

Sensor- Less Individual Cylinder Pressure Estimation and Closed Loop Control for Cold Start and Torque Balancing

2010-01-1269

Published
04/12/2010Chuck Rackmil and Daniel McKay
Delphi Powertrain Systems

Copyright © 2010 SAE International

ABSTRACT

The current paper presents a by cylinder IMEP estimator which operates completely free of direct cylinder pressure sensor measurement and which, when coupled with associated closed loop torque controller and commonly used engine control hardware, can provide significant improvement in the reduction to fuel sensitivity over conventional systems at minimal or no cost. Applications of the by cylinder estimator and closed loop torque/IMEP control are described including the use of the estimator during cold start before the O₂ sensor is active. The application of the IMEP estimator and controller to cold start can provide significantly improved idle quality as well as enhanced robustness to degraded fuel quality. Closed loop combustion strategies using spark and fuel are described and experimental data from V6 engine testing are presented for the estimator and available closed loop controllers.

INTRODUCTION

IMEP is an accepted standard method for measuring combustion in IC engines. The information is valuable to identify combustion quality and is used extensively in engine dynamometer work to characterize and quantify acceptable and unacceptable combustion performance. It may be used to determine the limits of engine dilution (EGR/Cam Phasing), spark advance, and fueling rich/lean limits and real time control. Although it is a valuable parameter for combustion development and controls, its use in real time controls has been limited due to the expensive and non-durable combustion analysis equipment required (Brand names ACAP, CASS, DSP), and the intrusive and expensive methods of measurement (combustion pressure sensors in the heads or the spark plugs). Other methods of combustion measurement, such as Ion Sense technology, require

hardware upgrades and are not generally available. Some estimation methods to calculate IMEP by cylinder have been published; however, they have not been accurate without some base IMEP pressure measurement for at least one cylinder¹. Others are computationally expensive and may not be well suited for real time embedded application in currently available microcontrollers^{2, 3}.

The IMEP estimation method described herein is completely free of cylinder pressure sensor measurement and uses separately available models for either: fully warmed up quasi-steady indicated torque, or; cold start up friction torque. These models represent two modes of estimator operation:

- Fully Warmed Up Steady-State - engine mapping based data, sensor inputs and calculations used to re-center the estimator around the quasi steady mapping result
- Cold Engine Start Up - a separate cold pumping and rubbing friction model is employed to determine friction torque prior to the onset of auxiliary loads

Fully warmed up quasi-steady cycle averaged indicated torque is commonly used in commercially available microcontrollers, and as such its use represents no additional computational burden on the microprocessor. Further, with the advent of drive by wire throttle controls and advanced transmission and traction control function, the accuracy and reliability of these torque estimates for real time control has gotten increased attention. Production applications currently focus considerable development resources on ensuring the accuracy of estimated torque values across a wide range of engine operating conditions. Under fully warmed up conditions, the method described in the current paper uses this aggregate engine IMEP estimate to seed the cylinder based estimator.

During cold start up operation and prior to the activation of switching type engine accessory or transmission loads, a separate model for cold engine start up friction is used. This cold engine friction model uses a physically based description of pumping and bearing friction during cold engine start up. Details of both the fully warmed up and cold engine friction model are described in greater detail below.

ESTIMATOR METHODOLOGY

FULLY WARMED UP STEADY STATE OPERATION

[Figure 1](#) graphically illustrates the various calculations performed in the current technique for estimating the IMEP values for each cylinder of the engine and resulting values of coefficient of variance of each cylinder's IMEP and for the engine as a whole.

<[figure 1](#) here>

Gross indicated engine torque is determined from measured engine air flow (MAP), speed, operating temperature, air fuel ratio, EGR and steady state engine performance maps (1). These maps also describe engine mechanical friction and pumping losses. During fully warmed up operation, the gross indicated engine torque is used to both 'seed' and continuously reenter (6) the cylinder IMEP estimator around the current cycle averaged value. During cold start up, estimates of mechanical friction, pumping losses and non-switching type auxiliary torques are used to determine inertia torque levels available for accelerating the reciprocating and rotating inertias of the engine.

Instantaneous values of engine speed are determined from a high data rate crank wheel (2, 3, and 4). A more detailed development of the equation described in block 4 of [Figure 1](#) is given in the following section (Rigid Crankshaft Model). Instantaneous engine speed is used to calculate engine angular acceleration. Changes in engine angular acceleration are then used to calculate changes in engine torque (and/or kinetic energy) from one cylinder/ ref event to the next (5). Using the seed value of estimated gross engine torque from (1); subsequent levels of torque needed to accelerate the engine at each ref event are evaluated. From these cylinder IMEP levels, corresponding values of coefficient of variance for each cylinder and the engine as a whole are determined.

RIGID CRANKSHAFT MODEL

The cylinder based torque estimator was developed using a mathematical model of a rigid crank shaft. The algorithm is based on the following principles and assumptions. Refer to [Figure 2](#) below for the mathematical development of the model.

- Equation of motion derived from a torque balance on a rigid crankshaft (1)
 - Torques comprised of transient plus cycle averaged values (2)
 - Load and Friction torque are assumed constant within each cycle (3)
 - The engine inertia (I_E) is assumed constant over each cylinder event
 - A numerical difference formula is used to represent engine angular acceleration
 - The resulting gas torque impulse is determined from engine acceleration values α_E (4)
 - Torque for each cylinder event is summed over time for resulting transient component of indicated torque on that cylinder (5)
 - The algorithm operates in two modes (6) as summarized above
- <[figure 2](#) here>

COLD PUMPING AND RUBBING FRICTION

There are four major constituents of the cold engine pumping and rubbing friction torque model - see [Figure 3](#) below. The first two are: cold quasi-steady engine pumping and rubbing torque (vs. engine speed), and; start up friction torque requirements due to engine components and bearing surfaces transitioning between boundary and hydrodynamic lubrication during start up.⁴ The latter is represented by a simple but useful model of engine tribology.

<[figure 3](#) here>

The above four constituents represent four physical characteristics associated with the development of engine friction during cold start up:

- a. Base cold pumping and rubbing friction as a function of engine speed ([Figure 3 a.](#))
- b. Cold pumping and rubbing friction multiplier as a function of effective number of cycles since start ([Figure 3 b.](#))
- c. Multiplier to the number of cycles since start to account for the effectiveness of the oil pump and internal crankcase lubrication to reduce friction ([Figure 3 c.](#))
- d. Cold pumping and rubbing friction multiplier as a function of oil temperature to account for temperature dependence of oil viscosity ([Figure 3 d.](#))

NUMERICAL OPTIMIZATION

After individual cylinder torque and IMEP values are determined, a numerically optimized technique is used to evaluate COVIMEP. This method utilizes a buffer of previously calculated cylinder IMEP values and a calculation which tracks the sum and the sum of squares of the buffer. The optimization reduces the computational requirements of calculating COVIMEP at each cylinder event through a reformulation of the coefficient of variance (COV) equation. This reformulation results in a computational savings of N-1 additions and subtractions (where "N" is the COV sample size), when compared to the traditional method of COV calculation. In addition a tabular representation of the square root is used as a look up for each COVIMEP calculation instead of the more computationally expensive square root function.

The Coefficient of Variance is equal to the standard deviation (σ) over the mean ($\bar{x}$):

$$COV = \sigma / \bar{x} \quad (7)$$

The standard deviation is equal to the square root of the sum of the square of the difference between the mean and the individual values divided by the number of samples minus one:

$$\sigma = \sqrt{\sum_{i=1}^N (\bar{x} - x_i)^2 / (N-1)} \quad (8)$$

Expanding the series and substituting for the mean

$\bar{x} = \sum_{i=1}^N x_i / N$
() yields a more computationally efficient form of the equation for COV:

$$COV = \sigma / \bar{x} = \sqrt{(\sum_{i=1}^N x_i^2 / \bar{x}^2 - N) / (N-1)} \quad (9)$$

By storing the individual sample values in a buffer and tracking the sum of the square and square of the average of the buffered values, the COV may be calculated in an efficient manner with no loss of accuracy. This method requires only one addition and one subtraction for each new value in the sample (adding and subtracting the newest and oldest values in the buffer, respectively, to their sums), compared to the N additions and N subtractions in the traditional COV calculation. This results in a savings of (N-1) additions and subtractions.

RESULTS OF THE ESTIMATOR

Figures 4,5,6,7 show comparisons of measured and predicated values for an idle neutral test of a 2.7L PFI engine run in a fully warmed up idle neutral condition and engine speed (neutral set speed) stepped from 600 to 1000 rpm (Figure 4). During the test, the air fuel ratio was maintained at a very lean condition (20:1) in order to produce high levels of combustion variability. Note that the IMEP estimator does a good job of predicting IMEP and COVIMEP values (Figures 5 & 6) for all six cylinders even during the transient. In the figures, estimated and measured values are shown with blue and red lines, respectively.

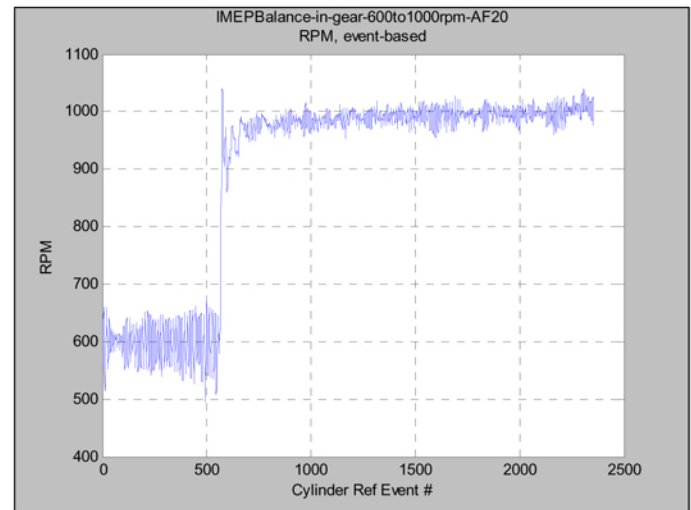


Figure 4. ICIE Verification Test - Neutral Idle @ 20:1 A/F and Step Change in Engine Speed at ~100 Cycles

<figure 5, 6 here>

ENGINE CONTROL METHODOLOGY AND APPLICATION OF IMEP ESTIMATOR

The individual IMEP estimator developed above provides acceleration based estimates of individual cylinder IMEP (torque) and COVIMEP values during cold start to fully warmed-up steady engine idle conditions. In principle these estimates could be used by any control or diagnostic algorithm interested in using the cylinder based combustion estimates the algorithm provides. The present paper describes two engine control applications: High Drivability Index Fuel Detection and Compensation and Individual Cylinder Torque Balancing.

HIGH DRIVABILITY INDEX FUEL DETECTION AND CONTROL

Hi-DI (High Drivability Index) for gasoline fuels is defined by eq. (10). The “High Drivability Index” value is a measure of the fuels ability to vaporize. It is metric for assessing fuel vaporization during the conditions present when the engine is started.

$$DI = 2.7 * T_{10} + 5.4 * T_{50} + 1.8 * T_{90} + 176 \quad (10)$$

Where

T_{10} = 10% distillation temperature
 T_{50} = 50% distillation temperature
 T_{90} = 90% distillation temperature

All temperatures are in degree C.

A high DI value is worse for vehicle starts and drivability with a cold engine. Poor start and drivability results from less fuel being vaporized due to a leaner in cylinder air/fuel mixture. A typical value of DI for nominal fuel is 1160 whereas a high drivability index fuel would have a value of 1250.

The High Drivability Index Fuel Detection and Control algorithm (HiDI) has been developed for use in detecting and compensating for high DI fuels. This feature utilizes individual cylinder IMEP estimates during engine cold starts. This algorithm contains the following features:

- Cylinder based IMEP HiDI fuel detection threshold and/or desired IMEP setting as a function of the number of combustion events since start
- PI gains in A/F units for fuel countermeasures and control during the crank to run transition as a function of the (IMEP) error term. Gains for both positive (fuel addition) and negative errors (fuel subtraction).
- Calibratable learning and correction window as a function of the number of combustion events since start.
- Calibratable ramp step for decrementing fuel control down to zero after exiting learning/correction window.
- Calibratable minimum and maximum clips on the integral and overall A/F correction value.

HI-DI FUEL DETECTION AND COMPENSATION RESULTS

As can be seen in [Figure 7](#), on nominal fuel, errors are in large part positive. The estimated IMEP (light green line in top plot) is above the calibrated threshold or desired levels

(blue line). As a result no fuel compensation is triggered (light green line in bottom plot). This is as intended for operation on nominal fuel. The model is calibrated over the range of expected combustion conditions all the way down to misfire and near stall ([Figure 8](#)). [Figure 9](#) demonstrates the level of fuel control activity expected during HiDI operation. Note that predicted IMEP values show good agreement to measured values (light green and red lines, respectively in [Figures 7, 8 & 9](#)). Predicted IMEP values are shown to accurately determine IMEP from start of combustion through the engine speed run up to desired speed, and also as engine speed reaches its desired value.

<[figure 7, 8, 9](#) here>

CYLINDER TORQUE BALANCING CONTROL METHODOLOGY

The Cylinder Torque Balancing (CTB) algorithm is an integral spark feedback controller which attempts to reduce differences in combustion variability (Coefficient of Variance of IMEP -COVIMEP) between cylinders in the engine. CTB provides functionality for improving idle combustion quality on ‘weak’ cylinders that may arise from: uncorrected cylinder fuelling errors (due to injector part variability, PCV or valve train related cylinder-to-cylinder fuel and/or air maldistribution), or; EGR maldistribution, as examples. Improving idle combustion quality is the primary objective of the CTB algorithm.

Secondarily, CTB may also provide improved lean tolerance during cold starts. This feature results from the ability of the algorithm to detect and compensate cylinders which may be near their lean combustion limit. Cold air/fuel maldistribution can result from injector variability or maldistribution of PCV. These differences may in turn result in A/F maldistributions when the engine is cold. Lean open loop calibrations coupled with injector variability or PCV maldistribution can result in some cylinders having worse combustion quality than others. CTB can act to neutralize these differences by providing more favourable spark on cylinders with worse COVIMEP during cold starts.

CYLINDER TORQUE BALANCING RESULTS

[Figures 10](#) and [11](#) demonstrate the affect of the cylinder torque balancing algorithm on a 3.8L Gas Direct Injected (GDi) engine during a cold start. During the engine start, the CTB control algorithm was toggled on and off (red line high and low correspond to on and off conditions respectively), to illustrate the algorithm's ability to both bring the weak cylinder's COVIMEP (dark blue line, [Fig. 10](#)) closer to the average cylinder COVIMEP (light green line, [Fig. 10](#)), and; reduce the overall engine's COVIMEP (dark blue line, [Fig. 11](#)).