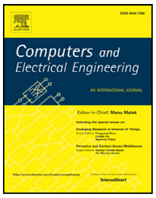
Computers and Electrical Engineering 000 (2017) 1–16

Contents lists available at ScienceDirect

Computers and Electrical Engineering

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



On-line indicated torque estimation for internal combustion engines using discrete observer[☆]

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ARTICLE INFO

Article history:
Received 2 August 2016
Revised 2 January 2017
Accepted 2 January 2017
Available online xxx

Keywords:
Internal combustion engines
Indicated torque
Sliding mode observer
Numerical modeling

ABSTRACT

Indicated torque of internal combustion engines (ICEs) is strongly associated with the evaluation and control of engine automations, emissions and faults. Traditional indicated torque estimation requires high-cost and low-durable sensors to measure cylinder pressure. Alternatively, estimating the indicated torque from the instantaneous crankshaft speed provides promising practical application potentials. This paper proposed a discrete sliding model observer (SMO) to on-line estimate the ICE indicated torque from its crankshaft speed fluctuation. Firstly, a crankshaft dynamic model of a six-cylinder ICE was established to describe the interaction between the engine torque and instantaneous speed. Then, the discrete SMO was designed to estimate the indicated torque from the crankshaft model. An experimental validation was conducted by using a 6135 G diesel engine. The analysis results demonstrate that the present discrete SMO can effectively estimate the ICE indicated torque, and hence, can provide great potential for on-line monitoring and control of ICEs in practical applications.

1. Introduction

With crucial concern on global environment and energy, automobile manufacturers strike to maintain good fuel economy of internal combustion engines (ICEs) to meet strict emission legislations [1]. Indicated torque, cylinder pressure, and load torque are regarded as the most basic performance parameters in ICEs and have been used to develop control signals to balance the conflict between the fuel economy and emissions [2]. In addition, indicated torque is very useful for condition assessment of ICE combustion [3]. Hence, it is important to obtain accurate indicated torque, cylinder pressure and load torque for optimal ICE control and diagnostic–subject to constrain of emission legislations.

Traditionally, in-cylinder pressure is measured directly using intrusive transducers [2]. The indicated torque can be then calculated according to the in-cylinder pressure and the engine geometry. However, it is often difficult to install the transducers into the cylinders because the installation involves changing the combustion chamber structure [1]. Moreover, the transducer software-hardware systems are costly and the transducers are readily to damage due to extremely harsh thermal environment. Although some low-cost transducers have been introduced into ICE pressure perception, for multi-cylinder

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[☆] Reviews processed and recommended for publication to the Editor-in-Chief by Guest Editor Dr. Z. Zheng.

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http://dx.doi.org/10.1016/j.compeleceng.2017.01.002
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engines (e.g., 6 cylinders), the price and reliability issue of the sensor systems is still a challenge [3]. Consequently, the transducer-based direct measure method is currently not suitable for most of practical scenarios though it can provide highly precise estimation results.

In order to overcome the limitations of transducers, some indirect techniques are developed to estimate ICE indicated torque/cylinder pressure from the crankshaft instantaneous speed. This is because, if ignore flexible deformation, an ICE can be considered as a dynamic system with indicated torque and load torque as the input and output, respectively, and any changes of the output torque caused by the system input are eventually transferred as the crankshaft speed fluctuations [4]. Hence, the crankshaft instantaneous speed contains important information about the indicated torque. This hidden information in the instantaneous speed can be used to reconstruct the indicated torque/cylinder pressure by three methodologies, i.e., response-function mapping box [5], statistical mapping [6,7], and crankshaft-dynamic estimation [1]. The first one use relationship between the crankshaft speed transients and indicated torque to establish a suitable response function, which can map the speed fluctuations to its corresponding indicated torque changes. In order to obtain the mapping box, the artificial neural networks [5] and fuzzy interference [8] have been applied to ICEs. The back-propagation neural network (BPNN) is the most popular one applied to ICE torque estimation. Togun and Baysec [9] used BPNN for gasoline engine torque estimation, Arcaklioglu and Cxelıkten [10] adopted BPNN for torque estimation of turbocharged diesel engines, and Zweiri and Seneviratne [11] employed BPNN for a single-cylinder diesel engine torque prediction. In order for on-line estimation, Hua et al. [12] presented the cerebellar model network and Ge et al. [13] proposed the Elman neural network for ICE indicated torque estimation. Li et al. [14] combined the ICE combustion model and neural network to on-line prediction of indicated torque. However, these mapping boxes required sufficient training samples with known knowledge about the indicated torque/cylinder pressure. The same issue exists in the statistical mapping models. It is always difficult to get enough samples in practice [3]. The third methodology uses the crankshaft-dynamic model to predict the indicated torque/cylinder pressure [15]. Because in most ICEs the speed sensors have been already installed, it is convenient to input the sensor data into the crankshaft-dynamic model to obtain the torque response. Hence, establishing an effective crankshaft-dynamic model does not require completing a large number of experiments [16]. The indicated torque/cylinder pressure can be simply estimated by applying an observer to the crankshaft-dynamic model. The Kalman Filter [17], high gain observer [2], model reference adaptive system [18] and sliding mode observer (SMO) [19], have been applied to estimate indicated torque for ICEs. Since SMO is simple and has good stability even with large model uncertainty and external disturbance [19], it is applicable for indicated torque estimation under not only steady state operation but also under transients [2]. Thus, SMO has received more attention in indicated torque estimation than the other observers. However, most SMOs were designed for off-line indicated torque estimation [2]. Off-line estimation is based on the collection of experimental data, and the estimation result is usually used to verify the designed methods but not used by the on-board vehicle control system to control and monitor the operation of the engines. By contrast, on-line estimation is permanently connected to the on-board vehicle control system. The prediction result is directly used for the engine control. An on-board SMO-based observer for indicated torque estimation is more profitable for ICEs [20]. Although the rapidly developed computer-hardware nowadays enables to conduct a large amount of calculation in a very short time, it is always a good choice to design discrete-time SMOs for practical application of ICE indicated torque estimation [20]. This is because, on one hand, it is computationally efficient to implement SMO in discrete-time domain, and on the other hand, it is necessary to design discrete SMOs for the slowly-sampled crankshaft-dynamic model. As a result, discrete-SMO is suitable and applicable for on-board estimation of ICE indicated torque in practical use. However, very limited work has been done to address the discrete-SMO for ICE indicated torque estimation, and to the best of our knowledge, little research has been found in the estimation of indicated torque for multi-cylinder engines using discrete-SMO [19]. Therefore, it is worth investigating discrete-SMO for ICE indicated torque estimation.

In order to address the aforementioned issue, this paper considers the sliding mode observer for the discrete-time estimation of a six-cylinder diesel engine. The goal of the present discrete-SMO is to realize on-line estimation of indicated torque of the diesel engine. The contribution of this paper is that a discrete-SMO method is proposed based on the crankshaft dynamic model of the six-cylinder engine for the purpose of on-line indicated torque estimation. In addition, an engine load torque calculation method is presented by comparing the mean minimum estimated indicated torque between engine idle running and load condition. The effectiveness of the proposed approach was evaluated using experimental data acquired from both normal and misfire-fault operating conditions of the diesel engine.

The remainder of this paper is organized as follows. Section 2 presents the crankshaft dynamic model of a six-cylinder ICE. In Section 3, a SMO that adopted the saturation function and exponential approach law is proposed to estimate the indicated torque. The performance of the SMO on indicated torque estimation is evaluated using experimental data in Section 4. Section 5 discusses the discretization of the designed SMO for on-line estimation of indicated torque. The conclusions of this study are drawn in Section 6.

2. Crankshaft dynamic model

A crankshaft dynamic model involves with the variations of reciprocating inertia torque, cylinder indicated torque, external load torque and friction torque in the rotational motion [1]. External load torque is a slowly varying variable, and hence, can be considered as a constant in a single cycle. The establishment of each torque component in the crankshaft dynamic model is described in the following section.

Please cite this article as: L. Zhixiong et al., On-line indicated torque estimation for internal combustion engines using discrete observer, Computers and Electrical Engineering (2017), http://dx.doi.org/10.1016/j.compeleceng.2017.01.002