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Recursive parameter estimation of exhaust gas oxygen sensors with input-dependent time delay and linear parameters

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ABSTRACT

Exhaust gas oxygen sensors are widely used for emission control in internal combustion engine systems. Due to their working principle and their positioning, these sensors are subject to input-dependent time delays and input-dependent linear parameters. Consequently, the corresponding time delays and linear parameters can vary fast, i.e. at the same rate as the respective input signals. This paper presents an extension of an existing gradient-based least-squares algorithm and its application to recursively estimate the input-dependent time delays and linear parameters of wide-range oxygen sensors in diesel engines. The extended algorithm is applied in a detailed simulation and experimental study involving real wide-range oxygen sensors that are affected by drift, aging, clogging and manipulation. The input-dependent time delay and linear parameter estimates obtained with the proposed recursive algorithm accurately reproduce the estimates obtained with a numerical offline optimization procedure.

1. Introduction

Many emission control systems in diesel engines are based on measurement signals obtained from wide-range exhaust gas oxygen sensors (Robert Bosch GmbH, 2004). The working principle and the positioning of these sensors in the exhaust pipe imply that they are subject to input-dependent time delays and input-dependent linear parameters as shown in Moser, Onder, and Guzzella (2013), Brück (2010), Klett et al. (2005) and experimentally investigated in this paper. Due to drift, clogging, aging and manipulation the input-dependent time delays and linear parameters can be subject to variation during the lifetime of the sensor.

However, designs of emission control systems often rely on the accurate knowledge of these quantities. Controller adaptation techniques can be used to account for such known variations of the time delay and other system parameters. For this purpose, accurate parameter and time delay estimation of oxygen sensors is crucial to maintaining the performance of emission control systems over their lifetime.

The estimation of parameters and especially time delays has been under research for several decades. Many survey publications review the known approaches for time delay estimation, for instance (Björklund & Ljung, 2003; Ferretti, Maffezzoni, & Scattolini, 1995; Fertner & Sjölund, 1986; O'Dwyer, 2000, 1996; O'Dwyer & Ringwood, 1999; Viola & Walker, 2003). In the following, several time delay estimation techniques are reviewed, which are not based on specific excitation scenarios. The goal of this literature review is to find an existing algorithm that can be adapted to estimate the input-dependent time delays and linear parameters of wide-range oxygen sensors in diesel engines.

A very common approach for time delay estimation is the correlation technique, see Fertner and Sjölund (1986), Viola and Walker (2003), Barsanti and Tummala (2003), Benesty, Chen, and Huang (2004), Chen, Benesty, and Huang (2006), Dooley and Nandi (1998), Elnaggar, Dumont, and Elshafei (1990), Grennberg and Sandell (1994), Hertz (1986), Jacovitti and Scarano (1993), Knapp and Carter (1976), Mamat and Fleming (1995), Najafi, Zekri, and Askari (2010), Ni, Shah, and Xiao (2008), Ni, Xiao, and Shah (2010), Nikias and Pan (1988), Park and Nam (2002), Rad, Lo, and Tsang (2003),Tabaru (2007) for examples thereof. The correlation technique is usually applied offline using a batch of input and output data or in a quasi-online way using a moving window data batch. As every estimation approach does, the correlation technique requires sufficient input excitation. However, it is not restricted to a characteristic input excitation scenario.

Due to its infinite dimensional nature no exact rational description of the time delay exists in the Laplace domain. Thus, time delay approximation techniques such as the Padé (Agarwal & Canudas, 1987; Durbin, 1985; Gawthrop & Nihtilä, 1985; Jones, 2004; O'Dwyer & Ringwood, 1994) or the Laguerre (Björklund & Ljung, 2009; Fischer & Medvedev, 1999; Hidayat & Medvedev, 2012; Isaksson, Horch, & Dumont, 2001) approximations have been developed. The publications listed present time delay estimation approaches that are based

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on such rational approximations of the time delay. The rational approximation of the time delay enables the application of linear parameter estimation algorithms. However, these approaches suffer from the drawback that they are restricted to rather small time delays, compared to the sampling interval of the system (only few multiples of the sampling interval). To overcome this drawback, various heuristic extensions of these approaches have been developed, which for instance can be found in the publications (Agarwal & Canudas, 1987; Durbin, 1985; Gawthrop & Nihtilä, 1985; Jones, 2004; O'Dwyer & Ringwood, 1994; Björklund & Ljung, 2009; Fischer & Medvedev, 1999; Hidayat & Medvedev, 2012; Isaksson et al., 2001).

Another approach for time delay estimation is the overparameterization method as presented for instance in Kurz and Goedecke (1981). The idea of that approach is to consider a weighted sum of multiple time delay shifted copies of the same input signal. The input weights are estimated using a standard linear parameter estimator. The input copy resulting in the largest weight designates the time delay present. This approach allows linear estimation techniques for time delay estimation to be used. However, depending on the time delay discretization chosen the approach can cause problems due to the large number of parameters to be estimated.

A widely used approach is the two-step parameter and time delay estimation (Elnaggar et al., 1990; Ahmed, Huang, & Shah, 2006; Bedoui, Ltaief, Abderrahim, & Ben Abdennour, 2011; Elnaggar, 1990; Elnaggar, Dumont, & Elshafei, 1989, 1990; Ettaleb, Dumont, & Davies, 1998; Ferretti, Maffezzoni, & Scattolini, 1991; Majdaldin, Marzieh, & Javad, 2007; Shafai & Roduner, 1997; Short, 2012; Wang, Liu, & Zhang, 2007; Zheng & Feng, 1991). The key idea of that approach is to divide the estimation of the linear system parameters and the time delay in two individual steps. Given a known time delay, the procedure thus consists of sequentially estimating the linear parameters of the system and vice versa until all the estimates have converged. The estimation of the linear parameters allows standard estimation techniques for linear parameters to be used. The time delay estimation is performed iteratively, for instance based on an analysis of the current estimates of the linear system parameters. As an example, the knowledge of the estimated zeros of the system can be used to direct the time delay estimation.

Other techniques simultaneously estimate the linear system parameters and the time delay. Gradient-based estimation approaches (Boer & Kenyon, 1998; Diop, Kolmanovsky, Moraal, & van Nieuwstadt, 2001; Etter & Stearns, 1981; Nordsjö, 1998; O'Dwyer, 2000; Ren, Rad, Chan, & Lo, 2005; Robinson & Soudack, 1970; Tuch, Feuer, & Palmor, 1994; Zhou & Frank, 2000) use a recursive algorithm whose convergence is determined by the first- or second-order gradient of a chosen error criterion. Due to the fact that the time delay shifts the input signal in time, the system nonlinearly depends on the variable which defines the time delay. Hence, the gradient of the error criterion with respect to this time delay variable cannot be calculated explicitly but needs to be approximated. In Banyasz and Kevtczky (1994), Bedoui, Ltaief, and Abderrahim (2013a), Bedoui, Ltaief, and Abderrahim (2012a), Bedoui, Ltaief, and Abderrahim (2012b), Bedoui, Ltaief, and Abderrahim (2012c), Bedoui, Ltaief, and Abderrahim (2013b), Bedoui, Ltaief, and Abderrahim (2013c), Lim and Macleod (1995) a first-order approximation of the gradient with respect to the time delay variable using the corresponding difference quotient is used.

The listed approaches can be further classified into batch approaches and recursive approaches. Batch approaches, to which belong most correlation techniques, are characterized by the recording and storing of signals, followed by the evaluation of the data. They are suitable if sufficient storage memory is available. Usually they have fewer convergence problems than recursive approaches do. If these batch approaches are applied for online parameter estimation they have to be implemented using a moving window that captures a desired data horizon. In contrast, recursive approaches, for instance many gradient-based algorithms, require a minimal amount of data storage. However, convergence of these algorithms cannot always be guaranteed.

To estimate and track slowly varying parameters the chosen algorithms should incorporate forgetting of past data. Slowly in the context of parameter variation means that the rate of parameter change is significantly slower than the rate of change in the input and output signals of the system under consideration. The forgetting can be used to put more weight on recent data than on earlier data. Recursive least squares techniques are the most common parameter estimation methods that can incorporate forgetting.

However, as experimentally shown in Section 3.3 wide-range oxygen sensors in the exhaust pipe of diesel engines feature parameters and time delays which vary at the same rate as an input signal of the system, because these variables directly depend on the respective input signal.

In Sun and Yang (2011) a moving horizon parameter and time delay estimation approach is proposed which is able to estimate a time delay that is a function of a known input signal. The proposed approach uses numerical offline optimization tools like mean least squares combined with branch and bound techniques to solve the mixed integer nonlinear programming problem to estimate the parameters and the input-dependent time delay. The time delay is known to be a multiple of a measurable input signal. A simulation study is presented which shows the trace of the true and the estimated time delay. The drawback of the proposed approach is its need for a numerical parameter optimization within the moving horizon window requiring large computational resources.

In view of a real-time capability with restricted computational resources, this paper proposes to use a recursive algorithm to estimate the input-dependent time delays and input-dependent linear parameters of oxygen sensors in diesel engines. Amongst the time delay estimation approaches reviewed above, gradient-based approaches allow the straightest extension to the estimation problem at hand.

This paper provides an extended reformulation of the known gradient-based, recursive estimation algorithms (Banyasz & Kevtczky, 1994; Bedoui et al., 2012a, 2012b, 2012c, 2013a, 2013b, 2013c; Lim & Macleod, 1995), using first-order gradient approximations for the nonlinear parameters given by the variables describing the input-dependent time delay. The nature of these variables implies that the gradient with respect to them cannot be calculated analytically like for other nonlinear parameters, but has to be approximated. Furthermore, the extension of the algorithm presented in this paper involves a formulation for equation error (EE) as well as output error (OE) models.

The main contribution of this paper is given by an extensive simulation and experimental study of drift, clogging, aging and manipulation of wide-range oxygen sensors in diesel engines using the extended recursive estimation approach proposed.

The paper is structured as follows. In Section 2 the derivation of the proposed extension of the existing algorithm is presented. The resulting general formulation of the algorithm allows to recursively estimate input-dependent time delays and linear parameters. In Section 3 the algorithm is applied to monitor wide-range oxygen sensors installed in the exhaust pipe of diesel engines. Based on measurement data, analytical expressions for the input-dependent characteristic curves of the time delay and the linear system parameters of these sensors are derived. The algorithm is successfully applied in a simulation study as well as in an experimental study using real sensors. The paper finishes with a conclusion summarizing the contribution of this work.

2. Method

This section presents a general extension and reformulation of a recursive estimation algorithm to cope with systems with