

Evaluation of a Closed Loop Spark Advance Controller Based on a Torque Sensor

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ABSTRACT

A closed loop spark advance control system was evaluated on a Volvo V70 5-cylinder spark ignited engine. The system utilises a crankshaft mounted torque sensor for combustion monitoring which provides individual cylinder combustion phasing information and enables individual cylinder spark advance control. The spark advance control system can compensate for changes in combustion operating conditions and hence limit the need for calibration.

The spark advance control system was used in a mode of cylinder balancing where the control target is to keep the combustion phasing in all cylinders at a defined setpoint. This control law was evaluated in vehicle tests in an emission test chamber, running pre-defined driving cycles FTP72 and Highway Fuel Economy Test. Analysis shows that the combustion phasing was kept close to the selected setpoint during both tests and, hence, robustness in that sense was demonstrated.

The torque ratio concept is used for combustion phasing monitoring based on crankshaft torque measurements. Analysis of the 50% torque ratio as a measure for combustion phasing shows that it is equivalent to 50% burned mass fraction.

INTRODUCTION

The reduction of the environmental impact of combustion engines motivates research to make engines more efficient and also to reduce emission levels. The effect of these efforts is a significant increase in calibration complexity since the number of degrees of freedom to optimise have increased. In order to make engine calibration less time consuming, feedback control could be used to reduce manual calibration of some of the parameters. A positive side-effect would be the automatic adaption of the control system for individual engines and property changes over time.

For each engine operating point there is an optimal spark advance that maximises the mean brake torque (MBT) [1]. However, the optimal spark advance differs for each operating point which implies calibration maps of increasing complexity using today's common control strategies. Also,

due to difficulties to per design ensure equal combustion premises for all cylinders in an engine, the optimal spark advance may not be the same for all cylinders for a given engine operating point. The differences are many; air injection, fuelling, internal and external EGR, cylinder cooling etc.

The spark advance complexity is reduced if the control tactics shifts from start of combustion to a more load and speed invariant measure of combustion phasing. Such measures exist but requires a combustion sensor to be used. Several types of sensors have been utilised, such as pressure sensors [2, 3], ion current sensors [4, 5], angular velocity sensor [6, 7], engine block accelerometers [8, 9], and crankshaft torque sensor [10, 11, 12]. The use of a combustion sensor also enables the individual optimisation of the combustions of each cylinder.

In this work a crankshaft torque sensor from ABB [13, 10] was used. The sensor is integrated in the crankshaft and positioned between the flywheel and the last crank throw. The positioning of the sensor enables the measurement of combustions in all cylinders using only one sensor, but adds complexity in the interpretation of the raw torque signal. The project has earlier reported on the development of torque signal models [14, 15, 16], a combustion classification model [17], spark advance controller performance [18] and the performance of closed loop control of spark timing in an engine dyno and steady-state conditions [12]. This paper contributes with a performance analysis of a vehicle installation of the control system, run under typical end-user transient conditions.

THE TORQUE SENSOR The torque sensor, viewed in Figure 1, has two parts. One is an integrated segment of the crankshaft, the sensor shaft, and the other part surrounds the shaft, the sensor house. The house holds a set of electric coils which by feed current induces and measures a magnetic field in the sensor shaft. The magnetic properties of the sensor shaft changes with mechanical stress and so also the measured field in the house coils.

THE CONTROL SYSTEM

The test setup is seen in Figure 2 and consists of several parts. The engine is a Volvo V70 5-cylinder naturally aspi-

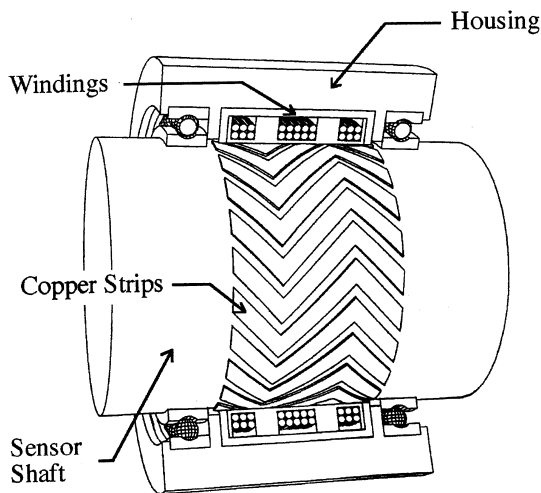


Figure 1: The "Torductor" from ABB.

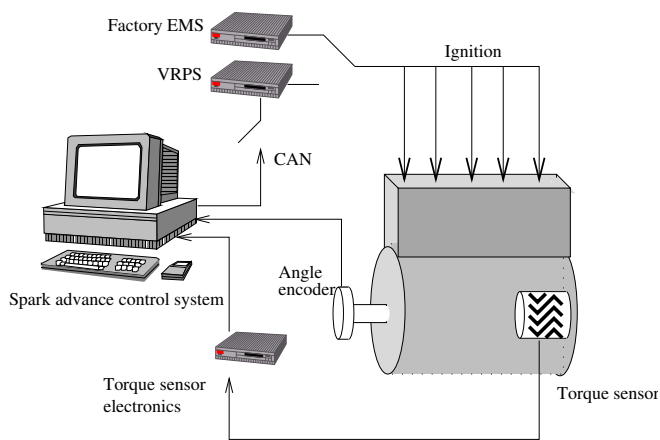


Figure 2: A schematic view of the experimental setup. There are three configurations of the setup, indicated by the switches in the scheme.

rated gasoline engine, fitted with a crankshaft torque sensor and spark plug pressure sensors. The engine management system (EMS) is available in two units, one is the vehicle original EMS unit with no other access than the normal EMS harness, and the other is an open unit called Volvo Rapid Prototyping System (VRPS) which allows access to the calibration data and sensor reading during operation. The VRPS has an open CAN link by which the spark advance calibration can be by-passed and allow external control. A desktop PC with a CAN port and AD converter cards from National Instruments runs the closed loop control code for spark advance. The PC samples the torque signal in crank angle based resolution. The torque sensor is governed by an electronic unit which supplies the feeder current and holds an active filter for the measured signal.

A standard MY2001 Volvo V70 vehicle was fitted with the crankshaft torque sensor modified 5-cylinder engine. All cylinders had spark plug pressure sensors for reference measurements.

The original EMS and the two modes of the VRPS makes in total three different EMS versions available, see Table 1. The original version (ver 1) and the VRPS version (ver 2) both works as stand-alone EMS, but have a little different status of their calibrations (here referred to as factory and development calibrations). The VRPS has the ability to allow external control of spark timing (ver 3).

Version	EMS unit	Comment
1	A	original EMS, factory calibration
2	B	modified EMS unit, VRPS, development calibration
3	B	modified EMS unit, VRPS, closed-loop control of spark timing

Table 1: The versions of EMS

Charge amplifiers for the pressure sensors, the torque sensor amplifier and an anti-alias filter were connected to the main PC AD-converters. An extra angle encoder was mounted on the free end of the engine to provide a 1 CAD resolution sampling trigger for the main PC system.

The PC is running a newly developed program for extracting combustion information online, from the torque and pressure sensors. The torque based combustion information is used by a controller to adjust spark timing via a CAN link to a modified EMS.

The algorithms for extracting the combustion information from the torque signal are based on the earlier work in this project. A short summary of these algorithms is given here.

THEORY

The spark advance control system consists of two parts; a combustion classification part where combustion phasing is calculated from the measured torque signal, and a controller which adjusts spark advance for each cylinder to meet the desired combustion phasing. Earlier publications [17, 15] presents the method for extracting the combustion phasing information from the torque signal. The individual cylinder contributions is extracted in the *cylinder separation* process. When the torque contribution from a single cylinder is known, a combustion classification is performed using the *torque ratio concept*, which gives a measure for the combustion phasing. A brief overview of the features of the torque signal and the torque processing algorithms is given here.

THE TORQUE SIGNAL The torque sensor measures the instant torque transferred by the crankshaft at the location of the sensor. The sensor is located between the flywheel and the last crank throw of the crankshaft. The mass of the flywheel is large relative to the crankshaft and the chosen location enables the measurement of torque from all cylinders. The torque signal is viewed in Figure 3.

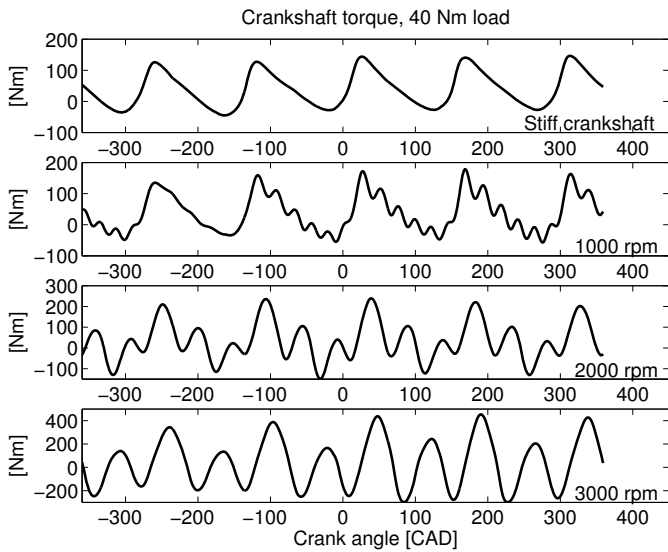


Figure 3: The measured torque signal at different engine speeds. The top graph shows a simulated torque signal which neglects crankshaft torsion.

The top graph shows a theoretical torque signal where the crankshaft torsional behaviour has been neglected. The other three graphs show measurements of torque at different engine speeds. The crankshaft acts as a mechanical spring-damper system. At every time instant, effects from several previous combustions are present in the measured signal simultaneously. The first step towards combustion classification is to extract the torque contribution in the signal which originates from the combustion of interest. This is called the *cylinder separation* part.

CYLINDER SEPARATION The torque signal is a result of the combustions and torsional vibrations in the crankshaft. In a linear systems approach to model the torque signal, it can be viewed as the sum of filtered individual cylinder torque contributions. A model for the measured torque signal is

$$T_m(t) = \sum_{i=1}^{N_{cyl}} H_i(p) (T_{g,i}(t) + T_{p,i}(t) + T_{fp,i}(t)) \quad (1)$$

where $T_m(t)$ is the torque sensor signal, $T_{g,i}(t)$ is the torque resulting from the gas pressure in cylinder i and $T_{p,i}(t)$ and $T_{fp,i}(t)$ are the torque originating from the inertial and frictional effects of the piston movements respectively. $H_i(p)$ denotes the filtering effect of the crankshaft which influences all cylinder contributions. The system description $H_i(p)$ is crucial and it is found by collecting a data set of cylinder pressure and crankshaft torque and applying system identification methods [16]. Herein lies the main calibration work associated with the development of this control system.

The separation method is the inversion of that linear model, which requires that only one cylinder is firing at any observed time point. This produces a recursive algo-

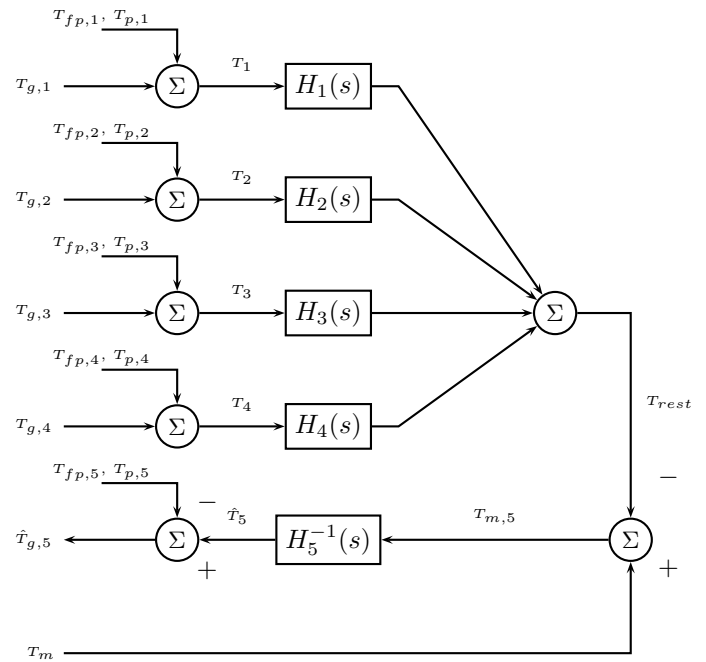


Figure 4: The cylinder separation scheme

rithm where earlier estimated combustion properties are used as inputs to the linear crankshaft model, to extract the present combustion contribution in the torque signal, see Figure 4. As the individual cylinder torque contribution $T_{g,i}$ is extracted, the cycle average cylinder torque $\bar{T}_i$ can be calculated as

$$\bar{T}_i = \frac{1}{4\pi} \int_{\theta} T_{g,i}(\theta) d\theta \quad (2)$$

The average cylinder torque is used by the spark advance controller to detect weak combustion, i.e. when the combustion is not strong enough to provide good combustion phasing estimates.

Combustion information, like its phasing, is normally calculated from cylinder pressure [1]. The cylinder torque contribution is a result of the gas pressure generated by the combustion which is transformed to torque by the crank-lever mechanism. The inverse transform from torque to gas pressure is difficult to make due to the singularity at top dead center (TDC). Therefore, combustion analysis is performed in the torque domain by a torque based combustion model operating on the extracted torque contribution. This is called the *torque ratio* concept.

TORQUE RATIO CONCEPT A parameterised combustion model was used to enable combustion classification of a single cylinder torque signal, i.e. the torque domain. The combustion model $TR(\theta)$ is formed as

$$TR(\theta) = \begin{cases} 1 & \theta_{start} < \theta < \theta_{end} \\ 1 + b \left(1 - e^{-\left(\frac{\theta - \theta_{start}}{\theta_{end} - \theta_{start}} \right)^{m+1}} \right) & \theta < \theta_{start} \\ 1 - b \left(1 - e^{-\left(\frac{\theta_{end} - \theta}{\theta_{end} - \theta_{start}} \right)^{m+1}} \right) & \theta > \theta_{end} \end{cases} \quad (3)$$