Control Engineering Practice 65 (2017) 26–35

Contents lists available at ScienceDirect

Control Engineering Practice

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

Adaptive feedforward control of exhaust recirculation in large diesel engines

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ARTICLE INFO

Keywords:
Exhaust gas recirculation
EGR
Diesel engines
Feedforward control
Adaptive control

ABSTRACT

Environmental concern has led the International Maritime Organization to restrict NO_x emissions from marine diesel engines. Exhaust gas recirculation (EGR) systems have been introduced in order to comply to the new standards. Traditional fixed-gain feedback methods are not able to control the EGR system adequately in engine loading transients so alternative methods are needed. This paper presents the design, convergence proofs and experimental validation of an adaptive feedforward controller that significantly improves the performance in loading transients. First the control concept is generalized to a class of first order Hammerstein systems with sensor delay and exponentially converging bounds of the control error are proven analytically. It is then shown how to apply the method to the EGR system of a two-stroke crosshead diesel engine. The controller is validated by closed loop simulation with a mean-value engine model, on an engine test bed and on a vessel operating at sea. A significant reduction of smoke formation during loading transients is observed both visually and with an opacity sensor.

1. Introduction

Emissions of CO_2, SO_x and NO_x have in recent years received an ever growing attention due to their environmental effects. The International Maritime Organization (IMO) has introduced a stepwise restriction to NO_x emissions from marine diesel engines, so far culminating in the Tier III standard (International Maritime Organization, 2013). For large two-stroke diesel engines this standard dictates a reduction by a factor of four compared to the Tier II standard and applies to vessels built after 1st of January 2016 when operating in specified NO_x Emission Control Areas (NECAs). As for now the North American coastal area is a NECA but serious steps have been taken toward including the North Sea and Baltic Sea as NECAs as well (HELCOM, 2016). The substantial reduction specified in the Tier III standard requires significant changes to the modern marine diesel engines and a number of solutions are being investigated and developed into products. The most common methods are to either remove NO_x from the exhaust with a selective catalytic reduction system or avoiding formation of NO_x in the first place either by implementing an exhaust gas recirculation system or by using a gas- or dual-fueled engine. This paper focuses on control of high-pressure Exhaust Gas Recirculation (EGR) for large two-stroke diesel engines.

The main source of NO_x emission from a large two-stroke diesel engine is thermal NO_x which is formed during the combustion process, where excessively high peak temperatures lead to reactions between nitrogen and oxygen. These reactions are known as the Zeldovich mechanism (Heywood, 1988). Recirculation of exhaust gas to the combustion process increases heat capacity and decreases the availability of oxygen, resulting in lower peak temperatures during combustion and thus decreased formation of NO_x. A simplified overview of the airflow of a large two-stroke engine with high-pressure EGR developed by MAN Diesel & Turbo is shown in Fig. 1. In the EGR string (on the left) exhaust gas is cleaned and cooled in the EGR Unit, pressurized by the EGR blower and mixed into the scavenge flow.

The amount of air that is to be recirculated in the EGR string is implicitly decided by calculation of a number of operating points in which the NO_x emission is within the legislated limits. These points are characterized by engine load and molar scavenge receiver oxygen fraction (O_{sr}) as seen in Fig. 2. The goal of the EGR controller is then to reach this O_{sr} setpoint given the engine load condition.

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http://dx.doi.org/10.1016/j.conengprac.2017.05.003
Received 12 October 2016; Received in revised form 11 March 2017; Accepted 12 May 2017
0967-0661/

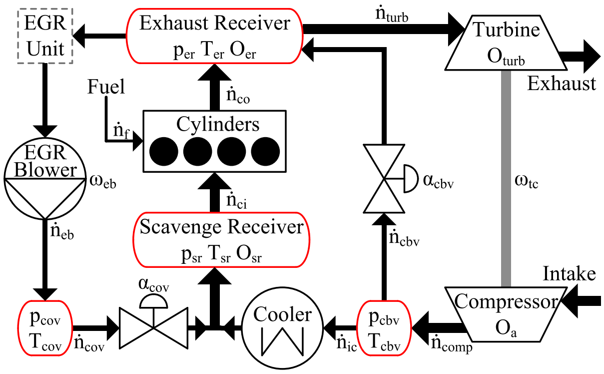

Fig. 1. Overview of main gas flows and components of the engine with exhaust gas recirculation and cylinder by-pass valve.

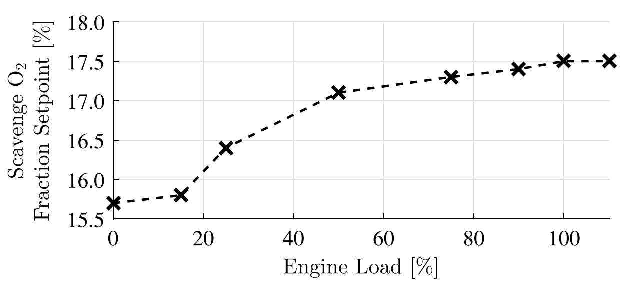

Fig. 2. An example of required scavenge oxygen fraction as a function of engine load. The linearly interpolated commissioning points are specific to the engine.

The reference EGR controller applies fixed gain proportional–integral feedback control. In steady engine load scenarios the O_{sr} setpoint is kept within desired bounds but whenever the engine load (and thus the fuel flow) changes, the EGR controller is in trouble. The slow nature of the system and a significant delay in the measurement of O_{sr} limit the possible disturbance rejection of the feedback control. In fast loading transients an increase in fuel injection decreases the oxygen fraction in the recirculated gas and thus less gas should be recirculated to keep the oxygen fraction in the scavenge mix at its setpoint. The delayed measurement and late reaction of the EGR controller can result in severe negative peaks in O_{sr} leading to formation of black exhaust smoke for more than 45 s. With the PI EGR controller it is necessary to restrict the engine loading rate in order to avoid this smoke. However, such a solution is not viable as the NECAs mainly cover ports and coastal areas where maneuvering capability is essential.

1.1. Literature

Extensive treatment of combustion engine processes and modeling can be found in works such as Eriksson and Nielsen (2014), Guzzella and Onder (2010) and Heywood (1988). Relevant treatment of large two-stroke crosshead engines mainly include governor design (engine speed control) as found in Banning, Johnson and Grimble (1997), Blanke (1986), Blanke and Nielsen (1990), Winterbone and Jai-In (1991) and Xiros (2002). This led to investigation and development of dynamical models of engine speed response, where turbocharger dynamics were proven to have a significant effect (Blanke & Andersen, 1984; Hendricks, 1986; Woodward & Latorre, 1985). IMO's stepwise introduction of NO_x emission limits led to research into the use of variable geometry turbines as in Stefanopoulou and Smith (2000). A more recent development and investigation of a large two-stroke engine model without EGR was recently published in Baldi, Andersson and Theotokatos (2015), Guan, Theotokatos and Chen (2015), Guan, Theotokatos and Zhou (2014), Theotokatos (2010) and Theotokatos and Tzelepis (2015).

Only few publications have been made about the EGR control for large two-strokes. Hansen et al. published two papers about modeling and control, respectively (Hansen, Blanke, Niemann & Vejlgaard-Laursen, 2013; Hansen, Zander, Pedersen, Blanke & Vejlgaard-Laursen, 2013). The model was extended and improved by Alegret et al. in Alegret, Llamas, Vejlgaard-Laursen and Eriksson (2015) by introducing the Cylinder By-pass Valve (CBV), changing the parameter estimation scheme and the development of a new exhaust temperature calculation. The authors of the present paper made a number of further extensions to the same model in Nielsen, Blanke, Eriksson and Vejlgaard-Laursen (2017), where a simpler control-oriented model (COM) of the scavenge oxygen fraction was derived as well. A similar COM had earlier been presented in Nielsen, Blanke and Vejlgaard-Laursen (2015) along with a nonlinear controller. A joint state and parameter observer for the COM was presented in Nielsen, Blanke and Eriksson (2017).

A much larger amount of publications are available on the EGR control for automotive engines, typically including a VGT (Huang, Zaseck, Butts, & Kolmanovsky, 2016; van Nieuwstadt, Kolmanovsky, Moraal, Stefanopoulou, & Jankovic, 2000; Wahlström & Eriksson, 2011a, 2011b, 2013; Wahlström, Eriksson, & Nielsen, 2010; Wang, Tian, Bosche, & El Hajjaji, 2014). An investigation into the effect of fuel mix on the intake oxygen fraction on an automotive engine with EGR and observer design for this system was published in Zhao and Wang (2013) and Zhao and Wang (2015). The design of EGR control for large two-stroke engines differ from the automotive engine especially in the differences between scavenging of 2-stroke and 4-stroke engines, lack of engine test bed availability (as explained in Xiros, (2002)), system time constants, sensor availability and the general maturity of the field.

1.2. Purpose

Existing EGR feedback control is able to control O_{sr} during steady operating conditions but suffers during loading transients. In Hansen and Blanke et al. (2013) it was shown that the achievable performance with SISO feedback control is limited. A nonlinear controller with direct use of fuel flow and turbocharger speed signals where suggested in Nielsen et al. (2015) but without thorough validation. The present paper extends the results from Nielsen et al. (2015) significantly. The main contributions of the present paper are

1. The controller concept introduced in Nielsen et al. (2015) is generalized to a class of first order Hammerstein systems that now include sensor delay.
2. Exponentially converging bounds of the control error are proven.
3. The controller is validated by closed loop simulation with an MVEM model, in an engine test bed and on a vessel operating at sea.

1.3. Outline of this paper

Section 2 provides a brief summary of the two EGR models used. Section 3 presents the new controller concept as generalized to a class of first order Hammerstein models and proves minimum convergence bounds of the control error. The control concept is applied to the control-oriented EGR model in Section 4. Section 5 shows the results of closed loop simulation and presents experimental validation both on an engine test bed and on a vessel operating at sea.

2. EGR system models

The controller presented in this paper is designed by the use of mathematical models of the EGR system behavior. A high-fidelity mean-value engine model (MVEM) is used for validation of closed loop properties. Controller synthesis by linearizing a similar MVEM was investigated in Hansen and Blanke et al. (2013) where it was shown difficult to achieve both performance and robustness. The MVEM model