder linings. Massey and Drallmeier [13] indicated that the noise is generated from the structural response of the engine structure due to rapid cylinder pressure rise.

Peak pressure rise rate (PPRR), ringing intensity (RI) and combustion noise level (CNL) are the three major in-cylinder pressure-based metrics which have been utilized to identify ringing operation in HCCI engines [9]. They also have been used for determining the upper zone of HCCI operation. PPRR is the maximum gradient of the pressure rise and can be easily calculated from in-cylinder pressure trace and is widely used to find the HCCI operation limit [14]. However, PPRR is not capable of identifying HCCI ringing operation because it is a scalar metric and cannot universally describe noise. It also cannot account for the frequency distribution of the pressure signal [10].

RI is a well-recognized metric to quantify and estimate the ringing extent in HCCI engines [9]. RI was first introduced by Eng [15]. In different studies [16–20] combustion noise limit and knock-free operation were found by RI over a wide range of HCCI engine operation conditions [21]. CNL is another combustion noise metric that is determined by an algorithm developed by Shahlari et al. [22] for calculating combustion noise for LTC engines. CNL and RI are related to each other [14], however RI has been more widely used in literature [8].

Calculation of noise in an HCCI engine by PPRR, RI and CNL require the whole in-cylinder pressure trace. For realtime combustion control, it is desired to detect combustion noise level with minimum required in-cylinder pressure data. To this end, an RI model is developed in this work that only requires in-cylinder pressure at four crank angles. In particular, in-cylinder pressure data at 5, 10, 15 CAD aTDC (P_5, P_{10} and P_{15}, respectively) and maximum in-cylinder pressure (P_{max}) are used for developing an artificial neural network (ANN) model to predict RI to identify engine operating points located in the ringing region. The ANN model is computationally efficient for HCCI combustion control which is a major challenge in HCCI engines.

Fig. 1 lists some of the studies which use ANN for identification of internal combustion engines (ICEs). These studies are divided into three main groups depending on the type of ICE studied. The

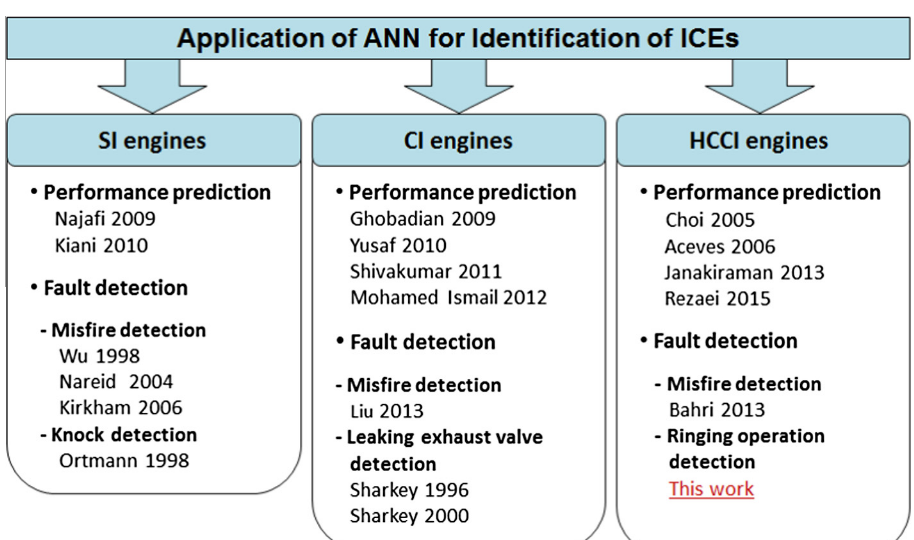

Fig. 1. Prior studies including application of ANN for performance prediction and fault detection in ICEs.