Mechanical Systems and Signal Processing 23 (2009) 1672–1682

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/jnlabr/ymssp

# A transient virtual-AFR sensor using the in-cylinder ion current signal

N. Rivara, P.B. Dickinson, A.T. Shenton *

*Department of Engineering, University of Liverpool, UK*

ARTICLE INFO

*Article history:*
Received 7 February 2008
Received in revised form
20 October 2008
Accepted 5 January 2009
Available online 20 January 2009

*Keywords:*
Air–fuel ratio
Ion current
Neural network
Principal component analysis
Spark ionization

ABSTRACT

This paper presents a neural network (NN) based air-to-fuel ratio (AFR) estimation scheme for spark ionization sensors in gasoline internal combustion (IC) engines. The proposed hardware and software estimation system results in a virtual wideband oxygen sensor for an individual cylinder. Principal component analysis (PCA) of the spark ionization signal is used with manifold absolute air pressure (MAP), fuel pulse width (FPW) and engine speed to train a NN offline to predict the AFR under transient engine load and speed settings. Experimental results from dynamometer tests on a port fuel-injected (PFI) four cylinder 1.6 l gasoline IC engine demonstrate that the NN based AFR prediction correlates well with AFR measured from a universal exhaust gas oxygen (UEGO) $\lambda$-sensor mounted in the exhaust manifold. The prediction is experimentally demonstrated to be robust to transients of load and engine speed. The experimental results significantly advance those of the previously published studies which have been largely restricted to simulation.



## 1. Introduction

The control of the air-to-fuel ratio (AFR) in internal combustion (IC) engines is still a considerable challenge. Increasing legislation for improvement in exhaust emissions requires precise fuelling control if performance and driveability are not to be sacrificed.

For a three way catalytic (TWC) converter to perform optimally, the AFR has to be kept within a window as small as 0.1% around the stoichiometric level [1] during steady state operation, which level is often expressed in terms of maintaining the $\lambda$ coefficient at unity where

$$\lambda = \frac{AFR_{\text{measured}}}{AFR_{\text{stoic}}}.$$

Optimization of the fuel control system to reduce emission levels requires accurate measurement of the post-combustion exhaust gases. Most production vehicles are fitted with a single oxygen sensor downstream of the confluence point on the exhaust system which is used for feedback control of the fuel injectors. A significant problem associated with this configuration is the difficulty of isolating individual cylinder behaviour. Individual cylinders may be operated rich or lean of $\lambda = 1$ due to mismatches in injectors and unbalanced airflow [2]. Since the sensor is fitted at the confluence point on the exhaust system, gases become mixed making it difficult to detect which cylinders are operating away from stoichiometric. Mixing of exhaust gases can occur not only between cylinders at the confluence point of the exhaust stream but also

* Corresponding author. Tel.: +44 1942 877210; fax: +44 151 794 4892.
*E-mail address:* shenton@liv.ac.uk (A.T. Shenton).

0888-3270/$ - see front matter 
doi:10.1016/j.ymssp.2009.01.004

between an individual cylinder's current and the previous exhaust cycle. This occurs because, the gas emerging from an exhaust port must first displace the exhaust gas from a previous cycle past the sensor before it can be detected [3].

Multiple sensor schemes, with oxygen sensors at each of the exhaust runners, are not installed in current production vehicles for two main reasons. Firstly the multiple deployment of the expensive sensors would significantly increase costs. Secondly, installing the sensors close to the exhaust ports to minimize time delays and mixing effects exposes the sensors to much greater exhaust temperatures which would, in turn, significantly reduce their longevity.

Most commonly, the type of AFR sensor fitted to vehicles is a non-linear heated exhaust gas oxygen (HEGO) sensor. This is often referred to as a 'switching type' sensor since the output is effectively one of two levels depending on which side of stoichiometric the engine is operating. The performance of the feedback control system is severely compromised by the use of this device rather than the linear 'wideband' universal exhaust gas oxygen (UEGO) sensor, due to the significant additional cost of the UEGO.

A significant proportion of hydrocarbon emissions occur during engine start-up, in part due to a lack of sensing for feedback control during this period [4]. Oxygen sensors are incapable of measuring AFR from an engine cold start-up due to their time to 'light-off', a duration required for the sensor to reach an elevated operating temperature [5]. During this period the engine is operated open-loop.

Further difficulties in AFR feedback control are associated with time delays. The most significant is due to the transportation of the exhaust gases following the combustion event to the detection at the oxygen sensor downstream. Additionally, the sensor is often considered to behave as a first order lag which acts to filter the signal [1].

To address some of the problems associated with oxygen sensors for feedback control a significant amount of research has focused on estimation using diverse combustion sensors including pressure sensors, optical sensors, hot-wire sensors and infrared sensors. The spark plug with appropriate diagnostic circuitry has also been extensively investigated for possible use in the measurement of in-cylinder combustion variables and as a 'virtual' lambda sensor [6].

Spark plug voltage analysis, more specifically, the voltage decay time can be used to study AFR [7]. The principle is that the spark discharge time is related to the number of ions in the flame and, hence, the quality of combustion. It was found that this discharge time was only sensitive to the AFR in lean mixtures.

Spark voltage characterization (SVC) is another alternative method. It involves analysis of the time-varying spark voltage vectors and a lambda accuracy has been achieved to within $\pm 0.1$ in about 95% of the time over its identified operating range [6].

### 1.1. Ion current sensing

It is well established [10], that ion current sensing can obtain in-cylinder combustion information in a low cost, non-intrusive manner by utilizing the existing spark plugs on a spark ignition (SI) IC engine. In this scheme an electric potential is applied across the plug electrodes producing an electrical field during the period of non-sparking and hence ion species, produced during combustion, generate a current as they move between these electrodes. Using a simple electrical circuit, the voltage across a resistor is measured and the resulting signal is rich in combustion information. It is found that a desirable signal waveform from a single combustion event possesses two interesting and separate phases after the SI pulse.

A typical unfiltered spark ionization current signal for a single combustion cycle is shown against measured in-cylinder pressure in Fig. 1.

The first phase (and first peak) represents the flame kernel growth as the fuel reacts with oxygen and is known as the chemical phase. It is in this phase of the spark ionization signal that information relating to the AFR is contained. The second phase (and second peak) is known as the thermal phase, and is the one in which re-ionization of the gases occur due to rising in-cylinder temperatures.

The ion current signal has so far been used in production vehicles exclusively for either the detection of knock—where one or more pockets of air–fuel mixture explode outside the envelope of the normal combustion front—or the detection of misfire—where a cycle produces no ionization of the air–fuel mixture within the cylinder [8,9].

Early work proposed that the 'pressure indicating' section of the ion current signal has a shape close to Gaussian curve functions [10]. The comparison was used to obtain an idealized model of the ionization current. This model was fitted in the least-squares sense to the measured ionization current. This process may be computationally heavy for operating at realistically high engine speeds. Gaussian parameterization was accordingly proposed, whereby the Gaussian curve is modelled by six parameters as a way of reducing data sizes [11]. In evaluating this scheme to estimate the AFR it was found, however, that under varying operating conditions, load, etc, the ionization signal varies significantly and a simple Gaussian function cannot fit the ionization signal acceptably well. This was found to be most evident at low load conditions where the signal is weak and non-repeatable. In an alternative approach, the ion current signal in the period between $10^\circ$ and $45^\circ$ after ignition (the flame front phase), can be related to AFR. The slope of this peak depends on the development of the flame and the derivatives of this show correlation to the AFR. Huang [12] characterized the in-cylinder ionization by the height and location of the peak and area under the ionization signal curve. Experiments were conducted using the Saab Trionic $^{TM}$(Saab Automobile AB) production unit. It was found that with the increase in equivalence ratio, the peak and the area under the curve increase to a maximum at slightly rich conditions and then decay as the ratio moves into very rich regions.