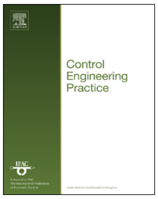
Control Engineering Practice 26 (2014) 233–244

Contents lists available at ScienceDirect

Control Engineering Practice

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



Using combustion net torque for estimation of combustion properties from measurements of crankshaft torque

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ARTICLE INFO

Article history:
Received 18 February 2012
Accepted 14 January 2014
Available online 27 February 2014

Keywords:
Internal combustion engines
Engine control
Engine management
Estimation algorithms

ABSTRACT

Two methods, both based on the concept of combustion net torque, for estimation of combustion properties using measurements of crankshaft torque data are investigated in this work. The first of the proposed methods estimates entire burned mass fraction traces from corresponding combustion net torque traces. This is done by solving a convex optimization problem that is based on a derived analytical relation between the two quantities. The other proposed estimation method estimates the well established combustion phasing measure referred to as 50% burned mass fraction directly from combustion net torque using a nonlinear black-box mapping. The methods are assessed using both simulations and experimental data gathered from a 5-cylinder light-duty diesel engine equipped with a crankshaft torque sensor and cylinder pressure sensors that are used for reference measurements. The results indicate that both methods work well but the method that estimates entire burned mass fraction traces is more sensitive to torque data quality. Based on the experimental crankshaft torque data, the direct combustion phasing estimation method delivers estimates with a bias of less than 1 CAD and a cycle-to-cycle standard deviation of less than 2.7 CAD for all cylinders.

1. Introduction

Combustion control is an increasingly important part of internal combustion engine development. Well designed combustion control systems offer possibilities to increase engine efficiency while simultaneously lowering the amount of generated emissions by enabling the use of more advanced engine concepts and combustion modes. The use of different fuel types, qualities, or blends is also, to a large extent, enabled by sophisticated control algorithms that detect and compensate for fuel property differences. These control systems rely on accurate combustion information being available to them. Combustion property estimation is therefore an essential part of such systems.

Traditionally, methods for analyzing combustion events and their properties, e.g. calculation of heat release or burned mass fraction, are based on cylinder pressure measurements as cylinder pressure is tightly coupled to the theory of thermodynamics, see e.g. Heywood (1988). However, mounting pressure sensors in all cylinders, an environment where they are directly exposed to the combustion, may introduce problems related to both cost and durability of these sensors. As a result, it is of interest to study possible combustion analysis methods based on alternative sensors. Such sensors may include ion current sensors, engine block accelerometers, engine speed sensors, or crankshaft torque sensors. The work presented in this paper focuses on the use of a crankshaft torque sensor.

One of the most important combustion properties to control, and thereby also to estimate, is the combustion phasing. This property indicates the timing of the combustion in relation to the piston's position in the cylinder. The reason for its importance is its strong correlation with both engine efficiency and emissions, see Heywood (1988). A common way of establishing a measure of combustion phasing is to define it as the piston position where half of the injected fuel mass has burned, referred to as 50% burned mass fraction, and thereby relate it to the cylinder pressure based calculation of burned mass fraction. However, when using measurements from a crankshaft torque sensor it is no longer possible to directly calculate the burned mass fraction. A method for torque domain combustion phasing estimation, or alternatively a method for estimation of burned mass fraction from torque, is therefore needed in this case. Such a torque domain method, referred to as torque ratio and introduced in Andersson and McKelvey (2004b), exists but can be computationally expensive. Alternative methods are therefore of interest.

This paper investigates combustion property estimation methods that are based on combustion net torque, first seen in Thor, Egardt, McKelvey, and Andersson (2011), instead of torque ratio. The analytical relation between combustion net torque and burned mass

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http://dx.doi.org/10.1016/j.conengprac.2014.01.014

Nomenclature

x	vector with scaled burned mass fraction rates (1/CAD)
$\hat{x}$	estimated vector with scaled burned mass fraction rates (1/CAD)
$\theta_{T_c}^{\nu_i}$	Crank angle position on the positive T_c flank (CAD)
θ_{T_c}	vector with crank angle positions on the positive T_c flank (CAD)
θ'_{T_c}	intermediate θ_{T_c} vector (CAD)
ν_i	T_c flank fraction (dimensionless)
n_p	number of $\theta_{T_c}^{\nu_i}$ points (dimensionless)
n_f	number of basis functions (dimensionless)
φ	basis function parameter vector
λ_0	basis function parameter (CAD)
λ_i	basis function parameter (dimensionless)
ϕ	basis function parameter (1/CAD)
ψ	basis function parameter (CAD)
J	performance criterion (CAD^2)
N	number of engine cycles (dimensionless)
ρ	correlation coefficient (dimensionless)
Q	released chemical energy (J)
Q_{tot}	total released chemical energy (J)
γ	ratio of specific heats (dimensionless)
p	cylinder pressure (Pa)
p_m	motored cylinder pressure (Pa)
p_0	cylinder pressure at datum point (Pa)
V	cylinder volume (m^3)
V_r	volume ratio function (dimensionless)
V_r^{LT}	lower triangular volume ratio matrix (dimensionless)
V_0	cylinder volume at datum point (m^3)
θ	Crank angle reference (CAD)
$\overline{\theta}$	Crank angle reference vector (CAD)
θ_0	Datum point (CAD)
$\theta_{x_b 50}$	50% burned mass fraction (CAD)
$\hat{\theta}_{x_b 50}$	estimated 50% burned mass fraction (CAD)
Θ	cylinder gas temperature (K)
U	internal energy (J)
W	work (N m)
Θ_0	cylinder gas temperature at datum point (K)
x_b	burned mass fraction (dimensionless)
β	Vibe function amplitude (dimensionless)
n	number of Vibe functions (dimensionless)
κ	constant (J)
h	Vibe function (dimensionless)
a	Vibe function shape parameter (dimensionless)
μ	Vibe function shape parameter (dimensionless)
R	mass specific gas constant (J/kg/K)
m	cylinder gas mass (kg)
m_0	cylinder gas mass at datum point (kg)
θ_{soc}	Vibe function start parameter (CAD)
$\Delta\theta$	Vibe function duration parameter (CAD)
x_{egr}	EGR fraction (dimensionless)
$\dot{m}_{egr}$	EGR mass flow (kg/s)
$\dot{m}_{air}$	air mass flow (kg/s)
T	torque (N m)
$\hat{T}$	estimated torque (N m)
T_c	combustion net torque (N m)
T_m	motored torque (N m)
T_m^D	diagonal motored torque matrix (N m)
A	Piston area (m^2)
L	Crank lever (m)
c_v	cylinder gas specific heat at constant volume (J/kg/K)
c_p	cylinder gas specific heat at constant pressure (J/kg/K)
δ	Crank angle difference (CAD)

fraction is described and two new estimation methods are proposed, one that estimates entire burned mass fraction traces from combustion net torque and another that directly estimates combustion phasing. The properties and performance of the proposed methods are thoroughly studied using both simulations and experimental data. A short introduction to crankshaft torque measurements and processing is also given.

2. Simulations and experimental setup

The study described in this paper uses both simulations and experiments as tools for investigating the properties of the proposed combustion net torque based methods for combustion property estimation. This section provides necessary details about these tools.

2.1. Cylinder pressure simulation

The simulations used in this work generate cylinder pressure traces from specified burned mass fraction traces in order to facilitate the investigation of combustion net torque for a large variety of combustion events. Burned mass fraction is a description of how the combustion evolves over time and is traditionally estimated from cylinder pressure measurements using one of the numerous existing methods, the first introduced in Rassweiler and Withrow (1938). Another approach, taken here, is to model the burned mass fraction based on the first law of thermodynamics using a single-zone heat release model similar to the one described in Gatowski et al. (1984). However, some simplifications have been made to this model as effects from mass flows, both fuel injection and flows in and out of crevice regions, and heat transfer are neglected. The result is often referred to as net heat release, see e.g. Heywood (1988). Given a cylinder pressure trace, this model describes the rate with which the chemical energy, $Q(\theta)$, is released as

$$\frac{dQ(\theta)}{d\theta} = \frac{\gamma}{\gamma-1} p(\theta) \frac{dV(\theta)}{d\theta} + \frac{1}{\gamma-1} V(\theta) \frac{dp(\theta)}{d\theta} \qquad (1)$$

Here, γ is the ratio of specific heats, $p(\theta)$ is the cylinder pressure, $V(\theta)$ is the cylinder volume, and θ is the angle reference expressed in crank angle degrees (CAD). Details on the derivation of (1) are available in Appendix A. Based on the released chemical energy, the burned mass fraction, $x_b(\theta)$, is estimated according to

$$x_b(\theta) = \frac{Q(\theta)}{Q_{tot}} \qquad (2)$$

where Q_{tot}, the total amount of energy released by the combustion, is described by

$$Q_{tot} = \max_{\theta} Q(\theta) \qquad (3)$$

If complete combustion efficiency is assumed, the right-hand side in (3) is equivalent to $m_f q_{lhv}$, where m_f is the total mass of the injected fuel and q_{lhv} is the injected fuel's mass specific lower heating value. Finally, as a measure of combustion phasing, the 50% burned mass fraction angle, $\theta_{x_b 50}$, is defined as

$$x_b(\theta_{x_b 50}) = 0.5 \qquad (4)$$

If, instead of examining characteristics of the combustion given a measured cylinder pressure trace, it is of interest to investigate the