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Closed-loop diesel engine combustion phasing control based on crankshaft torque measurements

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ABSTRACT

Methods for closed-loop combustion phasing control in a diesel engine, based on measurements of crankshaft torque, are developed and evaluated. A model-based method for estimation of cylinder individual torque contributions from the crankshaft torque measurements is explained and a novel approach for identification of crankshaft dynamics is proposed. The use of the combustion net torque concept for combustion phasing estimation in the torque domain is also described. Two different control schemes, one for individual cylinder control and one for average cylinder control, are studied. The proposed methods are experimentally evaluated using a light-duty diesel engine equipped with a crankshaft integrated torque sensor. The results indicate that it is possible to estimate and control on a cylinder individual basis using the measurements from the crankshaft torque sensor. Combustion phasing is estimated with bias levels of less than 0.5 crank angle degrees (CAD) and cycle-to-cycle standard deviations of less than 0.7 CAD for all cylinders and the implemented combustion phasing controllers manage to accurately counteract disturbances in both fuel injection timing and EGR fraction.

1. Introduction

The main task of an internal combustion engine control system is to make sure that the engine delivers the requested torque while minimizing the amount of fuel needed to do so under constraints on emissions and driveability. More stringent emission legislations lead to more complex engines as additional subsystems, e.g. intricate fuel injection and turbocharger systems, are required in order to meet these legislations. The control system's task, that basically translates into handling the rather involved interactions between all subsystems in the engine, is therefore also becoming increasingly complex. Adding to this complexity, recent engine control challenges also include handling effects such as component ageing, spread in manufacturing, and engines running on multiple fuels. For this purpose, closed-loop engine control offers advantages.

A vital part of controlling combustion events in closed-loop is to estimate the combustion properties of interest. This study focuses on the estimation and control of combustion phasing, a property that indicates the timing of the combustion event in relation to the piston's position in the cylinder. Combustion phasing influences both engine efficiency and engine out emissions, see Heywood (1988), and is commonly estimated based on measuring the pressure inside the cylinders of the engine. The use of cylinder pressure measurements has the advantage that this quantity is closely linked to the theory of thermodynamics. There are, however, still issues regarding cost and durability of these sensors. It is thus of interest to investigate the use of alternative sensors for combustion phasing estimation. This work demonstrates the use of measurements from a crankshaft torque sensor for combustion phasing estimation and control in a diesel engine. A similar concept for spark-ignited engines, although differing in some of the modeling and estimation approaches, has previously been reported in Larsson and Andersson (2008) and Andersson, McKelvey, and Thor (2008). Another approach for combustion phasing estimation in diesel engines has also been reported previously in Thor, Andersson, and McKelvey (2009a).

A crankshaft torque sensor offers measurements that are robust, as the sensor position is located outside of the combustion chamber, and cost effective, as only one sensor is needed, compared to cylinder individual pressure sensors. However, as the crankshaft torque is not as closely related to combustion theory, this signal requires more processing in order to obtain an estimate of the combustion phasing in each individual cylinder. The required processing steps include separation of the crankshaft torque into cylinder individual torque contributions, using torque and crankshaft dynamics models, as well as a method for using these torque contributions for combustion phasing estimation.

The work presented in this paper describes the components of a control system for closed-loop combustion phasing control based on measurements of crankshaft torque. As a part of this, a new

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method for identification of a nonparametric, frequency domain crankshaft model is presented. The proposed methods are implemented and evaluated online in a light-duty diesel engine where disturbance rejection is demonstrated. The first part of the paper is devoted to describing the proposed torque and crankshaft models and how they can be used for estimation of cylinder individual torque contributions. This part is followed by an introduction to the combustion phasing property and how this property can be estimated and controlled based on crankshaft torque measurements. After this, the performed experiments are described and experimental results are reported. The paper then concludes with a summary and discussion where the results are put in a larger perspective.

2. Crankshaft torque measurements, modeling, and separation

Crankshaft torque is a central concept in a torque based system for closed-loop combustion control. An introduction to how this torque can be measured, modeled, and separated into cylinder individual torque contributions is provided here.

2.1. Torque measurements

A crankshaft mounted torque sensor provides instantaneous measurements of crankshaft torque in this work. The sensor, depicted in Fig. 1, is named Torductor-S and is developed by ABB. Earlier efforts have demonstrated how this sensor can be used in automotive applications for e.g. misfire detection, see Sobel, Jeremiasson, and Wallin (1996), cylinder balancing, see Jeremiasson and Wallin (1998), and for racing purposes, see Wallin, Gustavsson, and Donovan (2002) and Wallin and Rapson (2009). Previous work involving this sensor also includes torque based combustion phasing control in a spark-ignited engine, see Larsson and Andersson (2008) and Andersson et al. (2008).

When a shaft made from ferromagnetic materials is subjected to torsional stress its magnetic properties change. This phenomenon is known as magnetoelasticity, see e.g. Brown (1966). The Torductor-S torque sensor measures crankshaft torque by detecting such property changes. A housing that includes two coils is placed around the shaft at the measurement position where one of the coils, referred to as the primary coil, is fed with an alternating current and thus induces a magnetic field in the crankshaft. The induced magnetic field will induce a current in the secondary coil. As the magnetic field in the crankshaft depends on the magnetic properties of the shaft, so does the current in the secondary coil. Due to the magnetoelastic effects, this current therefore serves as an indicator of the torque that is transferred through the shaft.

In this work, the torque sensor is placed between the final crank throw and the flywheel. This positioning means that the measured torque signal will include torque contributions from all cylinders as well as torque resulting from torsional effects in the crankshaft itself. In order to obtain the torque contributions from each cylinder and use them for combustion phasing estimation, the measured crankshaft torque needs to be separated based on a torque model.

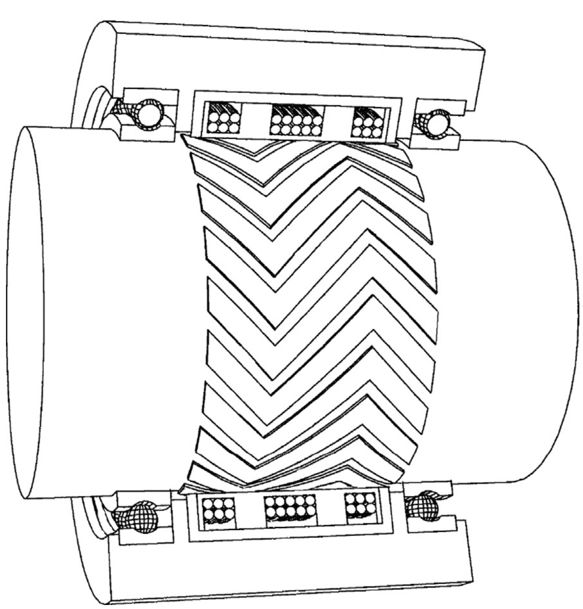

Fig. 1. An illustration of the Torductor-S torque sensor developed by ABB.

2.2. Torque modeling

A light-duty diesel engine's crankshaft is nonlinear in its nature. The measured crankshaft torque is in this study modeled as a sum of cylinder individual torque contributions that are filtered through the mechanical system that is the crankshaft. A linear assumption is hence imposed on the crankshaft dynamics. The torque model described here considers nonlinear crank angle and angular velocity dependent effects resulting from the motion of the pistons. If the torsional deformation of the crankshaft is assumed to be small and the engine speed is assumed to be constant during an engine cycle, these effects can, however, be transformed into input signals to a linear description of the crankshaft, see Schagerberg and McKelvey (2003). An example of the proposed model structure for an engine with five cylinders is available in Fig. 2.

Each cylinder individual torque contribution is assumed to consist of four different parts, two related to gas pressures and two related to the motion of the piston. The first part of the torque contribution from cylinder i is generated by the pressure, $p_i(\theta)$, of the gases trapped in that cylinder. This pressure varies as the cylinder volume is changed by the piston's motion and increases as chemical energy in the fuel is released during a combustion event. Through the crank-slider mechanism, a corresponding torque contribution, $T_i(\theta)$, is applied to the crankshaft according to

$$T_i(\theta) = p_i(\theta) A L_i(\theta) \quad (1)$$

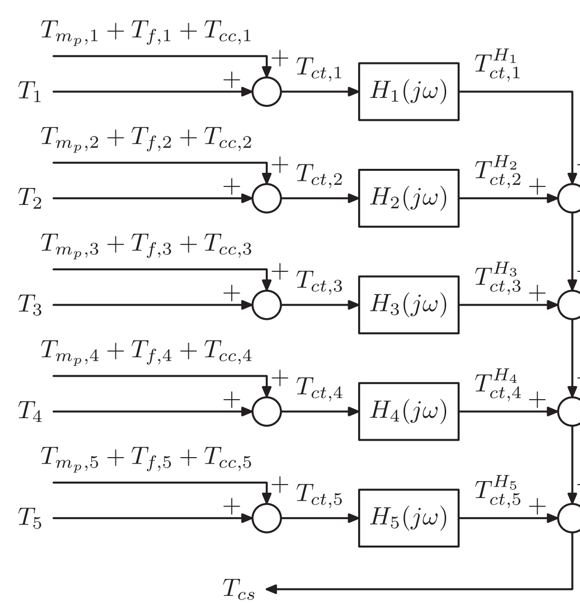

Fig. 2. An illustration of the crankshaft torque model of a 5-cylinder engine.